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CONTROLLING A STATIC SYNCHRONOUS COMPENSATOR WITH SUPERCONDUCTING MAGNETIC ENERGY STORAGE FOR APPLICATIONS ON PRIMARY FREQUENCY CONTROL

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Abstract— **At present, the advance of technology makes possible to include new energy storage devices in the electric power system. In addition, with the aid of power electronics devices, it is possible to independently exchange active and reactive power with the utility grid. This allows to perform a more effective primary frequency control and also to reduce the reserve power of generators. In this article, a model is presented of a Static Synchronous Compensator (STATCOM) with Superconducting Magnetic Energy Storage (SMES) used for controlling the primary frequency of the utility system. Moreover, a control algorithm for both devices is proposed. The performance of the presented STATCOM/SMES system is evaluated by using a test power system through the dynamic simulation in case of a tie-line tripping.**

Keywords— **Primary Frequency Control, Energy Storage, SMES, STATCOM, Control Algorithm.**

I. INTRODUCTION

One of the most important requirements during the operation of the electric power system is the operation security. This concept is related to the system capability of maintaining its operation in case of an unexpected failure of some of its components (e.g.: lines, generators, transformers, etc.). Hereof, it is derived the necessity of having available enough “short-term generation reserve” in order to preserve acceptable security levels. This reserve must be appropriately activated by means of the frequency control in order to keep the system frequency above the acceptable minimum level during the transient. Otherwise, serious problems could occur in the utility system.

Nowadays, the new energy storage systems (ESS) are a feasible alternative to decrease the reserve power of generators. By using proper energy storage devices, excess energy may be stored to substitute the power reserve of generators during the action of the primary frequency control.

In this sense, research in this field has been lately extended with the aim of incorporating power electronics devices into electric power systems. The goal pursued is to control the operation of the power system, a fact which clearly affects the operation security. In bulk power transmission systems, power electronics-based controllers are frequently called Flexible AC Transmission Systems (FACTS). Presently, these devices are a viable alternative as they allow to control voltages and currents of appropriate magnitude for electric power systems at an increasingly lower cost (Hingorani, 2000b).

While the FACTS/ESS combination has been proposed in theory (IEEE, 1996), the development of this FACTS/ESS combination has lagged far behind that of FACTS alone. Significant interest has been given to developing control strategies for a variety of FACTS devices in order to mitigate a wide range of potential bulk power transmission problems (Song and Johns, 1999). However, a comparable field of knowledge on FACTS/ESS control is quite limited. Therefore, in this work a methodology is proposed to control the system frequency, which uses FACTS controllers with energy storage. This can be carried out by using switching power converter-based FACTS controllers.

Among the different variants of FACTS devices, Static Synchronous Compensators (STATCOM) are proposed as the most adequate for the present application (Molina and Mercado 2002). The DC inner bus of the STATCOM allows incorporating a substantial amount of energy storage in order to enlarge the degrees of freedom of the STATCOM device and also to exchange active and reactive power with the utility grid. Based on a previous study of all energy storage technologies currently available (Molina and Mercado 2001, 2003), the use of Superconducting Magnetic Energy Storage systems (SMES) is proposed for the considered application.

The current article proposes a model of a STATCOM/SMES and a control algorithm for this combined system to carry out the primary frequency control of the electric system. This paper also lays the foundations for an increased operational flexibility by integrating energy storage devices with other power converter-based FACTS controllers’ structures, i.e. Static Synchronous Series Compensators (SSSC) and Unified Power Flow Controllers (UPFC).

II. INTEGRATION OF A SMES SYSTEM WITH A STATCOM

A. General Concepts

In principle, a Static Synchronous Compensator or STATCOM is a shunt-connected device which injects reactive current into the AC system. This leading or lagging current, which can be controlled independently of the AC system voltage, is supplied through a power electronics-based variable voltage source. The STATCOM does not employ capacitor or reactor banks to produce reactive power as the Static Var Compensators (SVC) do. In the STATCOM, the capacitor is used to maintain a constant DC voltage in order to allow the operation of the voltage-source converter.

A STATCOM controller with ESS is similar to an ideal synchronous machine which generates a balanced set of (three) sinusoidal voltages at the fundamental frequency, with controllable amplitude and phase angle. This ideal machine has no inertia, its response is practically instantaneous, it does not significantly alter the system impedance, and it can internally generate reactive (both capacitive and inductive) power. Furthermore, it can exchange dynamically active power with the AC system if it is coupled to an appropriate energy source that can supply or absorb this power.

