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Improvement in Frequency Regulation of Interconnected Thermal Power System with Optimal SSSC and SMES Controllers

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Abstract: ***The level of real and reactive power reserve with only contribution from rotor inertia of generators provides a very small margin of maneuverability in system operation. The use of energy storage device and "Flexible AC Transmission systems (FACTs)" devices solves the problem to a large extent particularly in larger interconnected system. In this work energy storage devices like "Superconducting Magnetic Energy Storage (SMES)" system and "Static Synchronous Series Compensator (SSSC)", are operated together in different combined two-area thermal system.***

Keywords: ***Automatic Generation Control; Thermal-Thermal; SMES; SSSC; CSA.***

I. INTRODUCTION

For disturbances in load of the power systems, there is an imbalance between sudden change in power production and the load. Hence increase/decrease in the load will result in frequency deviation. The deterioration & fluctuations in frequency affects consumer's equipments & power system as a whole in an adverse manner. Therefore, it is essential to control the frequency at its nominal value within a short span of time.

Interconnected power system of large capacity and more power consuming equipments [1] do not have sufficient frequency control abilities and may result a large problem of frequency variation, when the share of renewable energy based generation increases. The governor of a conventional power system may not absorb high frequency fluctuation because of its low inertia response. Therefore, newer methodologies of frequency control may become a necessary component in future.

To ensure more reliable and stable power system operation, it may be beneficial to introduce energy storage devices to alleviate power fluctuations. When energy storage system (ESS) connected at the output side, it has been shown to reduce the uncertainty, which leads to better scheduling of its generation [2] and beneficial for stabilizing frequency oscillations of power generation during peak demand periods.

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Energy storage devise has been used in various applications. Examples of some primary implementations are in traction and transportation systems [3], FACTs devices [4], uninterruptible power supplies (UPS) [5] and many more. The main benefits of ESS can be summarized as;

- Capability of instantaneous exchange of real power with the system using power electronic interface.
- Enables both storage and supply of energy, as it behaves both as source and sink.
- Further improvement in transient stability [6], by utilizing an ESS integrated FACTs devices.

The several types of ESS, such as "battery energy storage system (BESS)", super-capacitor (SC), "flywheel energy storage system (FESS)" [7] and SMES [8], are commonly applied in power system. Different factors need to be considered during the selection of a particular type of ESS, which include their size, rating, speed and cost. Some storage devices are better suited for larger ratings and their relative performance in terms of speed of exchange of energy to compensate for any real power demand differs from each other. Table 1 summarizes the principle of their energy storage, ranges of energy and power, charging time, power density and cost. It may be noticed that each of these parameters are different for each of them [9, 10].

Due to high energy density, discharge rate and capacity, SMES has been widely used in the frequency control of the electric power systems [2]. Among some more prevalent devices in the FACTs family, the use of supplementary control can be applied for devices connected in series with tie-line of thermal power systems to damp the inter-area oscillations and power flow control [11,12,13].

It is a well established fact that, FACTs devices and "fast acting energy storage systems" is used actively to reduce the frequency variations in a power system [14,15]. To verify the efficacy of various FACTs devices like SSSC and SMES in the problem of AGC, some selected devices are placed in interconnected thermal power system and their performance may be compared. The present study is discussed under following heads;

- To study the impact of "SSSC" in series with the tie-line for the same T-T system.
- To study the effect of different controllers like "SMES– SMES" and "SSSC–SMES" on interconnected power system for load fluctuation.

The present study is arranged in the following manner. In portion 2, it describes about the model used in this system. Portion 3 discusses about the different objective function, methodology and system parameter chosen. The simulation and findings are discussed in portion 4. At last, in portion 5 conclusions are presented.

II. AGC IN T-T INTERCONNECTED POWER SYSTEM WITH SMES AND SERIES FACTS CONTROLLER

Many problems in AGC, particularly in combined power system, have been used broadly and the commonly used model is given in Fig. 1. The use of “SMES” in frequency regulation in an AGC framework gives fast control over need of short or excess active power, by extracting the power from a huge inductor. According the requirement of power, the power supplied or absorbed from the inductor can be regulated by finely designed controller of the SMES. The detail understanding of the basic principles and primary modeling concept already described in [16].

