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Modeling and Control of Integrated STATCOM-SMES System to Improve Power System Oscillations Damping

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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 also to respond rapidly to emergencies. However, during the past decade, numerous significant sized blackouts occurred worldwide that resulted in serious economic losses. Therefore, the conclusion has been reached that the ability of the current PFC to meet an emergency is poor, and security of power systems should be improved. An alternative to enhance the PFC and thus security is to store excessive amounts of energy during off-peak load periods in efficient energy storage systems for substituting the primary control reserve. In this sense, superconducting magnetic energy storage (SMES) in combination with a static synchronous compensator (STATCOM) is capable of supplying power systems with both active and reactive powers simultaneously and very rapidly, and thus is able to enhance the security dramatically. In this paper, a new concept of PFC based on incorporating a STATCOM-SMES is presented. A complete detailed model is proposed and a new control scheme is designed, comprising an enhanced frequency control scheme, and a fully decoupled current control strategy in *d-q* coordinates with a novel controller to prevent dc bus capacitors voltage drift/imbalance. The performance of the proposed control schemes is validated through digital simulation carried out using MATLAB/Simulink.

Keywords: Energy storage, FACTS, Primary frequency control, SMES, STATCOM

1. Introduction

Primary frequency control (PFC) is one of the key means in order to ensure the stability and security of power systems. It can regulate short period random variations of frequency during normal operating conditions and respond rapidly to emergencies through proper activation of the available spinning reserve. However, during the past decade, numerous blackouts of significant size occurred worldwide that resulted in serious economic losses [1]. Therefore, it has been concluded that the ability of the current PFC to meet an emergency is poor, and security of all power systems (PS) should be improved [2]. In fact, this situation has become worse over the past few years with the significant growth of electric energy demand, in combination with financial and regulatory constraints, which has forced power utilities to operate the PS near its stability limits. Under the occurrence of such load changes, the system may be heavily perturbed from its normal operating state and oscillate; the stabilization of these oscillations (or swings) not being expected due to the low response of the conventional PFC. Generator governors may no longer be able to compensate for such power flow changes, therefore leaving them incapable of providing sufficient damping to the electric system [3]. In addition, as ongoing deregulation of power markets is currently taking place, generation and transmission resources are being utilized at higher efficiency rates, leading to a tighter control of the spare capacity. This has given rise to many opportunities to interconnect local and regional systems. With these extra electrical links, new electromechanical oscillation modes between electrically coherent power plants or areas have been introduced [4]. However, these frequency oscillations may experience a serious stability problem. In this way, the efficient use of modern PS while maintaining security levels requires more sophisticated control schemes using advanced technologies.

To overcome this problem, a number of ways are available for damping low frequency oscillations in PS. Indeed, there are mainly two types of electromechanical oscillations to deal with, referred to as local mode and inter-area mode, corresponding to a single-machine-to-infinite-bus structure, and interconnected power systems respectively [5]. Local oscillations often occur when a fast exciter is used in the generator, and to stabilize these, power system stabilizers (PSS) were developed and are the most commonly used for these swing modes. In most cases, the PSS works well in damping oscillations; however, because the

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parameters of PSS are tuned to the original system parameters, its control has less flexibility, which means the control results are far from ideal when the operating conditions and/or structures of the system change.

Other modern controllers used to damp PS oscillations can include high-voltage dc (HVDC) lines and flexible ac transmission systems (FACTS). FACTS devices have the flexibility advantage of being located at the most appropriate places to achieve the best control results. However, these devices can only utilize and/or redirect the power and energy available on the ac system and thus are limited in the degree of freedom and sustained action in which they can help the electric grid. In contrast, FACTS controllers integrated with energy storage systems (ESS) has the advantages in both energy storage ability and flexibility of its power electronics interface. This technology permits the rapid and simultaneous control of active and reactive power, still preserving FACTS benefits, but adding a degree of freedom for increasing the effectiveness of the overall control. In this sense, the combination of a static synchronous compensator (STATCOM) with superconducting magnetic energy storage (SMES) has been proposed as one of the most effective stabilizers of power oscillation modes [6,7]. In this way, the main features of SMES systems, such as rapid response, high power, high efficiency, and four-quadrant control combined with the high controllability provided by the STATCOM, can be effectively used to enhance the performance of the PS.

This paper presents a new concept of PFC based on incorporating a STATCOM coupled with a SMES system. A complete detailed model of the STATCOM-SMES controller is proposed, including a three-level forty-eight-pulse voltage source inverter (VSI), which incorporates a two-quadrant three-level dc-dc converter as the interface between the STATCOM and the SMES. Based on the state-space averaging method, a new three-level control scheme is designed, comprising an enhanced frequency control scheme and a full decoupled current control strategy in the synchronous-rotating *d-q* reference frame with a novel controller to prevent dc bus capacitors voltage drift/ imbalance. The dynamic performance of the proposed control schemes is fully validated through digital simulation carried out by using SimPowerSystems (SPS).

2. Detailed Modeling of the STATCOM-SMES

Fig. 1 summarizes the proposed detailed model of the STATCOM-SMES for dynamic performance studies in high power systems. This model consists mainly of the STATCOM, the SMES coil with the related filtering and protection system, and the interface between the STATCOM and the SMES, represented by the dc-dc converter [7].