A functional model of a STATCOM integrated with energy storage is shown in Fig. 1. The basic component of the STATCOM is the voltage-source inverter (VSI) with semiconductors devices having turn-off capabilities (typically GTOs). It is also made up of a coupling step-up transformer, a DC capacitor, an interface device with the energy storage system and the control block of the STATCOM/ESS. This control block produces the switching signals for the VSI thyristors and the interface with the ESS.

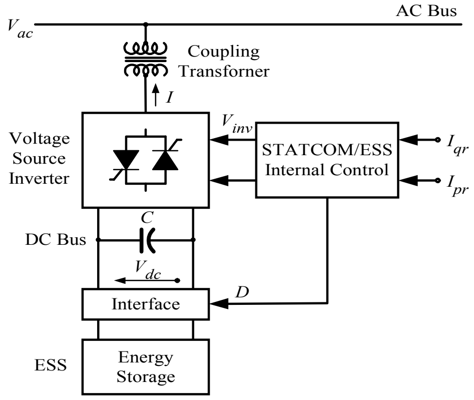

Figure 1. STATCOM Integrated with Energy Storage.

The STATCOM is appropriate for voltage control since it may rapidly inject or absorb reactive power to stabilize voltage excursions, and has been widely proven in industrial applications (Schauder *et al.*, 1995). Several prototype installations of STATCOM are currently in operation (Schauder *et al.*, 1997, 1998). However, a STATCOM/ESS combination can provide a better dynamic performance than a stand-alone STATCOM. The fast and independent control of both active and reactive power of the STATCOM/ESS system makes it the ideal candidate for many applications in the electric power systems. Among these applications is the capability to perform a very effective primary frequency control.

The traditional STATCOM has only two possible steady-state operating modes: inductive (lagging) and capacitive (leading). For this reason, it is not possible to significantly impact both active and reactive power simultaneously. In the case of a STATCOM/ESS, the number of operating modes is extended to four. These modes are namely, inductive with DC charge, inductive with DC discharge, capacitive with DC charge and capacitive with DC discharge. Due to the nature of ESS, the STATCOM/ESS cannot be operated infinitely in one of the four modes because of the storage device charge/discharge cycle; therefore, these modes represent a transient-state operation.

Figure 2 shows the transient-state operational characteristics of the STATCOM/ESS output. Note that in the steady-state, the output voltage of the traditional STATCOM spreads along the path shown in dashed lines. For the purpose of controlling the reactive power generation or absorption, the STATCOM must keep the voltage at the DC bus capacitor at a required level and thereby the amplitude of the output voltage of the controller (V_{inv}). This is accomplished by making V_{inv} lags or, in the case of reactive power absorption, leads the AC system voltage V_{ac} by a small angle (α_1). In this way, in order to provide capacitive or inductive compensation, the controller must absorb (or inject) a small amount of active power from (to) the AC system by using the DC capacitor, the limit values of α_1 being determined by the reactive compensation ratings of the STATCOM. In the case of a STATCOM/ESS, the output voltage can take any value within the circle during a time that is dependant both on the energy of the storage device and on the charge/discharge profile of the STATCOM/ESS. In this case, the voltage at the DC capacitor is controlled by using the interface of the energy storage device, i.e. by compensating reactive power. The active power generation (or absorption) in turns, is accomplished by phase-shifting (leading or lagging) the output voltage V_{inv} by an angle α_2 in relation to the AC system voltage (V_{ac}). The limit values of α_2 are determined by the active power ratings of the STATCOM/ESS. In this way, active and reactive power compensation can be independently controlled, giving the controller an additional degree of operating freedom which enhances the device performance.

Two works previously carried out by Molina and Mercado (2001, 2003) analyses the energy storage technologies currently available. Based on defined selection criteria for applications on primary frequency

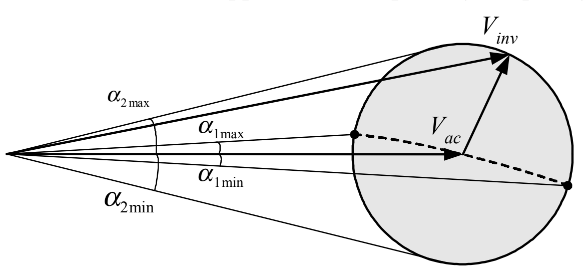

Figure 2. STATCOM/ESS Output Characteristics.

control, the most appropriate technologies were determined. Finally, the use of Superconducting Magnetic Energy Storage (SMES) for the considered application was proposed.

