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Power System Transient Stability Enhancement with SMES using Four Quadrant Active and Reactive Power Control

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Abstract

Among the Flexible Alternative Current Transmission Systems (FACTS), the Superconducting Magnetic Energy Storage (SMES) unit can be used to improve the stability of power systems. A control strategy for damping oscillations through control of power converter firing angles α_1 and α_2 of the SMES is proposed. The Western Systems Council Coordinating (WSCC) 3 machine-9 bus system is taken as a power system test. The behavior of the system is observed for three phase grounded fault on the network with and without the SMES unit. The paper shows that the SMES permits fast independent regulation of active and reactive power in four quadrants. A power system transient simulation program is developed to investigate the impact of the SMES. The approach makes the SMES have the ability to control active and the reactive power independently and rapidly within circular range containing four quadrants of the power domain is proposed. Simulation results show that the SMES unit can increase system stability within a short time and the proposed control scheme is very effective.

Key words

FACTS, SMES, Power System Control, Transient Stability

1. Introduction

FACTS have been proposed to improve the stability of the power system [1-3]. In the case of disturbances involving a long duration of the power frequency and tie-line power deviations because the governor system may not longer be able to absorb the frequency fluctuations due to its slow response, the SMES because of its fast response has been proposed [4]. Since the successful commissioning test of the Bonneville Power Administration 30MJ unit [5] and the development of high temperature superconducting materials [6] and power electronic technologies, the SMES devices have more widely applications in power systems [7,8]. The SMES unit is a device for efficiently storing energy in the magnetic field. It is very fast to exchange power between AC power system and superconducting coil. It is one of the effective measures to prevent failures. The SMES unit is designed to store electric power in the low loss superconducting magnetic coil. Power can be absorbed by or released from the unit according to the system requirement with unlimited number of charging and discharging cycles. The thyristor firing angles are varied in an appropriate manner for the energy exchange.

A lot of papers showed the ability of the SMES to enhance system transient performance by different methods [9-18]. This paper investigates the application of a SMES unit for enhancing transient stability of WSCC 3-machine, 9-bus system [19] taken as power system test using approach based on unequal firing angles α-mode. The determination of converter firing angles α_1, and α_2 of the SMES unit is illustrated. The behavior of the system is observed for three phase grounded fault on the network with and without the SMES unit. Based on the principles of SMES, a model of SMES system is formulated. A power system transient simulation program is developed to investigate the effect of SMES.

2. System model

The figure 1 shows the configuration of the SMES unit. The unit contains Y-Y/Y-Δ connected transformer, two sets of six-pulse cascaded bridges forced commutated Gate Turn Off (GTO) converters in series, and a DC superconducting inductor. The control of the firing angles α_1 and α_2 of the bridges makes the SMES have the ability to control active and the reactive power independently and rapidly within circular range containing four quadrants of the power domain [20].

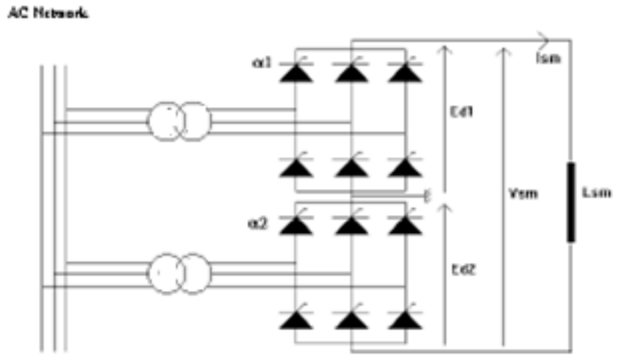

Fig. 1. Configuration of the SMES unit

GTO thyristors allow us to design such type of the converter DC output current Ism passing through the superconducting inductor being unidirectional. However, the voltage Vsm across the inductor terminals can be varied in a wide range between positive and negative values through the control of firing angles α_1 and α_2. By this way both active and reactive power of the system can be modulated. If $\alpha_1=\alpha_2$ is selected, many problems will arise and the SMES unit will be less effective. However, if unequal α-mode is selected, all problems associated with the equal α-mode can be alleviated. The necessity of incorporating an extra controller can also be eliminated. The voltage Vsm of the DC side of the 12-pulse converter is expressed by

$$V_{sm} = V_{sm0}(\cos\alpha_1 + \cos\alpha_2) \tag{1}$$

V_{sm0} is the ideal no-load maximum DC voltage of the 6-pulse bridges.