The STATCOM basically consists of the voltage source inverter with the 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 practice, conventional PWM switching techniques are regarded as uneconomic for high power applications since the VSI produces very high switching losses [8]. In this way, this work proposes a fundamental switching frequency scheme involving multi-connected, elementary three-level inverters in an appropriate multipulse arrangement. The VSI makes use of a three-level twelve-pulse structure, also known as neutral point

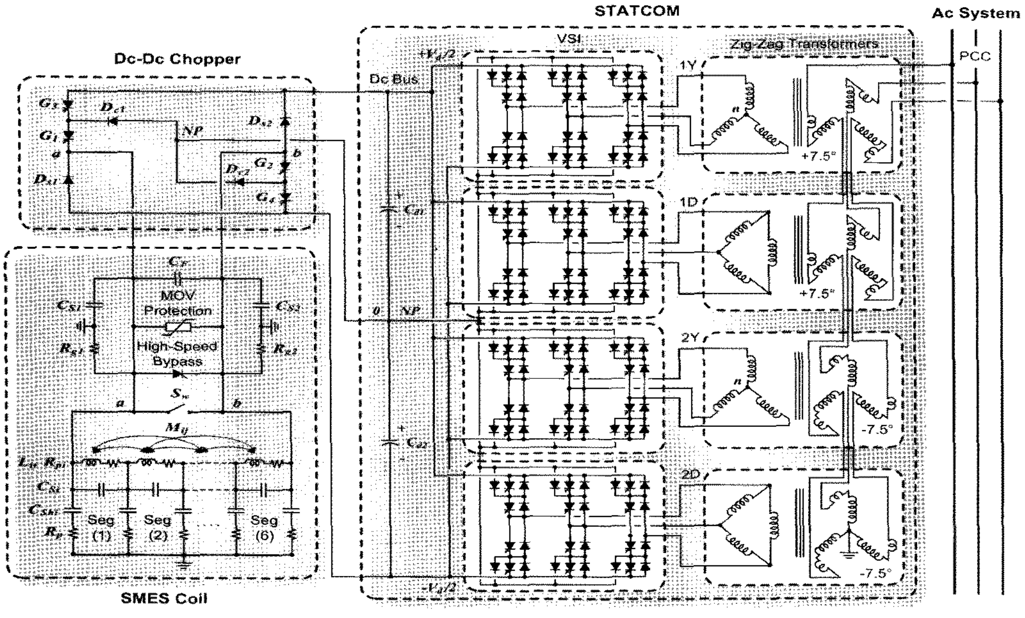


Fig. 1. Detailed model of the proposed STATCOM-SMES controller

clamped (NPC) structure, instead of a standard two-level six-pulse structure [9]. Thus, a pseudo forty-eight-pulse VSI topology that avoids using ac capacitor banks for harmonics filtering is created with just four transformers, while it maintains the advantages of multi-level inverters. This topology can be applied to reactive power generation almost without voltage imbalance problems. But when active power exchange is included, as is proposed here, the inverter can not have balanced voltages without sacrificing output voltage performance and auxiliary converters that would be needed in order to provide a compensating power flow between the capacitors of the dc link. For this reason, the use of a two-quadrant three-level dc-dc converter or chopper is proposed as the interface between the STATCOM and the SMES (top left side of Fig. 1), instead of a standard two-level one. This converter allows regulating the power exchange between the SMES coil and the STATCOM through a buck-boost topology control mode in opposition to a bang-bang control mode that is much simpler yet produces higher ac losses in the SMES coil [10,11]. Moreover, the chopper makes use of the extra level to solve the above-mentioned possible problems of voltage imbalance. This is achieved by employing the various redundant switching states for generating the same output voltage vector but with different charge balance of the dc bus capacitors.

The equivalent circuit of the SMES coil depicted at the bottom left side of Fig. 1 makes use of a lumped parameters network represented by a six-segment model comprising self inductances (L_i), mutual couplings between segments (i and j, M_{ij}), ac loss resistances (R_{si}), skin effect-related resistances (R_{pi}), turn-ground (shunt–C_{Shi}), and turn-turn capacitances (series–C_{Si}). This model is based on [12], and is reasonably accurate for electric systems transient studies, over a frequency range from dc to several thousand Hertz.

3. Novel Three-level Control Scheme of the STATCOM-SMES

The proposed hierarchical control of the integrated STATCOM-SMES consists of an external, middle, and internal level, as depicted in Fig. 2.

3.1 External Level Control Design

The external level control, which is outlined in Fig. 2 (left side), is responsible for determining the active and reactive power exchange between the STATCOM-SMES and the utility grid. This control strategy is designed for performing two major objectives with dissimilar priorities.

- Frequency control mode (FCM): Case of a STATCOM-SMES controller with active and reactive power exchange capabilities.
- Voltage control mode (VCM): Case of a traditional STATCOM with only reactive power compensation capabilities.

The frequency control mode is the highest-priority control mode accomplished by the upper blocks of the external level. This mode aims at controlling the PS frequency through the modulation of both the reactive component of the output current i_q (case of a conventional STATCOM) and the active component i_d (case of a STATCOM-SMES). In the case of controlling i_q, the set-point of the VCM, i.e. the voltage reference signal V_r, is varied with a stabilizer voltage signal proportional to Δf (defined as $f_r - f$) which directly represents the power oscillation of the PS. This added signal causes the output quadrature current of the STATCOM, i_q, to vary around the operating point defined by V_r, the purpose of this variation being to improve the damping of the power oscillations. In this way, the voltage at the PCC is forced to decrease when the frequency deviation Δf is positive aiming at reducing the transmitted power through the transmission system and thus providing an effective fast-acting voltage reduction reserve that opposes the deceleration of generators in the PS. This action is performed in the opposite way when the frequency deviation Δf is negative, and then generators accelerate. Two transfer functions, including a lag-compensator, are used to assist in shaping the gain and phase characteristics of the frequency stabilizer for the case of modulating the output quadrature current of the STATCOM.