B. Voltage Source Inverter

The voltage source inverter is a DC to AC switching power converter using Gate Turn-off (GTO) thyristors in appropriate circuit configurations in order to generate a balanced set of three sinusoidal voltages at the fundamental frequency (Hingorani and Gyugyi, 2000a). From the control point of view, it is important to distinguish between two types of voltage source inverters that can be used. One type is based on a phase control scheme involving multi-connected, elementary inverters in an appropriate multi-pulse configuration. The other inverter type operates on the basis of Pulse Width Modulation (PWM) switching techniques where active and reactive power supplied by the inverter can be independently controlled. In practice, for high power utilities applications, phase control is used in a scheme of *k*-pulse inverters. Presently, PWM is regarded uneconomical for transmission applications due to high switching losses and unavailability of fast switching GTOs.

An elementary voltage source inverter based on a phase control scheme consists of six self-commuted semiconductor switches, each of which is shunted by a reverse parallel-connected diode. With a DC voltage source, the inverter can generate a balanced set of three quasi-square voltage waveforms at a given frequency.

The output voltage waveform of the elementary six-pulse inverter contains high harmonics level, making this simple inverter impractical for high power applications. By using the principle of harmonics neutralization (Gyugyi, 1994), the input and output of *n* basic six-pulse inverters, operated with appropriate relative phase-shifts, can be combined so as to obtain an overall *k*=6 *n* multi-pulse structure.

Figure 3 depicts the connection scheme of four 6-pulse elementary VSIs, making up an equivalent structure of a 24-pulse VSI. The four inverters are shunt-connected in the DC side and series-connected in the AC side through coupling transformers.

By combining two 24-pulse VSIs, phase-shifted 7.5 degrees from each other, an equivalent 48-pulse inverter can be created, thus avoiding the use of large banks of capacitors for harmonics filtering. The output voltage waveform of the 48-pulse inverter is not a perfect sine wave; it is a staircase approximation of a sine wave. However, the multi-pulse converter supplies an almost sinusoidal current to the AC system, the current being smoothed through the tie-reactance of the coupling transformer. As a result, the net three-phase instantaneous power (VA) at the output terminal of the converter fluctuates slightly, making the 48-pulse inverter satisfactory for high power utility applications.

Taking into account what is stated above, it follows that it is possible to model the VSI of the STATCOM with sufficient accuracy under balanced conditions as a voltage source operating at fundamental frequency (Molina and Mercado 2002). Thus, it is possible to explain the interaction of the VSI with the AC system by means of a single-phase equivalent shown in Fig. 4.a. From the voltage and current phase diagram drawn in Fig. 4.b, the active and reactive power flow exchanged by the STATCOM at the coupling bus or output terminal (node 2) for each phase can be expressed through Eqs. 1 and 2 respectively;

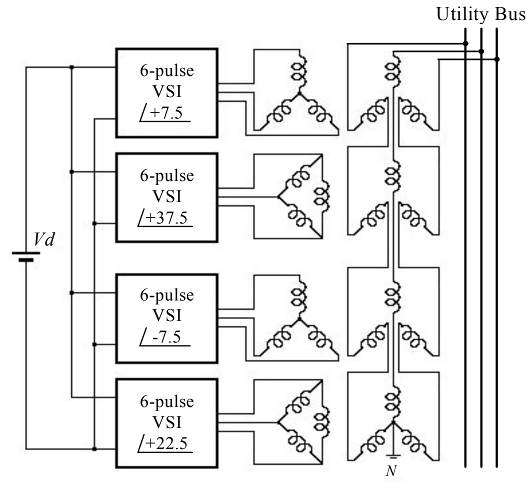

Figure 3. 24-pulse VSI.

$$P = \frac{V_{ac} \cdot V_{inv}}{X} \sin\alpha \qquad (1)$$

$$Q = -\frac{V_{ac}^{\;2}}{X} + \frac{V_{ac} \cdot V_{inv}}{X} \cdot \cos\alpha \qquad (2)$$

where: V_{ac} is the rms voltage at the output terminal of the STATCOM (node 2); $X = \omega L$ is the coupling transformer equivalent impedance due to the transformer leakage inductance; α is the phase-shift between the voltage generated by the inverter, the rms voltage of which is V_{inv} (node 1), and the output terminal voltage of the STATCOM.

From these equations, it can be concluded that the reactive power exchange between the inverter and the AC system can be controlled fundamentally by varying the amplitude of the three-phase output voltage V_{inv}.