The current and voltage of superconducting inductor are related as

$$I_{sm} = \frac{1}{L_{sm}}\int V_{sm}d\tau + I_{sm0} \tag{2}$$

I_{sm0} is the initial current of the inductor.

The real and reactive power absorbed or delivered by the SMES unit are :

$$P_{sm} = V_{smo} I_{sm} (\cos\alpha_1 + \cos\alpha_2) \tag{3}$$

$$Q_{sm} = V_{smo} I_{sm} (\sin\alpha_1 + \sin\alpha_2) \tag{4}$$

The energy stored in the superconducting inductor is

$$W_{sm} = W_{sm0} + \int_{t0}^{t} P_{sm} d\tau \tag{5}$$

W_{sm0} is the initial energy in the inductor. It is such as :

$$W_{sm0} = \frac{1}{2} L_{sm} I_{sm0}^{2} \tag{6}$$

For ΔV_t the voltage deviation at the terminal bus of the generator because of sudden change in the system, the desired Q_{sm}-modulation of the SMES unit is :

$$Q_{sm} = \frac{K_{vs}}{1 + sT_{dc}} \Delta V_t + Q_{sm0} \tag{7}$$

Q_{sm0} is the reactive power of the SMES before the fault and K_{vs}, is the amplifier gain. T_{dc} is the delay time of the converter. For Δω the speed deviation, the active power modulation of the SMES unit P_{sm} is :

$$P_{sm} = \frac{K_{ps}}{1 + sT_{dc}} \Delta\omega + P_{sm0} \tag{8}$$

P_{sm0} is the active power of the SMES before the fault and K_{ps} is the gain of the amplifier. At any time, the active and reactive power delivered or absorbed by the SMES unit is given by equations (3) and (4). Because Vsm, is uniquely defined by α_1 and, α_2, its value can be varied in a wide range of positive and negative values via the control of α_1 and α_2. Ism is always unidirectional. Thus reversibility as well as magnitude control of power flow is achieved continuously and smoothly through the control of both firing angles α_1 and α_2.

Using equations (3) and (4) and considering $S_b = V_{smo} I_{sm}$ as power base, we can express the exchange power in pu between the AC power and the SMES unit as :

$$P = \frac{P_{sm}}{V_{sm0} I_{sm}} = \cos\alpha_1 + \cos\alpha_2 \tag{9}$$

$$Q = \frac{Q_{sm}}{V_{sm0} I_{sm}} = \sin\alpha_1 + \sin\alpha_2 \tag{10}$$

Expressions (9) and (10) can be written as :

$$P = 2\cos\frac{\alpha_1 + \alpha_2}{2}\cos\frac{\alpha_1 - \alpha_2}{2} \tag{11}$$

$$Q = 2\sin\frac{\alpha_1 + \alpha_2}{2}\cos\frac{\alpha_1 - \alpha_2}{2} \tag{12}$$

The figure 2 shows the four zones defining the values of the power exchange between the AC power and the SMES unit.

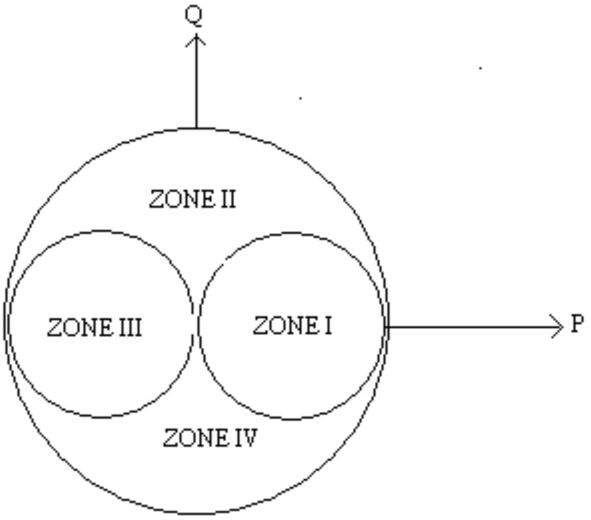

Fig. 2. P-Q simultaneous control scheme of SMES unit

The firing angles depend on the exchange power P and Q between the power system and the SMES. The values of the firing angles are determined as follow :