Although the power oscillation damping approach of the standard STATCOM is rather effective, the most effective compensation action for power oscillation damping and thus for PFC is carried out by rapidly exchanging active power with the utility system, that is to say by controlling the output direct current of the STATCOM-SMES, i_d. Considering this case, as in the previous case, the reference of the STATCOM-SMES output direct current, i_{dr}, is directly derived from Δf. Since a robust and efficient frequency control scheme requires the effective damping of a wide range of generators' power oscillations, ranging from less than 0.2 Hz for global oscillations to 4 Hz for local oscillations of units, a flexible multi-band structure (MBS) controller is proposed in this work. Despite the potential of modern control techniques with different structures (adaptive control, neural networks, fuzzy control, etc.), power system utilities still prefer the fixed structure controller. In this way, the novel proposed compensator architecture depicted in Fig. 2 presents several degrees of freedom for achieving a robust tuning over a wide range of frequencies while keeping the same structure. The basic idea is to separate the frequency spectra into two decoupled bands for covering small signal frequency disturbances: the intermediate band is used for inter-area modes usually found in the range of 0.2

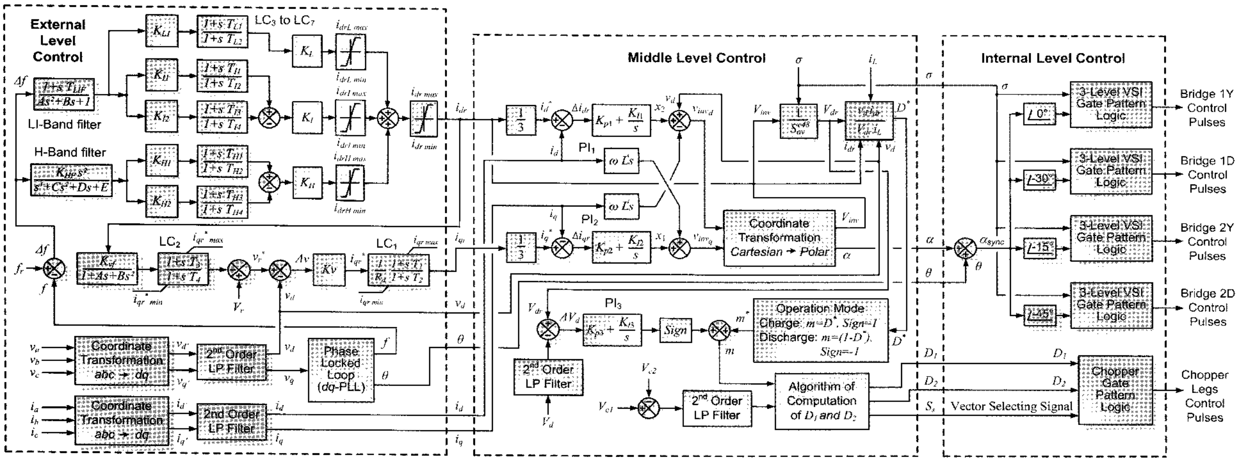


Fig. 2. Proposed three-level control scheme of the STATCOM-SMES device

to 1.0 Hz and the high band deals with local modes, either plant or inter-machines, with a typical frequency range of 0.8 to 4.0 Hz. Appropriate damping of power swings in both spectral bands require from the controller a frequency response with an increasing gain from low to high bands and phase leading in the whole range of action. This condition is achieved by employing differential filters synthesized through lead-lag compensators, providing intrinsic dc washout and zero gain at high frequency and phase leading up to the resonant frequency. Since the band-pass filters used show symmetry in respect to the central frequency for the gain response and asymmetry for the phase response, as is illustrated in the corresponding Bode locus of Fig. 3, the constraints are met by simply tuning the intermediate band filter at 0.9 Hz and the high pass filter at 8 Hz. Subsequently, the two resulting compensators are superposed in order to obtain a combined frequency stabilizer with an adequate phase characteristic for all small frequency deviation modes. Selection of the controller gains reflects a tradeoff between performance and robustness, resulting in satisfactory values in most studies for intermediate and high bands, 125 and 250 respectively.

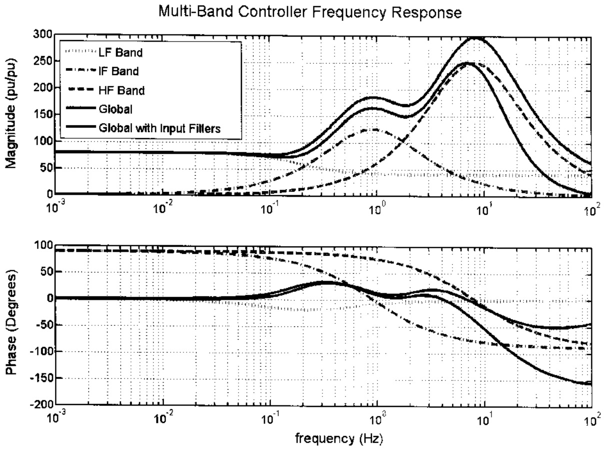


Fig. 3. Proposed frequency controller transfer function magnitude and phase versus frequency

