JOURNAL OF ELECTRIC POWER AND ENERGY CONVERSION SYSTEMS (JEPECS)
JEPECS VOL. 1, NO. 2, PP. 79-84, SUMMER 2016
ISSN: 2345-4830 print/2345-4733 online

Power Swings Damping Improvement with STATCOM and SMES Based on the Direct Lyapunov Method

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In this paper a comprehensive approach is presented to improve power swings damping based on direct Lyapunov method. The approach combines superconducting magnetic energy storage (SMES) system with static synchronous compensator (STATCOM). Considering the energy absorption/injection ability of SMES, in transient states the combination exchanges both active and reactive powers with power system. Since direct Lyapunov method relies on time derivative of both active and reactive powers, it can offer an effective control strategy for the integrated STATCOM-SMES system to decrease power swings damping time. Line current is proposed as synchronous reference frame for d-q transformation which satisfies the direct Lyapunov method application as optimized approach and also provides decentralized control strategy. Steady state control strategy with respect to proposed reference frame and also SMES existence is given. PSCAD/EMTDC simulation results for a typical multi-area system are presented.

Keywords: Direct Lyapunov Method, Power Swings, UPFC, SMES.

Received Aug. 2015; Revised Feb. 2016; Accepted June 2016.

I Introduction

One of the most significant problems in power systems is weakly damped power swings between synchronous generators and subsystems that must be controlled in appropriate way, in spite the power system will encounter a serious problem and lose the normal operation. Flexible AC transmission system (FACTS) controllers are emerging as viable and economic solutions to the problems of large interconnected ac networks. Energy storage systems are added to FACTS devices to increase their flexibility in improvement of power system dynamic behavior by exchanging both active and reactive powers with power grids. In this paper STATCOM and SMES are considered to cooperate and emerge as a controller with prominent capability in power swings damping improvement. The fundamental principle of a STATCOM installed in a power system is the generation ac voltage source by a voltage source inverter (VSI) connected to a dc capacitor. The active and reactive power transfer between the power system and the STATCOM is caused by the voltage difference across the leakage reactance of VSI transformer [1, 2]. There are different technologies for energy storage such as ultra-capacitors, batteries, flywheels and SMES which may differ from the viewpoint of energy density, charging/discharging rate, maintenance and economical considerations. SMES systems for power utility applications have received considerable attention due to their characteristics, such as rapid response (milliseconds), high power (multimegawatts), high efficiency, and four-quadrant control [3]. Advances in both superconducting technologies and the necessary power electronics interface have made SMES a viable technology that can offer flexible, reliable, and fast-acting power compensation. The effects of integrating SMES with static synchronous compensator (STATCOM) on power system dynamic behavior have been investigated in [3] and [4]. In [5] the application of SSSC-SMES for frequency stabilization is examined. As power systems consist of a large number of generator sets and possess strong nonlinearities, it is expected that controller design approaches based on the nonlinear model will have better dynamic performance than schemes based on linear approximations [6]. Among the novel control ideas, direct Lyapunov method or energy function approach in power system has attained considerable attention in control process. This method has been applied for STATCOM-SMES control in [4] and for UPFC in [7] and [8].

II Power System Model

Structure preserving model (SPM) of power systems has been introduced to improve the modeling of generators and load representations such that system components represent more realistic behavior [7]. Generators are modeled as one-axis generator model that includes one circuit for the field winding and also loads are modeled by constant active power and reactive power with following equation.

$$Q_{Lk} = Q_{Lk0}\left(\frac{V_k}{V_{k0}}\right)^{mq} \tag{1}$$

Where Q_{Lk} is reactive power at the nominal voltage and is an arbitrary integer from 0 to 3 [7]. A power system with N buses and M generators without exciter and governor is considered.