ZONE I : $\alpha_1 = \cos^{-1}\left[\frac{P + AQ}{2}\right]$ $\alpha_2 = 2\pi - \cos^{-1}\left[\frac{P - AQ}{2}\right]$

ZONE II : $\alpha_1 = \cos^{-1}\left[\frac{P - AQ}{2}\right]$ $\alpha_2 = \cos^{-1}\left[\frac{P + AQ}{2}\right]$

ZONE III : $\alpha_1 = 2\pi - \cos^{-1}\left[\frac{P - AQ}{2}\right]$ $\alpha_2 = \cos^{-1}\left[\frac{P + AQ}{2}\right]$

ZONE IV : $\alpha_1 = 2\pi - \cos^{-1}\left[\frac{P - AQ}{2}\right]$ $\alpha_2 = 2\pi - \cos^{-1}\left[\frac{P + AQ}{2}\right]$

where

$$A = \sqrt{\frac{4 - (P^2 + Q^2)}{P^2 + Q^2}}$$

The automatic voltage regulator (AVR) and the speed governor used as classical control for comparison with the SMES unit control are illustrated by the s-domain block diagrams shown in figures 3 and 4.

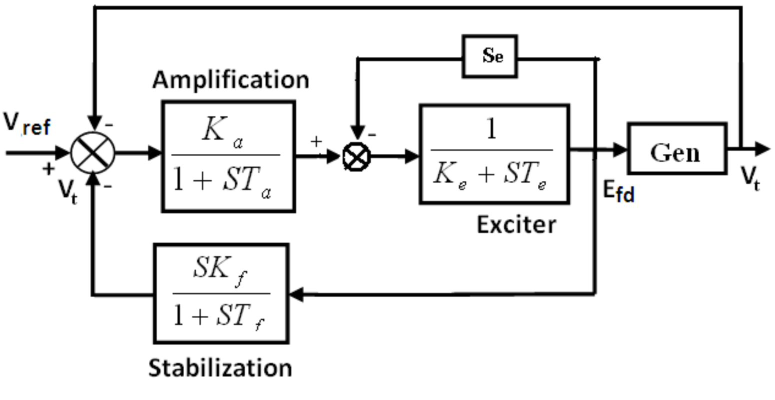

Fig. 3. Automatic Voltage Regulator type IEEE1

V_{ref} is the reference voltage and the V_t is the terminal voltage of the machine. The saturation function Se is of the form

$$S_e = A_{ex} e^{B_{ex} E_{fd}} \tag{13}$$

A_{ex} and B_{ex} are constants depending upon the exciter saturation characteristic.

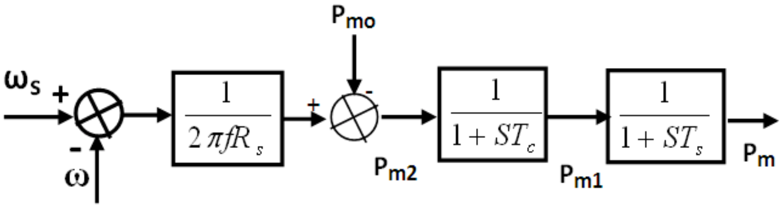

Fig. 4. Diagram of the speed governor

f : frequency of the system
P_{m0} : initial mechanical power
P_m : output mechanical power
R_s : speed regulator

3. Power system model

The figure 5 shows the studied system which consists of a 3 machines and 9 bus where G1, G2 and G3 are the generators of the power system and A, B and C the loads connected respectively to the bus 5, 6 and 7. The simulated fault is a three-phase short circuit to ground on point F at line 5-7 near the bus 7. After 80ms of a fault's duration, the line 5-7 is open. The optimal position of the SMES to improve the system stability depends on the fault's location [21, 22]. In this case, the SMES unit must be connected to the bus 2.