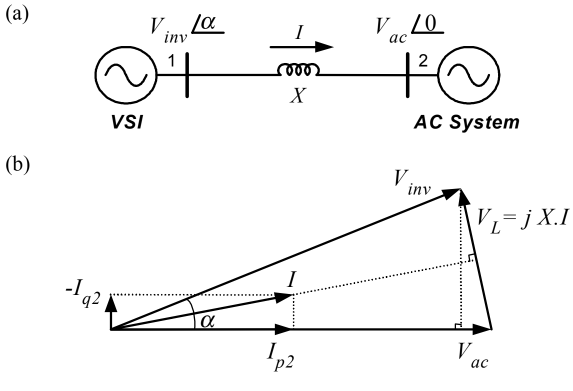

Figure 4. (a) Single-phase equivalent circuit of a STATCOM/ESS and Utility System, (b) Voltage and Current phasor diagram for fundamental frequency operation.

That is because practical phase-shift ratings are within ±10º so that the impact of this variable in Eq. 2 is lower than ±1.5%. In a similar way, the active power exchange between the inverter and the AC system can be controlled basically by varying the phase-shift α. This is due to the fact that the impact of V_{inv} voltage variations with respect to V_{ac} in Eq. 1 is not higher than 5%.

C. DC-DC Chopper

The inclusion of an ESS in the DC bus of the STATCOM requires the use of an interface to adapt the voltage and current levels of both devices. In the case of using a SMES device, a two-quadrant *n*-phase DC-DC converter is adopted as interface. In such interface *n* is related to the maximum current driven by the superconducting device. This converter, which is shown in Fig. 5, was designed to solve the problems of the high power rating requirements imposed by the superconducting coil (S-Coil) to the STATCOM. Furthermore, it permits to vary the magnitude of the output voltage of the VSI, which is not possible to carry out with the phase control scheme used by the VSI controller.

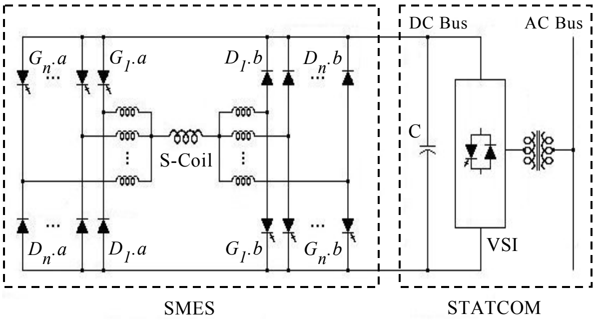

Figure 5. Two-quadrant *n*-phase DC-DC Chopper.

The DC-DC chopper allows to reduce the ratings of the overall power devices (VSI, Transformer) by regulating the current flowing from the superconducting coil to the inverter of the STATCOM (Lasseter and Lalali, 1991a). Therefore, the chopper ensures that the VSI can be rated for the maximum DC voltage and current levels of the superconducting coil. Otherwise, the coil will cause high levels of reactive power demands and consequently the power devices should be overrated.

The two-quadrant, multi-phase chopper is composed of many shunt-connected diode-thyristor legs, which permit driving the high current ratings stored in the supermagnetic coil. A smooth transition from charge to discharge mode and vice-versa is ensured by the two-quadrant configuration. By making small adjustments on the DC voltage by means of the chopper allows independent control of active and reactive power exchange between the STATCOM/SMES and the utility system.

The DC-DC chopper has three modes of operation, in order to perform the charge, the discharge and the storage in the SMES device. The chopper is operated in a step-down (Buck) configuration in the charge mode of the superconducting coil. Here, the set of thyristors "*a*" are operated with duty cycle *D* while the set of thyristors "*b*" are kept ON at all times. The relationship between the coil voltage and the DC bus voltage is stated by Eq. 3;

$$V_{smes} = D \cdot V_{dc} \qquad (3)$$

Once completed the charging of the superconducting coil, the operating mode of the DC-DC converter is changed to the stand-by mode for which the set of thyristors "*a*" are kept OFF all the time while the set of thyristors "*b*" are kept ON constantly. Thus, the set of diodes "*a*", also called free-wheeling diodes, permits the stored current to flow continuously until it is required (neglecting losses at semiconductors).

Finally, in the discharge mode the chopper is operated in a step-up (Boost) configuration. Here, the set of thyristors "*b*" is operated with duty cycle *D* while the set of thyristors "*a*" is kept OFF at all times. It should be remarked that the capacitor of the STATCOM also works like part of the DC-DC chopper to increase the voltage applied by the SMES device to the DC bus. The relationship between the coil voltage and the DC bus voltage is stated by Eq. 4;

$$-V_{smes} = (1-D) \cdot V_{dc} \qquad (4)$$

The DC-DC chopper can be operated in a continuous spectrum of duty cycle values ranging from 0 to 1. The voltage in the DC bus is related to the output voltage of the VSI of the STATCOM/ESS system through Eq. 5;

$$V_{dc} = k_a \cdot |V_{inv}| \qquad (5)$$

where: $k_a = k a$ is a constant associated with both the pulse-number of the VSI (constant *k*) and the voltage ratio *a* of the coupling transformers.