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With assuming lossless power system, the following equations can be written to govern the system:

$$\begin{aligned} &\dot{\delta}_i = \omega_i \\ &M_i\dot{\omega}_i = P_{mi} - P_{Gi} - D_i\omega_i \quad i = 1...M \\ &T'_{doi}\dot{E}'_{qi} = \tfrac{x_{di}-x'_{di}}{x'_{di}} V_{M+i}\cos(\delta_i - \theta_{M+i}) \\ &\qquad + E_{fdi} - \tfrac{x_{di}}{x'_{di}} E'_{qi} \end{aligned} \tag{2}$$

Generated active and reactive electric powers are given by:

$$\begin{aligned} P_{Gi} &= \tfrac{1}{X'_{di}} E'_{qi} V_{M+i} \sin(\delta_i - \theta_{M+i}) \\ &\quad - \tfrac{x'_{di}-x_{qi}}{2x'_{di}x_{qi}} V_{M+i}^2 \sin(2(\delta_i - \theta_{M+i})) \\ Q_{Gi} &= \tfrac{1}{X'_{di}} \left[E'_{qi} V_{M+i}\cos(\theta_{M+i} - \delta_i) - V_{M+i}^2\right] \\ &\quad + \tfrac{x'_{di}-x_{qi}}{2x'_{di}x_{qi}} V_{M+i}^2 \left[\cos(2(\delta_i - \theta_{M+i}) - 1)\right] \end{aligned} \tag{3}$$

The injected real and reactive powers into k-th node are:

$$\begin{aligned} P_k &= \sum_{i=M+1}^{M+N} B_{ki} V_k V_i \sin(\theta_k - \theta_i) \\ Q_k &= -\sum_{i=M+1}^{M+N} B_{ki} V_k V_i \cos(\theta_k - \theta_i) \end{aligned} \tag{4}$$

III DIRECT LYAPUNOV METHOD

Let $w(x)$ be the direct Lyapunov function or energy function defined for the power system model described by equations 1 through 4. Any disturbance in power system involves a power imbalance that moves the system trajectory from the pre-fault stable equilibrium point to a transient point $x_i(t)$ that has a higher energy level than post-fault equilibrium point $\hat{x}_i(t)$. If $\dot{w}_i$ is negative, the direct Lyapunov function decreases with time and tends towards its minimum value which appears at the post-fault equilibrium point $\hat{x}_i(t)$. The more negative value of $\dot{w}_i$ means the system returns to the equilibrium point $\hat{x}_i(t)$ rapidly (i.e. the better damping in power system) [7, 8]. With assumption of $\hat{x}_i(t) = 0$, the direct Lyapunov function for SPM power system without control is given by:

$$\begin{aligned} &w(\omega, \delta, E'_q, V, \theta) = w_1 + w_2 + C_0 \\ &w_1 = \frac{1}{2}\sum_{k=1}^{M} M_k\omega_k^2 \\ &w_2 = \sum_{i=1}^{8} w_{2i} \end{aligned} \tag{5}$$

Where w_1 is kinetic energy and w_2 is overall potential energy which is defined as:

$$\begin{aligned} w_{21} &= -\sum_{k=1}^{M} P_{mk}\delta_k \\ w_{22} &= \sum_{k=M+1}^{M+N} P_{Lk}\theta_k \\ w_{23} &= \sum_{k=M+1}^{M+N} \int \tfrac{Q_{Lk}}{V_k} dV_k \\ w_{24} &= \sum_{k=M+1}^{2M} \tfrac{1}{2x'_{dk-M}} \begin{bmatrix} (E'_{qk-M})^2 + {V_k}^2 \\ -2E'_{qk-M} V_k \cos(\delta_{k-M} - \theta_k) \end{bmatrix} \\ w_{25} &= -\tfrac{1}{2} \sum_{k=M+1}^{M+N} \sum_{l=M+1}^{M+N} B_{kl} V_k V_l \cos(\theta_k - \theta_l) \\ w_{26} &= \sum_{k=M+1}^{2M} \tfrac{x'_{dk-M} - x_{qk-M}}{4x'_{dk-M}x_{qk-M}} \left[{V_k}^2 - {V_k}^2\cos(2(\delta_{k-M} - \theta_k))\right] \\ w_{27} &= -\sum_{k=1}^{M} \tfrac{E_{fdk}E'_{qk}}{x_{dk} - x'_{dk}} \\ w_{28} &= \sum_{k=1}^{M} \tfrac{(E'_{qk})^2}{2(x_{dk} - x'_{dk})} \end{aligned}$$