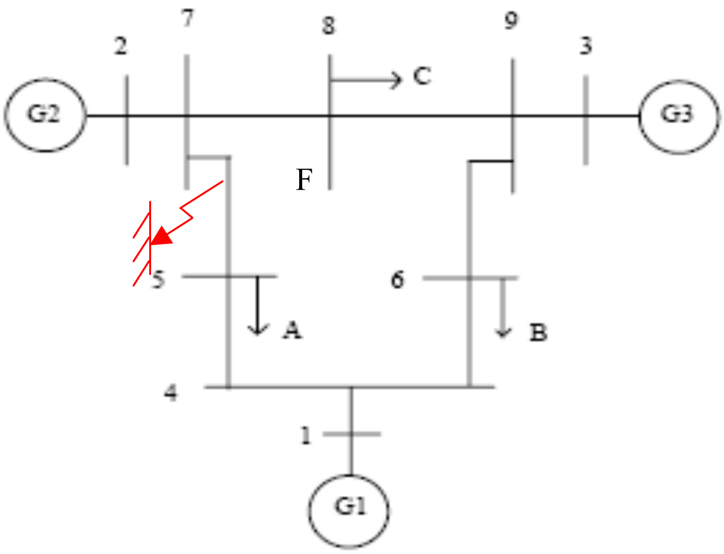

Fig. 5. WSCC 3 machine-9 bus System

The nonlinear dynamic behavior of each synchronous generator is described by two axis in Park model where the armature transient voltage of quadrature and direct axis are described by the equations (14) and (15)

$$\dot{E}'_q = [E_{fd} - E'_q + (X_d - X'_d)I_d]/T'_{do} \tag{14}$$

$$\dot{E}_d = [-E'_d - (X_q - X'_q)I_q]/T'_{qo} \tag{15}$$

E_{fd} is the field excitation voltage. T'_{qo} and T'_{do} represent q-axis and d-axis transient time constant respectively. The components of the terminal voltage V_t on the quadrature and direct axis are :

$$V_q = E'_q - rI_q + X'_d I_d \tag{16}$$

$$V_d = E'_d - rI_d - X'_q I_q \tag{17}$$

r is the armature resistance. The swing equation for the generator connected to the SMES can be written as

$$\dot{\omega} = \frac{\omega_S}{2H}[P_m - P_e - P_{sm} - D\omega] \qquad (18)$$

P_m, D and H are respectively the mechanical power, damping coefficient and inertia constant. The electromagnetic power transferred in the air gap P_e is expressed by :

$$P_e = E'_d I_d + E'_q I_q + (X'_d - X'_q) I_d I_q \qquad (19)$$

P_{sm} is the active power absorbed by or released from the SMES. The mechanical input power P_m is regarded as constant. The rotor angle equation is

$$\frac{d\delta}{dt} = \omega - \omega_s \qquad (20)$$

δ, ω and ω_s are, respectively, the rotor angle, the rotor speed and the synchronous speed.

4. Simulation Results

To show the performance of the SMES unit we carried out a series of simulations on the network test. The parameters of the simulated system are specified in the appendix. First, the behavior of the system without any regulator is studied. Then, we introduce the AVR and speed governor to take them as comparison criteria. Finally, the SMES unit connected at the bus 2 is used. The real power P_{sm} and the reactive power Q_{sm} are controlled continuously depending on the measured speed deviation of the rotor and the measured voltage deviation of the generator bus terminal respectively by using the P-Q simultaneous control scheme of the SMES unit showed by the figure 2. We examine the behavior only for the machine G2 of the multimachine system (Fig.5) because it is the most disturbed machine : the fault being near to it. . The dynamic responses of the system when a shortcut fault occurs followed by opening the line 5-7 after 0.08s are displayed in the figures 6 to 10. Results show that the SMES has the capability of maintaining the stability of the system. Figures 6, 7 and 8 show, respectively, the behaviors of the rotor angle, the terminal voltage and the speed of the most perturbed generator and the influence of the different regulations. When the SMES unit is connected to bus 2, the classical regulator does not exist at this bus. We can see the good performance of the SMES which maintains the stability of the different characteristics of the machine. Figures 7 and 8 show the very small transient phase less than 0.2s obtained with a SMES unit (red curve) compared to the phase obtained with classical regulator (green curve).