III. STATCOM/SMES CONTROL

The proposed control system for the STATCOM/SMES combination is divided into two quite distinct blocks: an internal control block and an external control block.

A. Internal Control

The internal control block is responsible for generating the switching signals for the different thyristors of the VSI of the STATCOM and the DC-DC chopper (triggering and blocking control signals of the GTOs).

A simplified functional scheme of the internal control of the STATCOM-SMES system is shown in Fig. 6. The control scheme that is proposed coordinates the control subsystems of the chopper and the VSI of the STATCOM. The control scheme of the DC-DC chopper uses as a basis a control algorithm presented by Lasseter and Lalali (1991b). Necessary modifications were introduced on this algorithm in order to incorporate the model of the multi-pulse VSI of the STATCOM. In addition, the control of the inverter is of the decoupled type according to components of active and reactive power. This control has independent inputs of the reference signals of the current injected in the connection bus, that is to say, the component of the wanted reactive current I_{qr} and the component of the wanted active current I_{pr}. From these reference signals, the internal control determines the amplitude and phase ratings of the voltage at the VSI of the STATCOM respect to the voltage at the AC system (Eqs. 1 and 2).

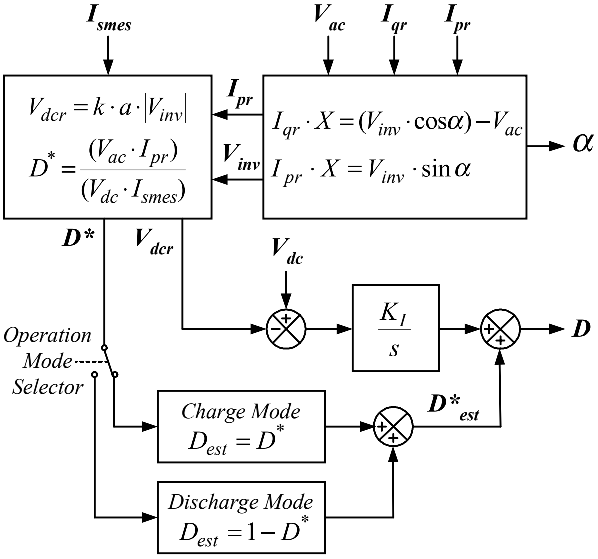

Figure 6. Simplified Internal Control Algorithm of the VSI and DC-DC Chopper.

The duty cycle D is estimated (D^*_{est}) from the active power ratings that the STATCOM should inject ($V_{ac} \cdot I_{pr}$), from the voltage at the DC bus (V_{dc}) and from the current stored into the supermagnetic coil I_{smes}, as it is shown in Fig. 6. This estimated value (D^*_{est}) is adjusted through a closed loop control whose function is to eliminate the voltage error between the calculated and the real voltage ratings at the DC bus.

B. External Control

The external control is responsible for determining the active and reactive power exchange with the electric system, necessary to recover the system frequency after eventual faults of some components of the system. The output signals of this control block, i.e. the components of active and reactive current, are used as inputs for the internal control previously described.

The simplified external control algorithm of the STATCOM/SMES is shown in Fig. 7. This control has the responsibility of minimizing the magnitude and duration of system disturbances by regulating the output terminal voltage of the STATCOM and by damping power oscillation. The purpose of this is to keep the system frequency above the acceptable minimum level during the transient.

The standard control loop of the external control consists in regulating the voltage at the STATCOM bus through the control of the reactive component of the output current (Schauder *et al.*, 1995). The AC voltage measurement system is modeled as a low-pass filter with a gain K_m and a time delay T_m. A phase-lag compensator is used to enhance the performance of the voltage regulation system. A voltage regulation droop (or slope) R_d and a proportional gain K are also included in order to allow the terminal voltage of the STATCOM to vary in proportion with the compensating current. In this way, a higher operation stability of the FACTS device is obtained.

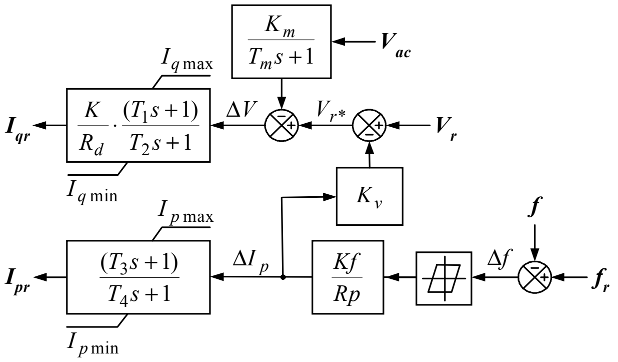

Figure 7. Simplified External Control Algorithm of the STATCOM/SMES System.