C_0 is a constant, such that at post-fault equilibrium point, the total energy, (5), is equal to zero. More details about energy function are given in [7] and [9]. As it can be shown, the time derivative of the direct Lyapunov function along the trajectories of the uncontrolled system is given by:

$$\dot{w}_{_{uncontrol}}(x) = -\sum_{k=1}^{M} D_k\omega_k^2 - \sum_{k=1}^{M} \frac{T'_{dok}}{x_{dk} - x'_{dk}} \left(\dot{E}'_{qk}\right)^2 \le 0 \tag{6}$$

Increasing the negativeness of (6) leads to decrement in power swings damping time.

IV STATCOM AND SMES MODEL

The main task of the STATCOM is power flow control in steady-state. However its high speed operation makes it possible to be used dynamically. STATCOM system is shown in Fig. 1 and consists of a standard three-phase Gate Turn-Off (GTO) Transistor based 3-leg VSI bridge with the input ac inductors and a dc bus capacitor to obtain a self supporting dc-bus. STATCOM supports grid voltage by reactive power exchange with power system. Therefore the output voltage of VSI ($\bar{V}_{sh}$) is in phase with voltage of connected bus ($\bar{V}_i$). But if dc-bus voltage ($\bar{V}_dc$) can be supported by an energy storage system, the VSI voltage angle (θ_{sh}) will varies from 0 to 2π and satisfies the condition of active power exchange.

In SMES unit energy is stored in the magnetic field which is generated by the dc current flowing through a super conducting coil. Since energy is stored as circulating current, it can be drawn from an SMES unit with almost instantaneous response with energy stored or delivered over periods, ranging from a fraction of a second to several hours. More specifications about SMES have been given in [10]. The SMES stored energy and

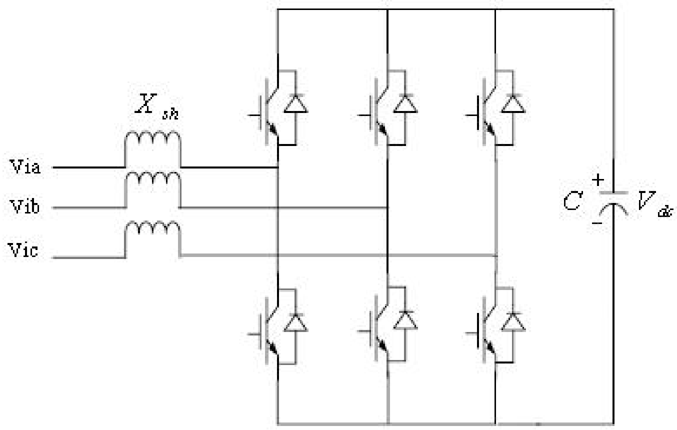

Figure 1: STATCOM schematic diagram

the rated power can be expressed as following:

$$E_{smes} = \frac{1}{2} L_{smes} I_{smes}^2 \tag{7}$$

$$P_{smes} = \frac{dE_{smes}}{dt} = L_{smes} I_{smes} \frac{dI_{smes}}{dt} = V_{smes} I_{smes}$$

SMES coil is connected to the STATCOM dc-bus through a dc-dc chopper which controls dc current and voltage levels. The control is achieved by converting the STATCOM dc-bus voltage to the adjustable voltage across the SMES coil terminal. A simple typical chopper is shown in Fig. 2. The chopper operation can be defined by :

$$V_{smes} = (1 - 2d) V_{dc} \tag{8}$$

According to (8) if d is less than 0.5 the SMES average voltage is positive, consequently chopper will be in charging mode and absorbs the energy and I_{smes} is increased. Vice versa when d is more than 0.5, chopper operates in discharging mode and injects the energy into the power system. Chopper operation will be in standby mode when d is 0.5 and the average voltage across SMES coil will be zero. In this case, no energy is exchanged with power system.