In the case of large signal frequency disturbances characterized by common modes in the frequency range below 0.1 Hz, the controller experiences new constraints. Since the STATCOM-SMES participates in the primary frequency control, the gain needed for the low frequency band is lower than the previous two cases and roughly constant for all the spectral band of interest which extends from near dc to 0.1 Hz. A speed-droop (typically 3%) is also necessary to be included in order to obtain a stable load division among several fast-response devices operating in parallel. This characteristic is analogous to the one included in generators' speed governors. In these conditions, the low-pass filter is tuned at 0.12 Hz, with a gain for lower band of about 30 % of the high band and phase zero for all the range of action; thus ensuring an effective positive damping while maintaining performance and robustness in the intermediate and high bands. This frequency compensator structure controls the rapid active power exchange between the STATCOM-SMES and the PS, forcing the SMES coil to absorb active power when generators accelerate (charge mode), or to inject active power when they decelerate (discharge mode). This global architecture ensures almost the same good performance in damping power oscillations at all modes of interest. The resulting stabilizer signal composed from all bands is passed through a final limiter for setting the reference i_{dr}.

Two input frequency filters are used for processing the frequency deviation signal, Δf, obtained from the phase locked loop (PLL). The first one is associated with the low and intermediate bands, and guarantees a plane response in the 0 to 2.0 Hz range. The second input frequency filter is designed for the high band with a frequency range of 0.8 to 4 Hz. Fig. 3 depicts the frequency response of the band differential filters and the global response of the proposed multi-band controller including the effects of the input frequency filters. In all cases, the frequency signal is derived from the positive sequence components of the ac voltage vector measured at the PCC of the STATCOM-SMES, through a PLL. The design of the PLL is based on concepts of instantaneous power theory in the *dq* reference frame. This device also synchronizes, by providing the phase θ, the coordinate transformations from *abc* to *dq* components in the voltage and current measurement system. These signals are then filtered by using second-order low-pass filters in order to obtain the fundamental components employed in the control system.

The voltage control mode is the subordinate mode which has the goal of controlling (supporting and regulating) the voltage at the PCC to the electric grid. It has proved to have a very good performance in conventional STATCOM controllers through the modulation of the reactive component of the output current, i_{qr}. To this aim, in the present work the instantaneous voltage at the PCC is computed by employing a *d-q* synchronous-rotating reference frame. In consequence, the instantaneous values of the three-phase ac bus voltages are transformed into *d-q* components, v_d and v_q, respectively. By defining the *d*-axis always coincident with the instantaneous voltage vector v, v_d results equal to $|v|$ while v_q is set at zero. Consequently, only v_d is used for computing the voltage error vector which is introduced to a proportional-integral (PI) controller with output restriction including an anti-windup system to enhance the dynamic performance of the VCM system. A voltage regulation droop R_d (typically 5%) is included in order to allow a higher operation stability of the STATCOM-SMES device in cases that more high-speed voltage compensators are operating in the area. This characteristic is comparable to the one included in generators' voltage regulators. As a result, the PI controller including a droop feedback acts as an overall first-order lag-compensator.

3.2 Middle Level Control Design

The middle level control allows the expected output, specifically the actual active and reactive power exchange between the STATCOM-SMES and the ac system, to dynamically track the reference values set by the external level. The middle level control design, which is depicted in Fig. 2 (middle side), is based on a linearization of the state-space averaged mathematical model of the STATCOM-SMES in *d-q* coordinates described in [7], as follows:

$$s\begin{bmatrix} i_d \\ i_q \\ V_d \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{L'_s} & \omega & \frac{S_d^{e48}}{L'_s} \\ -\omega & \frac{-R_s}{L'_s} & \frac{S_q^{e48}}{L'_s} \\ -\frac{3}{C_d}S_d^{e48} & -\frac{3}{C_d}S_q^{e48} & -\frac{2}{R_pC_d} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ V_d \end{bmatrix} - \begin{bmatrix} \frac{|v|}{L'_s} \\ 0 \\ 0 \end{bmatrix}, \quad (1)$$

where:

R_s: equivalent resistance accounting for transformer winding resistance and VSI semiconductor conduction losses.

L'_s: equivalent leakage inductance in the *d-q* reference frame for the four VSI step-up transformers.

C_d: equivalent capacitance of the dc bus capacitors.

ω: synchronous angular speed of the network voltage at the fundamental system frequency f.

In order to achieve a decoupled active and reactive power control, it is required to provide a full decoupled current control strategy for i_d and i_q. Inspection of (1) shows a cross-coupling of both components of the STATCOM-SMES controller output current through ω. Therefore, in order to decouple the control of i_d and i_q, appropriate control signals have to be used. Thus, by employing conventional PI controllers with proper feedback of the STATCOM-SMES output current components, as shown in Fig. 2, i_d and i_q respond in steady-state to x_1 and x_2, respectively with no crosscoupling [7].