Power oscillation damping can be carried out by the modulation of the reactive component of the output current (as in a traditional STATCOM), by the modulation of the active component of the output current (only with a STATCOM/SMES combination), or by the modulation of the two of them.

In both modes of power oscillation damping, the input signals of the system are produced by direct frequency measurement of the AC system, yielding Δf. This frequency error is proportional to the rate of change of the generator angle $d\delta / dt$ involved, which represents directly the power oscillation of the system. A dead-band block is incorporated into the control loop with the purpose of managing the participation of the STATCOM/SMES system in the primary frequency control of the utility system. The dead-band adjustment allows determining the activation of the controller in case of different severity levels of the disturbances. A proportional gain Kf and a speed-droop Rp (or regulation characteristic) is used to get a stable load division among several generating units operating in parallel. The output current signal ΔI_p represents the flow of active current that needs to be injected for compensating the frequency deviation of the system.

Let us consider first the power oscillation damping by the modulation of the reactive output current. As shown in Fig. 7, the voltage reference signal V_r is modulated with a voltage signal proportional to ΔI_p (through gain K_v). This added signal causes the output reactive current of the STATCOM to vary around the operating point defined by the fixed voltage reference V_r with the purpose of damping the power oscillation produced by the disturbance. It forces the output terminal voltage either to decrease when the frequency deviation Δf, defined as $f_r - f$, is positive in which case it decreases the transmitted power through the electric power system thereby opposing the deceleration of the generator, or to increase when Δf is negative. This mode of oscillation damping of the STATCOM is quite effective and has shown a good performance in many applications (Schauder *et al.*, 1997). However, the most effective control action for power oscillation damping and mainly for controlling the system frequency is carried out by exchanging active power with the utility system.

Let us consider now power oscillation damping by the modulation of the active output current. In this case, the reference of the active component of the output current of the STATCOM/SMES is directly derived from ΔI_p. A phase-lag compensator is used to enhance the performance of the frequency control system. Thus, the active power exchange between the STATCOM/SMES device and the electric system is controlled, forcing the FACTS device to absorb active power when the generators accelerate, or to supply active power when they decelerate.

According to the mode of frequency control to be used, either a continuous control mode or one for severe disturbances, the SMES device must be partially charged at a specific rating to allow power to be absorbed or injected from or into the grid at any time. This permits to counteract positive and negative power changes in the utility system.

IV. CONTROL SYSTEM PERFORMANCE

A. Test System

The 7-bus electrical network used to test the proposed control approach of the STATCOM/SMES in form of a simplified single-line diagram is shown in Fig. 8.

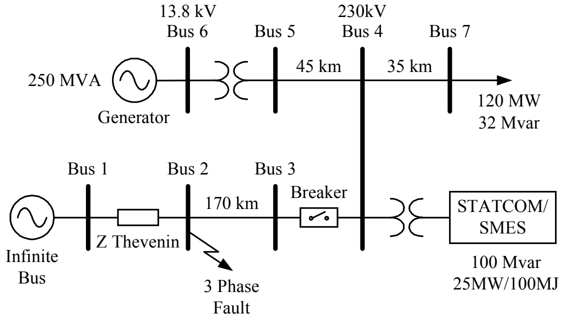

Figure 8. Test System.

The transmission system is operated at 230kV/50Hz and is composed of lines of different lengths modeled as distributed-parameters lines with their R, L, C /km rates specified in positive and zero sequence components. The load is grouped at bus 7 and consists of an impedance modeled as a RL load (120MW/32Mvar) supplied by a single generator (250MVA/13.8 kV) and a bulk power system modeled as an infinite bus (10GVA/230kV) via two transmission lines. The generator is powered by a multi-stage tandem-compound steam turbine which is connected to the network through a $Y-\Delta$ step-up transformer (350 MVA, 13.8/230 kV). The controls of the unit include a standard IEEE voltage regulator and a speed governor with PSS (Power System Stabilizer). Automatic switching from the droop speed control to the isochronous speed control in case of separation of the generator from the bulk power system has also been implemented. The STATCOM/SMES system is placed at main bus (bus 4) with the purpose of participating in the primary frequency control of the electric system together with the generator, in cases severe disturbances occur. Time constants and gain values are taken within typical ranges suggested by international references (IEEE, 1991).