As mentioned earlier at the transient states SMES maintains constant dc-bus voltage for STATCOM. Therefore STATCOM can be modeled as ideal voltage source series with transformer leakage reactance as shown in Fig.3:

Suppose STATCOM-SMES is connected to bus i and its voltage amplitude is related to V_i by r_{sh}. Therefore VSI voltage can be written as:

$$\bar{V}_{sh} = r_{sh} V_i e^{j\theta_{sh}} = V_i [r_{sh} \cos(\theta_{sh}) + j r_{sh} \sin(\theta_{sh})] \tag{9}$$

This voltage is written as direct and quadrature components in synchronous reference frame as follow:

$$\bar{V}_{sh} = r_{sh} V_i e^{j\theta_{sh}} = V_i [u_d + j u_q] \tag{10}$$

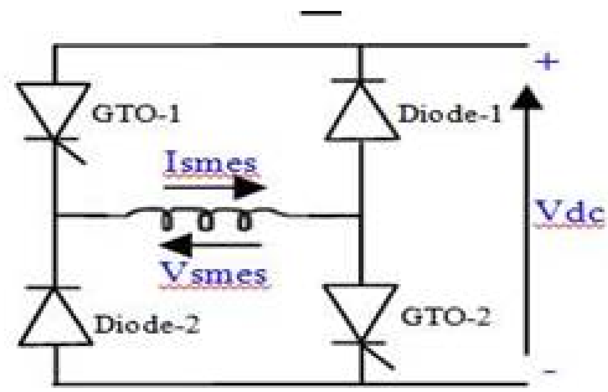

Figure 2: dc-dc chopper

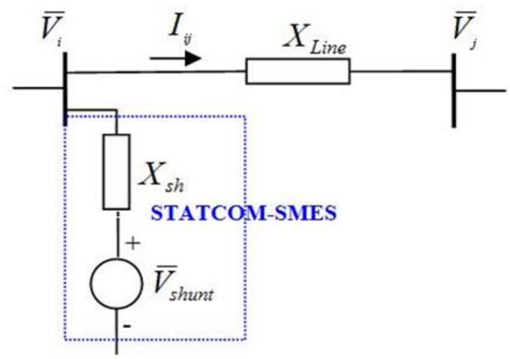

Figure 3: Equivalent circuit of STATCOM

The presence of STATCOM-SMES into the power system will modify the load flow equations (4) and also time derivative of Lyapunov function (6) will be changed. The powers equilibrium at bus i is:

$$\begin{aligned} P_i + P_{Li} - P_{Gi} + P_{shi} = 0 \\ Q_i + Q_{Li} - Q_{Gi} + Q_{shi} = 0 \end{aligned} \tag{11}$$

Where P_{shi} and Q_{shi} are active and reactive powers which are exchanged between STATCOM-SMES and i bus and are defined as follow:

$$\begin{aligned} P_{shi} &= b_{sh} V_i^2 [u_d \sin(\theta_i) - u_q \cos(\theta_i)] \\ Q_{shi} &= b_{sh} V_i^2 [1 - u_q \sin(\theta_i) - u_d \cos(\theta_i)] \\ b_{sh} &= 1/X_{sh} \end{aligned} \tag{12}$$

After control addition to power system the time derivation of Lyapunov function is changed as:

$$\dot{w} = \dot{w}_{uncontrol} - P_{shi} \dot{\theta}_i - Q_{shi} \frac{\dot{V}_i}{V_i} \tag{13}$$

Due to (13) it is straightforward that control inputs application increases the negative rate of Lyapunov function. The control parameters (u_d, u_q) consist transient (u''_d, u''_q) and steady state components (u'_d, u'_q) which have large time constant and their effectiveness in improvement of system dynamic behavior is on considerable. Therefore only transient components are considered for power swings damping. By substituting (12) into (13) and the control law is extracted

$$\begin{aligned} \dot{w} &= \dot{w}_{uncontrol} - b_{sh}V_i\tfrac{d}{dt}\left[-V_i\cos(\theta_i)\right]u''_d \\ &\quad -b_{sh}V_i\tfrac{d}{dt}\left[-V_i\sin(\theta_i)\right]u''_q \end{aligned} \tag{14}$$