Fig. 2 (middle side) shows the implementation of (1) through the PI controllers. The coordinate transformation from Cartesian to Polar yields the required magnitude of the output voltage vector produced by the VSI (V_{inv}) and the phase-shift rating α of this vector from the reference position, represented by the voltage vector measured at the PCC of the STATCOM-SMES. From V_{inv}, the required voltage at the dc bus (V_{dr}) is derived and the duty cycle of the chopper thyristors (D^*) is estimated through a balance of dc power in the chopper, taking into consideration the active power injection ratings required from the STATCOM-SMES and the actual current of the SMES coil i_L. This estimated value yields m^* by relying on the various modes of operation of the dc-dc chopper (quadrants of operation). A corrective integral-type action (PI controller) is needed for an accurate computation of the duty cycle (m). Therefore, dc bus voltage deviations caused by actual VSI switching losses and capacitors power losses can be counteracted. Finally, duty cycles D_1 and D_2 are computed through a novel controller in order to prevent dc bus capacitor voltage drift/imbalance. This extra dc voltage control block provides the availability of managing the redundant switching states of the chopper according to the capacitors charge unbalance measured through the neutral point voltage, $v_{PN}=v_{c1}-v_{c2}$. It allows generating the same output voltage vector through various states but with dissimilar charge conditions on the *NP*, and thus maintaining the charge balance of the dc capacitors. In this way, this condition greatly reduces instability problems caused by harmonics in the STATCOM-SMES device and in the power system.

3.3 Internal Level Control Design

The internal level provides dynamic control of input signals for the dc-dc and ac-dc converters. This level is responsible for generating the triggering and blocking control signals for the different valves of the forty-eight-pulse three-level VSI and the three-level dc-dc chopper according to the control mode and types of valves used.

Fig. 2 (right side) shows the basic scheme of the internal level control of the STATCOM-SMES. This level is mainly composed of a line synchronization module and a firing pulse generator for both the STATCOM VSI and the dc-dc chopper. The line synchronization module simply synchronizes the STATCOM-SMES switching pulses with the positive sequence components of the ac voltage vector at the PCC through the PLL phase signal, θ. In the case of the firing pulse generator block, the controller of the VSI is made up of four basic three-level six-pulse switching generators with specific phase-shifting in order to obtain an overall equivalent forty-eight-pulse structure. The phase-shifting between control pulses of Bridges 1Y and 1D makes an equivalent structure of a twenty-four-pulse VSI. Hence, by lagging the control pulses of the second equivalent twenty-four-pulse structure by 15° in respect to the first, according to the phase-shifting of zigzag transformers primaries, a pseudo forty-eight-pulse VSI is obtained. Even though the semiconductors' conduction angle, σ, can be changed to control the output voltage amplitude of the VSI, in this work the amplitude is controlled just by using the duty ratio, m, of the chopper. In this way, σ is kept constant at 172.5° in order to obtain the lowest voltage THD for this topology, independently of the output voltage amplitude.

4. Performance Assessment of the STATCOM-SMES Modeling Approach and Control Laws

The dynamic performance of the proposed full detailed modeling and control approach is assessed through digital simulation carried out in the MATLAB/Simulink environment [13], by using SimPowerSystems (SPS). The test system employed for small and large signal assessment is presented in Fig. 4 as a single-line diagram. This 7-bus transmission system operates at 230kV/50Hz, and implements a dynamically-modeled single generator-type small utility linked to a bulk power system represented by a classical single machine-infinite bus type (SMIB) system used for the studies of FACTS devices [7]. The generator is powered by a steam turbine and the controls of the unit include a dc type-1a standard IEEE voltage regulator and a speed governor.

For full performance studies, a three-phase-to-ground fault is applied at bus 2 in the bulk power system at t= 0.1 s, and cleared 10 cycles later (200 ms) by tripping the tie line with the opening of the circuit breaker Bk 1. Two different case studies relative to basic protection rules are considered, permitting carry out of a full large-signal and small-signal performance study of the STATCOM-SMES for various control modes. The first case study (Case 1), which corresponds to a severe disturbance, considers a permanent fault that needs to be isolated by the instantaneous trip operation of Bk 1. The second case study (Case 2), which represents a significantly less severe disturbance than the prior case, assumes that the fault is temporary for a certain amount of time and implements an instantaneous trip action with automatic breaker reclosing at a preset delay-time of 250 ms prior to lock-out. A load shedding scheme (LS) is included in order to prevent the system frequency collapse during severe disturbances, but also to make use of the activated steps and consequently the rejected load as a performance comparison index for various scenarios including the STATCOM-SMES. This last device is placed at bus 4 aiming at enhancing the PS dynamic security.

4.1 Case Study 1: Large-signal Performance Assessment

The performance of the standard control of the power system, i.e. the base case without using any compensating device, is analyzed through the simulation results of Fig. 5, shown in black dashed lines. For the configuration presented in the test case prior to the fault in steady-state, the generator power production is 80 MW, and the active power demanded by the load is 120 MW so that the utility system needs to import about 40 MW from the bulk power system. In this interconnected operation, the system frequency is at its rated value (50Hz) and the voltage at bus 4 is 1.01 p.u. After the fault is cleared and the tie-line tripped, the generator is operated in island conditions. Under these circumstances, the generator itself has to supply all the power required by the load. As can be seen from the simulation results, the spinning reserve of the unit is neither sufficiently large nor fast enough for supporting the system frequency through the PFC and thus avoiding the