The control system performance is examined in detail after application of a three-phase-to-ground fault at bus 2 in the bulk power system (at t=0.1s) and clearance of it. This is done by tripping the tie-line five cycles (100ms) after the fault through the action of the circuit breaker located between buses 3 and 4.

For the configuration presented in the test case prior to the fault in the steady-state, the generator power production is 100MW, and the active power demanded by the load is 120MW so that the utility system must import about 20MW from the bulk power system. In this interconnected operation, the generator governor is set at the droop speed control mode, which is a proportional-type control used to regulate the turbine output power during multimachine operation. In this state, the system frequency is at its rated value (50Hz) and the voltage at bus 4 is 0.988p.u. (Base voltage 230kV). After the fault is cleared and the tie-line tripped, the generator is operated in island conditions, i.e. working entirely isolated from the bulk power system. Under these circumstances, the generator itself has to supply all the power required by the load; therefore, the speed governor must be automatically switched to the isochronous mode. This mode sets the governor at constant speed, by adding an integral-type control so that the system frequency can be recovered to its rated value.

As can be seen from the simulation results of Fig. 9 (Simulink, 2003), the generator spinning reserve is enough to supply the increased power demand and to recover the system frequency. The large power reserve of the unit allows a new system stable equilibrium point to be reached, after the fault is cleared and the bulk power system is isolated. Thus, the system frequency is returned to its reference value in approximately 40 seconds by the action of the isochronous speed control of the generator (secondary frequency control). In addition, as shown in Fig. 9, the system frequency with the generator at the droop speed control (dashed line) would need about 30s to reach the stable state but with a frequency error of 2.7mHz (primary frequency control). It may be noted that all the active power demanded by the load must be supplied now by the generator, which

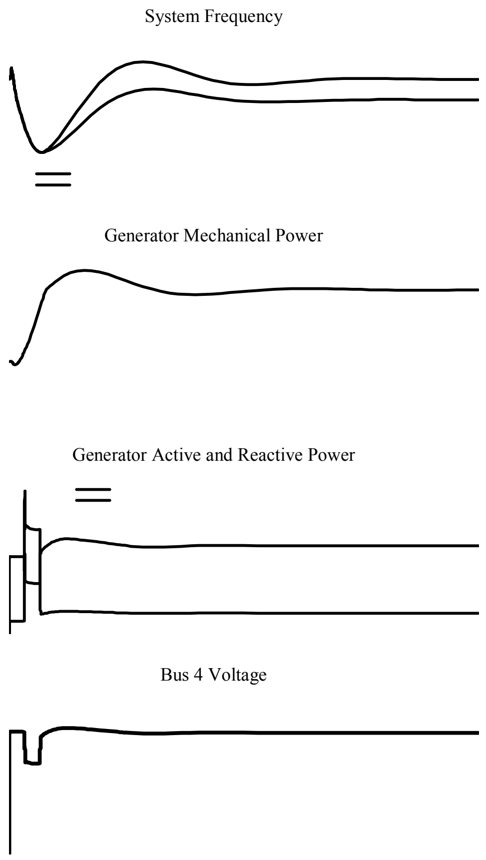

Figure 9. Fault results for the test system without STATCOM/SMES.

imposes a large spinning reserve requirement to the system. Notice in the generator active power simulation that not all of the active power demanded by the load is supplied. This is so because the voltage level at load undergoes a reduction after the fault, reaching a level of 0.9802p.u. in the steady-state.

Now consider the incorporation at bus 4 of a 100Mvar STATCOM controller combined with a 25MW/100MJ SMES device. The two significant external control modes previously described will be analyzed, namely the voltage control mode (traditional STATCOM) and the frequency control mode (STATCOM/SMES).

B. STATCOM in Voltage Control Mode

In this case, the action of the traditional STATCOM controller can be seen through the simulation results in Fig. 10. The good performance of the voltage regulator of the FACTS device is clearly depicted here. In the steady-state prior to the fault, the controller raises the voltage at bus 4 up to 0.998p.u. by compensating reactive power. This voltage level is reached by compensating about 8.6Mvar. During the fault and after this, the controller is highly required and the voltage profile is outstandingly enhanced. In this way, the voltage drop during the fault is kept at 0.833p.u. versus 0.7292p.u. in the case of the system without STATCOM. In a similar way, after the fault removal the voltage quickly reaches a steady-state with a settling time of approximately 3 cycles (60ms), versus 1.4s in the case of the system without compensation. In the post-fault steady-state, the voltage level at bus 4 is set at 0.9937p.u. with a compensation of 20.5Mvar. The STATCOM action allows greater power to be supplied to the load, thereby impairing the frequency profile. Thus, the system frequency falls down to nearly 0.9885p.u. versus 0.9905p.u. in the previous case. This clearly shows that the voltage control aim (at bus 4) is opposite to the frequency control aim.