($\bar{V}_i$) is written into the synchronous reference frame as:

$$\bar{V}_i = V_i\cos(\theta_i) + jV_i\sin(\theta_i) = V_{di} + jV_{qi} \tag{15}$$

Substituting of (14) into (15) results:

$$\dot{w} = \dot{w}_{uncontrol} - b_{sh}V_i\frac{d}{dt}(-V_{di})u''_d - b_{sh}V_i\frac{d}{dt}(-V_{qi})u''_q \tag{16}$$

In order to keep the negative sign of (16), the transient control components,u''_d and u''_q , must have the same sign as their coefficients. Therefore the STATCOM control law is extracted from (16) as:

$$\begin{aligned} u''_d &= k_1\tfrac{d}{dt}\left(-V_{di}\right) \\ u''_q &= k_2\tfrac{d}{dt}\left(-V_{qi}\right) \end{aligned} \tag{17}$$

Where K_1 and K_2 are positive gains which are chosen individually to obtain appropriate damping time. In order to decentralize control method, all of the measurement signals must be local. In other words, due to obtained control strategy (17) a reference frame signal is required which must be a local signal. If V_i is considered as reference frame, the u''_q into equation (17) will be zero and Lyapunov method will not be an optimize strategy. Therefore we propose I_{ij} (is shown in Fig.3) to provide the synchronous reference frame to compute the direct- and quadrature-axis components of AC parameters. The proposed control scheme provides a complete decentralized control law.

V STEADY STATE OPERATION

The steady state control components, u'_d and u'_q, are determined according to 1) constraint of not having the active power exchange with power grid and 2) changes in STATCOM connected ac-bus voltage,V_i. With assuming lossless converter the first condition is written as:

$$\begin{aligned} P_{shi} &= b_{sh}V_i\left(u'_dV_{qi} - u'_qV_{di}\right) = 0 \\ u'_dV_{qi} &- u'_qV_{di} = 0 \end{aligned} \tag{18}$$

The voltage error value (V_{refi}) is given to PI-controller to create control signal (λ'_{qsh}) which is related to STATCOM reactive power. Therefore following equations can be written:

$$\begin{aligned} V_i - u'_dV_{di} - u'_qV_{qi} &= \lambda'_q \\ u'_dV_{di} + u'_qV_{qi} &= \lambda_q \\ \lambda_q &= V_i - \lambda'_q \end{aligned} \tag{19}$$

From (18) to (19) the control parameters for steady state can be obtained as:

$$\begin{aligned} u'_d &= \tfrac{\lambda_qV_{di}}{(V_{qi})^2+(V_{di})^2} = \tfrac{\lambda_qV_{di}}{V_i^2} \\ u'_q &= \tfrac{\lambda_qV_{qi}}{(V_{qi})^2+(V_{di})^2} = \tfrac{\lambda_qV_{qi}}{V_i^2} \end{aligned} \tag{20}$$

Control block diagram including transient and steady state conditions is in Fig. 4.

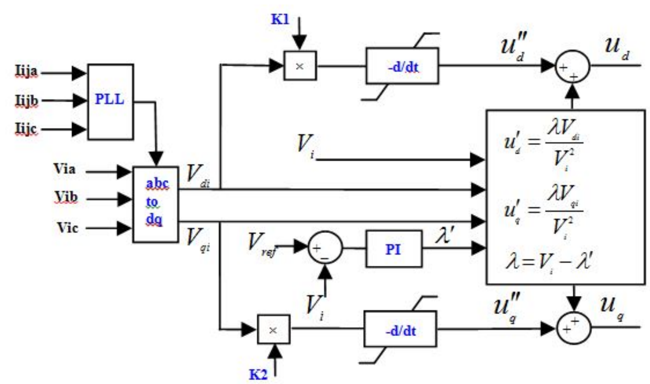

Figure 4: STATCOM control block diagram

VI SIMULATION RESULTS

The effectiveness of the proposed control strategy will be illustrated using a three-machine test system which is used in [8]. Single line diagram of test system is shown in Fig. 5 . The parameters of this sample system are given in appendix. Generator G3 is large and considered as infinite bus-bar. Generators G1 and G2 are driven by hydraulic and steam turbines respectively. Therefore, the swings of generator G2 are faster than those of G1. A temporary short circuit considered in B5 while STATCOM-SMES is located in line L4. A 100MJ/10H SMES system is used in simulation and also $k_1 = 0.55$ and $k_2 = 0.64$.