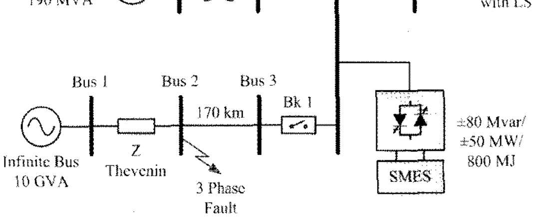


Fig. 4. Test power system for the STATCOM-SMES performance assessment

frequency drop which could cause the system to collapse. The activation of the LS scheme with 8 frequency steps (total load rejected of 40 MW/16 Mvar) is required in order to recover the frequency to its scheduled value. Under this situation, the isolated system experiences a common low frequency mode of about 0.08 Hz. The generating unit must be able to ramp-up very fast in order to decrease the amount of load rejected, and to ramp-down quickly for reducing the frequency deviation overshoot and settling time after the demand is stabilized, as can be derived from the mechanical power of the machine. After the fault clearance, a voltage overshoot of near 11.4 % occurs until the voltage regulator of the unit stabilizes the bus voltage.

Consider now the inclusion at bus 4 of a standard ±80 Mvar STATCOM controller in the voltage control mode (VCM). The impact of the operation of this FACTS controller can be analyzed by the simulation results of Fig. 5, shown in blue solid lines. The good performance of the voltage regulation at the PCC of the STATCOM is evidently depicted by the compensation of reactive power. The rapid exchange of reactive power after the fault clearance permits limiting the maximum voltage overshoot to near 7.5%, i.e. almost 3.9% lesser than the base case shown in dashed lines. The settling time obtained for this case study is 0.2 s, approximately 30% lesser than the base case. However, this control objective of the standard STATCOM device is contradictory with the PFC of the PS. Thus, by controlling the voltage at bus 4, a larger active power flow is forced in the electric system which causes an increase of the system frequency drop and its rate of change after the disturbance. In this way, the common low frequency mode damping of the system is decreased, so that 2 extra frequency steps of load rejection need to be activated in respect to the base case (total 10 steps) in order to recover the system frequency during the disturbance effect. In the post-fault steady-state, the voltage level at bus 4 is enhanced by the STATCOM providing a compensation of approximately 30 Mvar, which allows increasing the voltage from 1.012 V in the base case to 1.043 V, representing a 3% improvement.

The effect of incorporating a 50 MW/800 MJ SMES coil into the dc bus of the conventional ±80 Mvar STATCOM device, yielding an enhanced integrated STATCOM-SMES controller, can be studied in the frequency control mode through the simulation results of Fig. 6, shown in blue solid lines. These results clearly indicate the outstanding dynamic performance of the FCM of the STATCOM-SMES. The rapid active power supply added to the conventional reactive power compensation quickly absorbs the sudden power loss occurred after the tie-line tripping and thus enhances the damping of low-frequency oscillations. Hence, the generator is able to find the balance with the load at a lower speed than in the previous test case without producing a significant frequency deviation, resulting in a much smoother variation of the mechanical power of the machine. This condition permits a significant decrease in the power strain of the generating unit, which results in an improvement of the reliability of the power system. In this case, the effects of the disturbance are totally mitigated in a shorter time than in the base case without being necessary to activate the load shedding scheme. In fact, the frequency drop is drastically reduced and maintained far away from the load shedding limit. The minimum frequency reached during the disturbance is 0.9921 p.u. versus 0.9619 p.u. for the base case (shown in black dashed lines). Furthermore, the voltage profile at bus 4 is improved with respect to the base case without requiring shedding load, showing a better performance than the standard voltage regulation of the generating machine, although the voltage profile obtained with SMES in FCM is somewhat worse than the STATCOM device in the VCM. However, the SMES adds extra flexibility to the power system, allowing both objectives to be accomplished at the same time without rejecting the load. The improvement of the PFC is obtained by the immediate action of the SMES coil for supplying/absorbing active power, which provides active power for about 30s (approximately 735 MJ of energy).

4.2 Case Study 2: Small-signal Performance Assessment

The performance of the standard control of the power system (base case) is now analyzed for Case Study 2, through the simulation results of Fig. 7, shown in black dashed lines. The disturbance occurring in the power system after the fault clearance and subsequent automatic reclosing of the breaker Bk1 causes electromechanical oscillations of the generator. These local oscillations between the electrical machine and the rest of the electric system must be effectively damped to maintain the PS stability. During the fault period, the transfer of energy from the machines to the infinite bus is considerably reduced, and hence, the input mechanical energy during this period appears as an increase in the kinetic energy of the system with the consequent increase in the speed of the unit. Since the line resistances are inherently low, oscillations persist for a long time. As can be noted from digital simulations, a local mode of approximately 1.25 Hz that settles down to its steady state value only after 12 s is induced in the electric system. As expected, this low frequency power swing influences not only the system frequency, the rotor angle deviation, and the active and reactive power supplied by the generating machine, but also the voltage profile at bus 4.