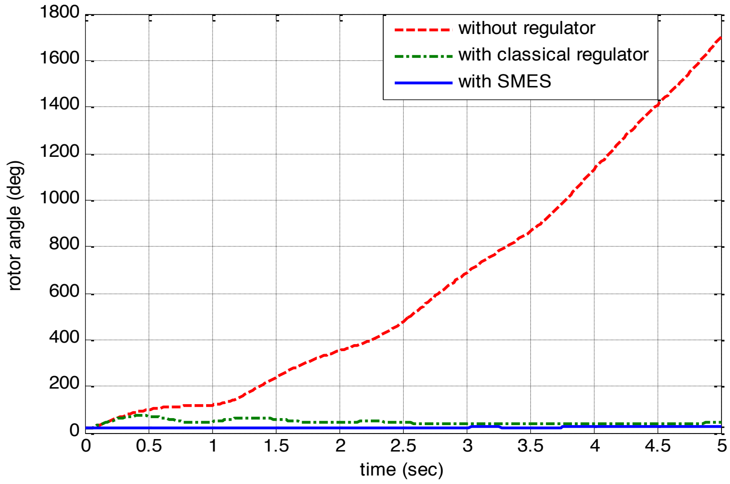

Fig. 6. Response of the rotor angle **δ**

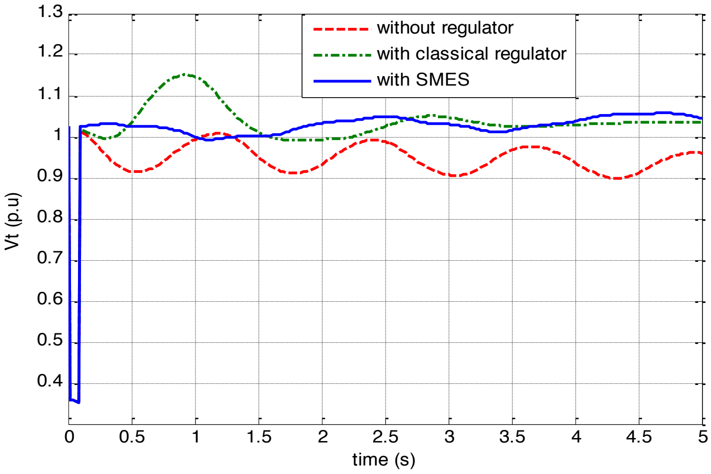

Fig. 7. Response of the machine voltage ***Vt***

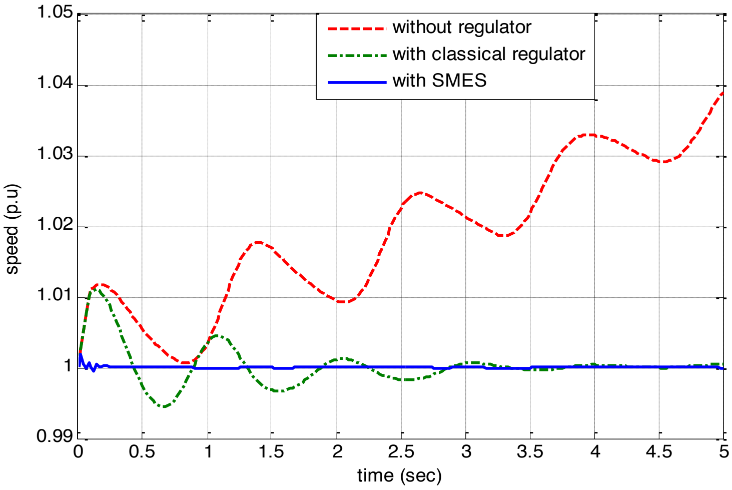

Fig. 8. Response of the speed **ω**

The figures 9 and 10 show the active and reactive power delivered by the SMES unit. This corroborates the active and the reactive power release/absorption properties of the SMES unit. During the dynamic period, the SMES unit releases power to the system to contribute to its stabilization. To determine the energy exchanged between the power system and the SMES unit, we calculate it from the equation (6) by using the trapezoidal method. The volume of energy storage is W_{SMES} =32 Joules. The volume of energy storage system is a very important factor because it affects the dimension and cost of installation.