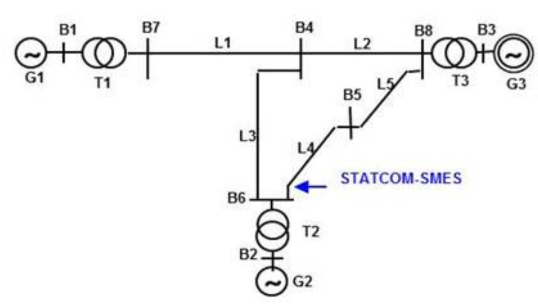

Figure 5: 3-machine test system

System responses which are the output active power of generators, with and without STATCOM-SMES presence are shown in Fig. 6 . Because of SMES application, the first swing reduction is also considerable that is not attained in [8]. SMES current and STATCOM dc-bus voltage are shown in Fig. 7.

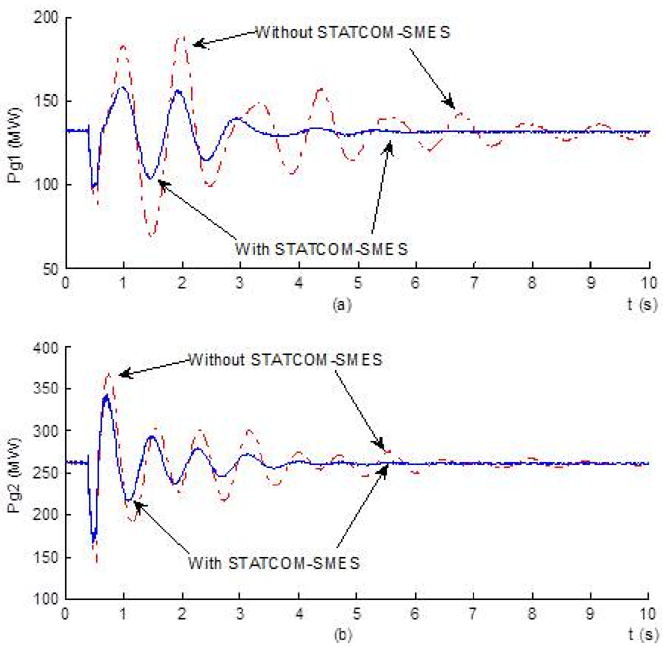

Figure 6: a) Generator No.1 active power b) Generator No.2 active power

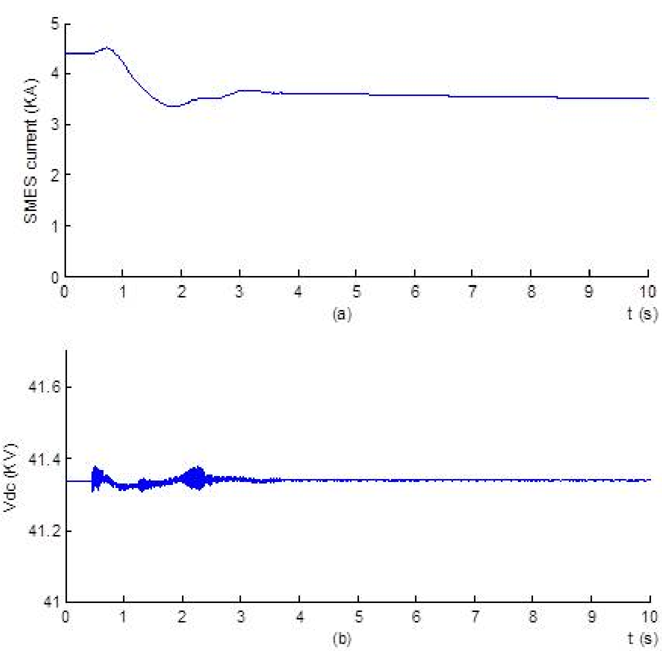

Figure 7: a) Generator No.1 active power b) Generator No.2 active power

It can be observed from Fig.7-a that SMES current is increased immediately after fault occurrence. This phenomenon demonstrates energy absorption by SMES and leads to reduction in first swing peak point which is critical consideration in clearing time determining of system protective relays.