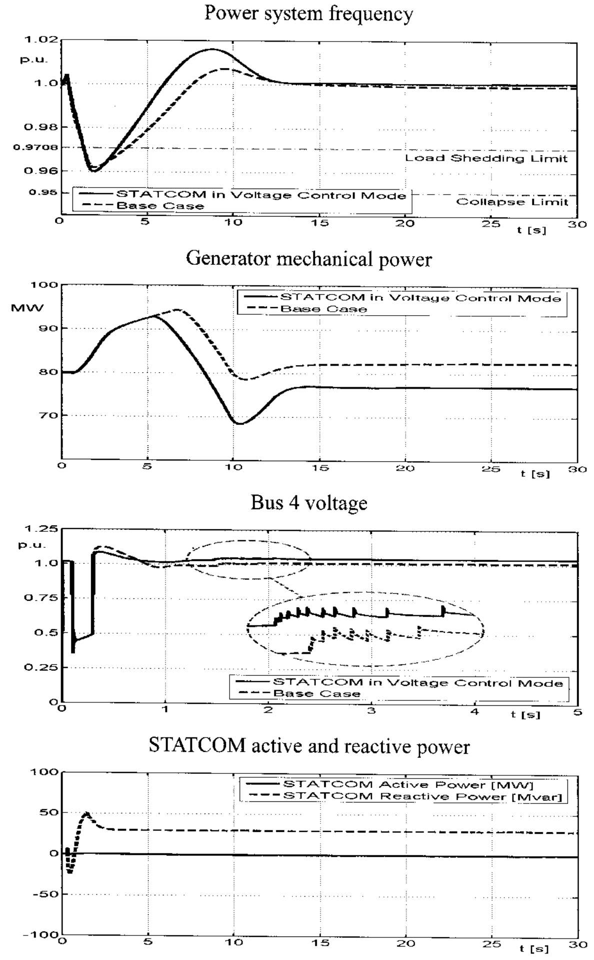


Fig. 5. Case Study 1: fault results for the base case and the case with a standard STATCOM in the VCM

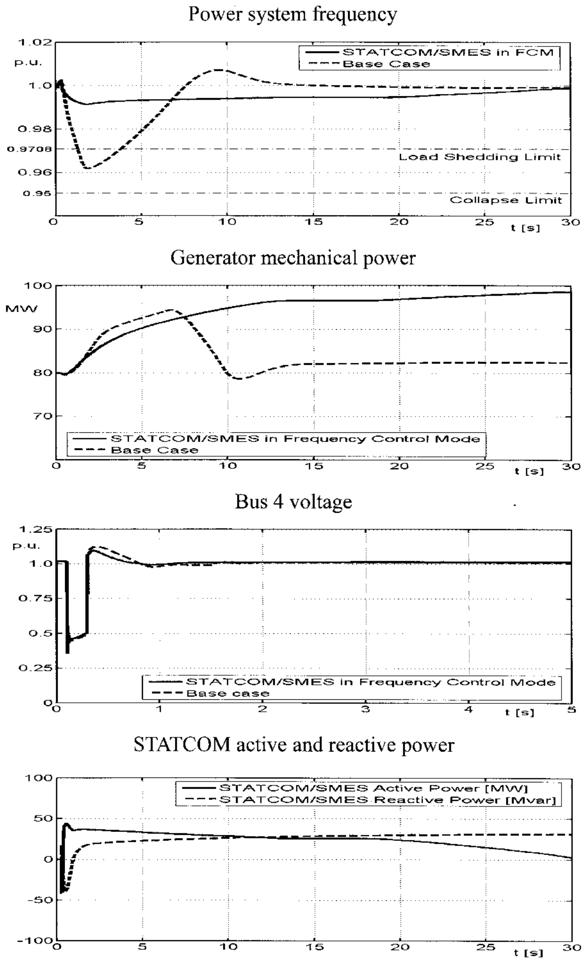
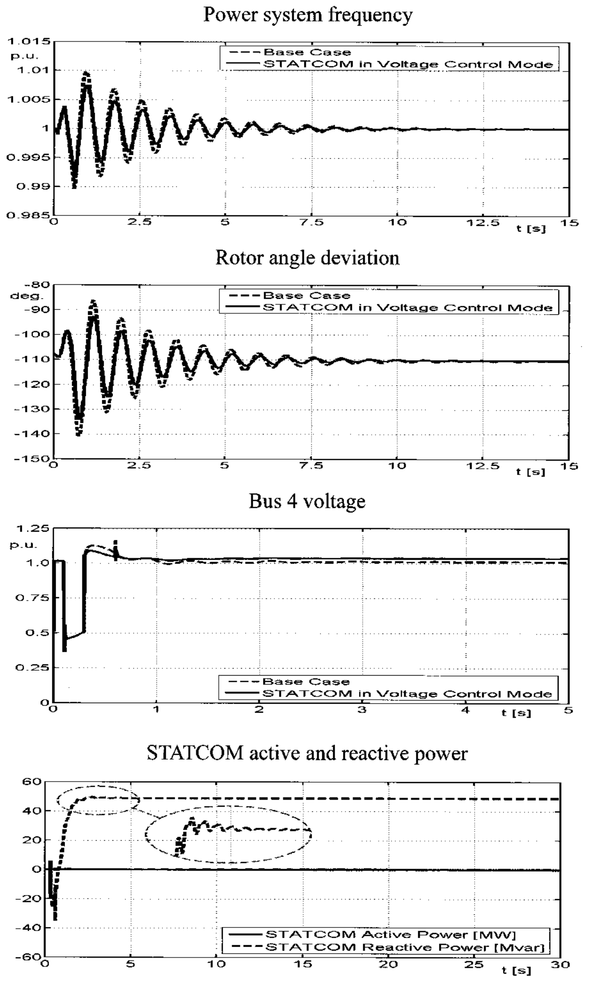


Fig. 6. Case Study 1: fault results for the base case and the case with a STATCOM-SMES controller in the

As in the previous case study, consider now the inclusion at bus 4 of a standard ±80 Mvar STATCOM operating in the VCM. The impact of incorporating this conventional FACTS controller can be studied by the simulation results of Fig. 7, shown in blue solid lines. Although the objective of this control system mode is to support and regulate the voltage at the PCC of the STATCOM, which can be verified through the voltage profile at bus 4, the good performance of the voltage controller also succeeds to moderately damp the low frequency oscillation mode. Aiming at controlling the voltage at bus 4, the compensation signal for voltage support (about 50 Mvar) also includes a superimposed oscillating component for stabilizing the voltage profile and thus reducing the amplitude of the oscillations.