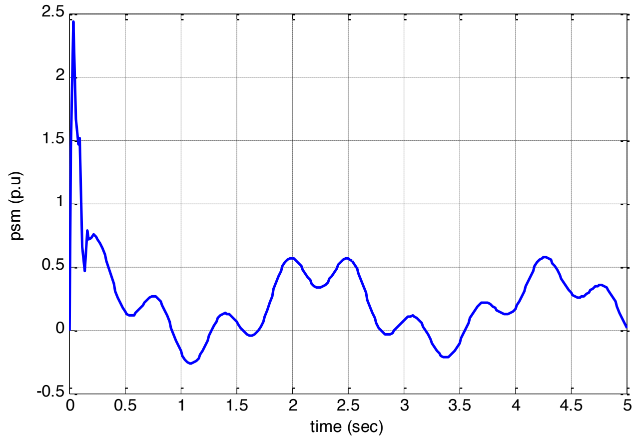

Fig. 9. Psm active power released by the SMES unit

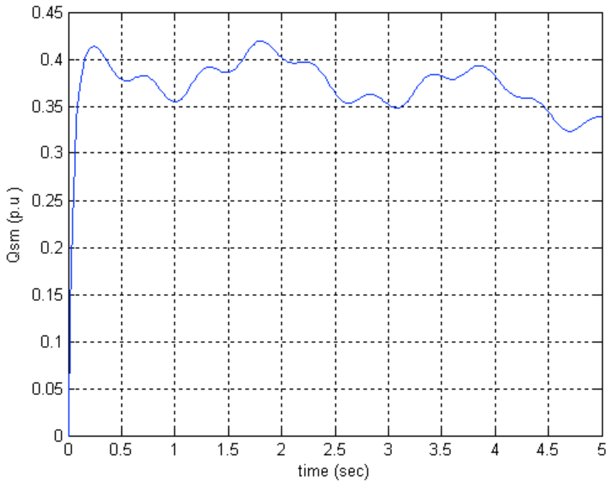

Fig. 10. Qsm reactive power released by the SMES unit

5. Conclusion

In this paper, the SMES unit under unequal α-mode is proposed to enhance the transient stability of multimachine power system under the effect of a three phases fault by simultaneous control of active and reactive power delivered by the SMES unit. A mathematical model of the SMES unit is developed. Active and reactive power of SMES unit can be controlled simultaneously by changing the firing angles.

Computer simulations on a 3-machine-9bus system show that the effect of improving transient stability by the SMES unit using active and reactive power control is very significant compared to the classical regulator. The stabilizing control is most effective when the SMES is located at the bus where the most perturbed generator is. It has been shown also that under unequal a-mode, the necessity of using an extra controller can be eliminated. The results show a good performance of the SMES with its configuration of the figure 3 and verify its effectiveness. The control scheme is very simple and it needs a very little hardware to be implemented. We have calculated the necessary energy storage that we need to maintain the stability of the system. This volume affects the dimension of SMES installation.

Appendix

p.u values on 100MVA base and 230kV base

Table I : Line parameters

Line	Resistance (pu)	Reactance (pu)	Admittance (pu)
1-4	0.0000	0.0576	0.0000
2-7	0.0000	0.0625	0.0000
3-9	0.0000	0.0586	0.0000
4-5	0.0100	0.0850	0.0880
4-6	0.0170	0.0920	0.0790
5-7	0.0320	0.1610	0.1530
6-9	0.0390	0.1700	0.1790
7-8	0.0085	0.0720	0.0745
8-9	0.0119	0.1008	0.1045

Table II : Load parameters

Load bus	5	6	8
P (MW)	125	90	100
Q (MVAR)	50	30	35

Table III : Generator parameters

Generator	1	2	3
S (MVA)	247.5	192	128
E (MJ)	2364	640	301
r (p.u)	0.0	0.0	0.0
Xd (pu)	0.146	0.8958	1.3125
Xd' (pu)	0.0608	0.1198	0.1813
Xq (p.u)	0.0969	0.8645	1.2578
Xq' (p.u)	0.0969	0.1969	0.25
T'do (s)	8.96	6.0	5.89
T'qo (s)	0.5	0.535	0.6

For each generator, the inertia constant H is defined as H=E/S

Table IV : AVR parameters

	Ka	Ta(s)	Ke	Te(s)	Kf	Tf(s)	A_{ex}	B_{ex}
AVR1	100	0.4	-0.17	0.60	0.5	1	0	3.7884
AVR2	50	0.3	-0.17	0.50	0.5	1	0.0013	1.3547
AVR3	25	0.3	-0.17	0.65	0.5	1	0.0015	1.5833

Table V : Speed governor parameters

	Rs	Tc(s)	Ts(s)
Speed governor 1	-0.04	0.05	0.06
Speed governor 2	-0.04	0.05	0.06
Speed governor 3	-0.04	0.05	0.06

SMES parameters

Lsm=0.015pu, Tdc=0.045s, Kps=11, Kvs=2.8,

Psmin=-3pu, Psmax=3pu, Qsmin=-3pu, Qsmax=3pu

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