VII CONCLUSION

Direct Lyapunov method applied to control STATCOM-SMES integration for power swings damping improvement. Proposed control strategy optimized by choosing appropriate reference frame which implies both active and reactive powers in increasing the negativeness of time derivative of Lyapunov function and moves the system trajectory to post-fault stable equilibrium point. Simulation results illustrated that beside power swings damping time improvement, the first swing reduced which results power system security increment.

VIII APPENDIX

Table 1: List of Parameters

δ_i, ω_i	i-th generator mechanical angle and velocity
M_i, D_i	i-th generator inertia and damping coefficient
E'_{qi}	i-th generator q-axis voltage transient reactance
x_{di}, x_{qi}	i-th generator d and q-axis synchronous reactances
T'_{doi}	i-th generator d-axis transient OC time constant
x'_{di}	i-th generator d-axis transient reactance
E'_{ifd}	i-th generator exciter voltage
P_{mi}, P_{Gi}	i-th generator mechanical and electrical power
V_i, θ_i	Magnitude and phase angle of i-th bus voltage
B_{ki}	k-i branch susceptance
P_k, Q_k	Real and reactive power injected into k-th node
P_{Lk}, Q_{Lk}	Real and reactive power of k-th load
P_{smes}	SMES Real power
C	dc capacitance
V_{dc}	SSSC dc-bus voltage
E_{smes}	SMES stored energy
d	dc-dc chopper duty cycle
L_{smes}	Inductance of SMES coil
$\bar{V}_{sh}$	STATCOM voltage
X_{sh}	STATCOM leakage reactance
θ_{sh}	STATCOM voltage phase angle

Table 2: TRANSMISSION LINES FOR TEST SYSTEM

Line	Node	Node	R	X	$B/2$
			Ω	Ω	μS
L1	B7	B4	6	59.5	300
L2	B4	B8	10.7	90	420
L3	B6	B4	3.5	30.8	180
L4	B5	B6	6.35	50	200
L5	B5	B8	6.35	47	230

Table 3: NODAL DATA FOR TEST SYSTEM .

Node	U	θ	P_L	Q_L	P_g	Q_g
	kV	Deg	MW	$MVAR$	MW	$MVAR$
B8	209.2	0	44.0	18.0	-210.1	-47.3
B7	237.3	19.8	15.0	9	130.3	42.7
B6	232.0	15.5	30.0	20.0	260.1	100.6
B5	220.7	7.8				
B4	226.5	12.7	80.0	55.0		

Table 4: GENERATING UNITS FOR TEST SYSTEM

Generator			G1	G2	G3
	S_n	MVA	235	426	9999
	U_n	kV	15.75	22	20
	$\cos\phi$		0.85	0.85	0.85
	T_m	s	9	5.5	10
	R	pu	0.0015	0.0016	0.00188
	X_d	pu	1.88	2.6	2.56
	X_q	pu	1.69	2.48	2.4
	X'_d	pu	0.275	0.33	0.36
	X'_q	pu	0.44	0.53	0.58
	X''_d	pu	0.191	0.235	0.242
	X'_q	pu	0.23	0.29	0.295
	T'_{do}	s	6.4	9.2	9.2
	T'_{qo}	s	0.72	1.095	1.076
	T''_{do}	s	0.168	0.42	0.211
	T''_{qo}	s	0.053	0.065	0.072
Transformer	S_n	MVA	240	426	9999
	U_n	kV	242	250	429
	U_{nT}	kV	15.75	22	20
	U_{shc}	pu	0.16	0.12	0.143
	ΔP_{Cu}	kW	792	267	411.6

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