The effect of incorporating a ±50 MW/800 MJ SMES coil into the dc bus of the conventional ±80 Mvar STATCOM can be verified through the simulation results of Fig. 8. In this case, the proposed multi-band structure (MBS) of the FCM, which is shown in blue solid lines, is compared with a classical structure (CS) described in [7], which is shown in red solid lines. The transient response clearly proves the outstanding small-signal dynamic performance of both FCMs of the STATCOM-SMES, the same as in the case for the large signal studied. However, the proposed MBS demonstrates superior tuning for the local mode to be damped than the CS. The SMES unit acts as an efficient damper, absorbing surplus energy from the system and releasing energy at the appropriate time when required. The SMES unit with the proposed controller is capable of damping the oscillations in a short time and reducing the amplitude of the pulsations on the frequency considerably. In the present analysis, the settling time for the system frequency is about 2 s when the SMES unit is used for active power compensation employing the MBS, against 2.5 s for the case of the CS. This implies a reduction with the MBS of almost 10 s in respect to the base case. Furthermore, the frequency and rotor angle deviations are greatly reduced to values lesser than the maximum reached at the end of the fault when the peak increase in the kinetic energy of the system exists. A noteworthy point is that the capacity rating of the SMES


Power system frequency

Rotor angle deviation

Bus 4 voltage

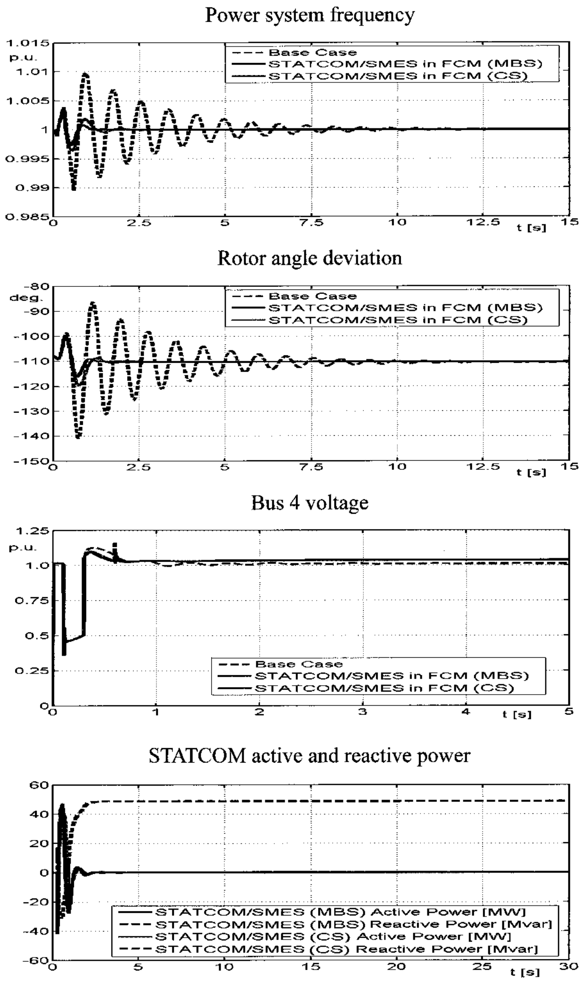
STATCOM active and reactive power

Fig. 7. Case Study 2: fault results for the base case and the case with a standard STATCOM in the VCM.

unit used in this case study for damping low frequency power swings is only 6.3 MJ with a power rating of almost ±50 MW.

5. Conclusion

This paper presents a new concept of PFC that incurporates a Static Synchronous Compensator coupled with a SMES coil, and utilizes a flexible multi-band structure controller for improving power system oscillation damping in the frequency range of up to 4.0 Hz. The STATCOM-SMES frequency controller is composed of three distinct working bands dedicatedly to low, intermediate, and high frequency modes, respectively. The proposed structure is very flexible and easy to be tuned, but at the same time very robust and efficient, and uses a fixed structure controller. A real detailed full model of the enhanced compensator and a novel control algorithm based on a decoupled current control strategy in the synchronous-rotating d-q reference frame are also proposed. The novel multi-level


Power system frequency

Rotor angle deviation

Bus 4 voltage

STATCOM active and reactive power

Fig. 8. Case Study 2: fault results for the base case and the case with a STATCOM-SMES controller in the

control scheme ensures fast controllability of the STATCOM-SMES operating in the four-quadrant modes, which enables effective increase of the transient and dynamic stability of the PS. The incorporation of the SMES into the STATCOM also permits the reduction of the requirement of spinning reserve of the electric system and the power strain of the generators. The SMES with proposed novel control can efficiently act as a buffer between the PS and the disturbances that have arisen in the system.

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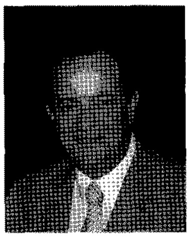

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