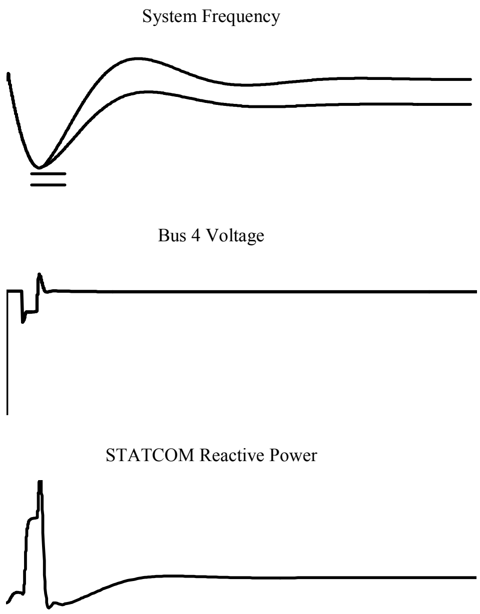

Figure 10. Fault results for the test system with a traditional STATCOM.

C. STATCOM/SMES in Frequency Control Mode

The action of the SMES device linked to the DC bus of the STATCOM can be studied through the simulation results of Fig. 11. This shows the excellent performance of the frequency regulator of the STATCOM/SMES system. After the fault, when the frequency deviation exceeds the dead-band limits, the SMES device is activated through the I_p compensator. The rapid active power supply absorbs the sudden generation lost occurred after the tie-line tripping. Thus, the generator is able to find the balance with the load at slow speed without producing a significant frequency deviation. In this case, the system frequency for both types of control, namely, the droop and the isochronous speed control, falls down to nearly 0.9937p.u. versus 0.9904p.u. in the case of the system without STATCOM/SMES (see Fig. 9); the deviation is fully mitigated in a shorter time (almost half the time) than in the previous case, the overshoot being considerably decreased (more than 75%). Simulation results show that the SMES device provides active power for about 20s, supplying approximately 55MJ of energy.

The incorporation of this SMES device into the

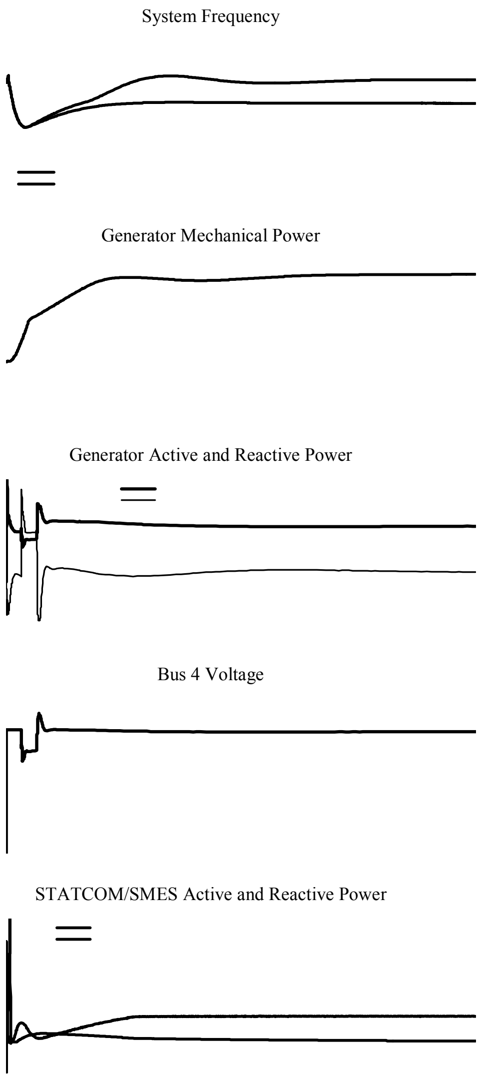

Figure 11. Fault results for the test system with STATCOM/SMES.

STATCOM makes it possible to reduce the requirement of spinning reserve of the electric system. Furthermore, it provides an effective enhancement in the transient stability of the system.

V. CONCLUSIONS

These preliminary results firmly establish the feasibility of using a STATCOM/SMES combination to carry out an enhanced primary frequency control of the power system. Dynamic system studies demonstrate the effectiveness of the proposed control approaches and the presented models. Based on the above, the research is currently directed to enhance the models of both the STATCOM controller and the SMES device to obtain a more accurate representation of these devices in a variety of power system studies.

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