SSSC is a key device of FACTs group, which may be incorporated in series with the system. To have characteristic change on its reactance within two extremes from being capacitive to inductive, the SSSC can signify to be active in regulating the flow of power distribution. SSSC is applied for frequency stabilization in series with the tie-line power between T-T power systems [17]. The system model of SSSC is depicted in Fig. 2. The frequency controller SSSC is used in interconnection with a 2nd order lead-lag compensator as depicted in Fig. 3.

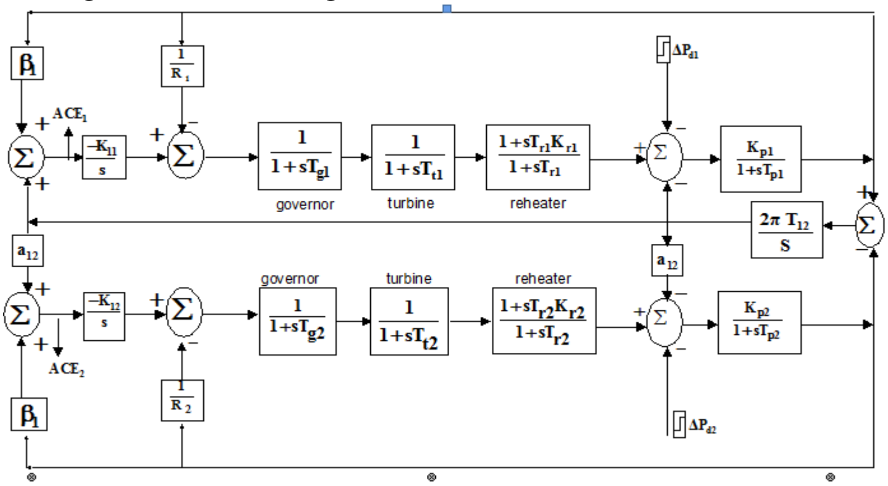

Fig. 1. AGC of two areas reheat thermal power plant.

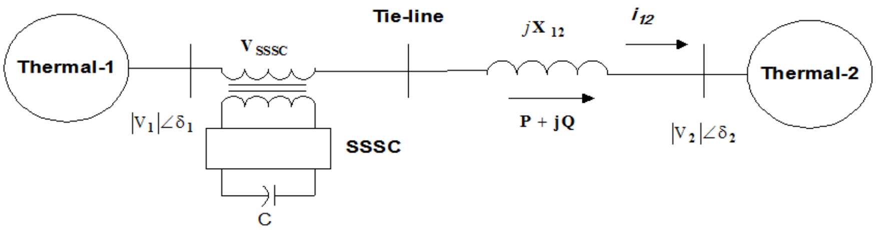

Fig. 2 Diagram showing interconnected Thermal-Thermal with SSSC in tie-line.

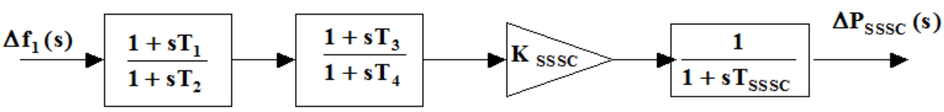

Fig. 3 Diagram showing SSSC as a frequency controller

In this study the time constants taken are, T_{SSSC} = 0.05 S, T_2 =0.5 S and T_4 =0.5 S [17]. K_{SSSC}, T_1 and T_3 may be suitably tuned to obtain a desired performance in terms of frequency regulation.

III. METHODOLOGY AND SYSTEM PARAMETER CHOSEN

The two area thermal (T-T) and wind system data are described in [18]. In this work, both the control areas have been assumed to have identical integral controllers whose gains (Ki1, Ki2) are denoted as Ki. The real and p.u. value of "SMES device" are described in [16]. The components of the AGC, SSSC and SMES are optimized by using CSA, which has been already established in [16,18] to be giving better performance in optimization. CSA gives better performance compare to other single objective tuned methods [19, 20].

The objective function J is given below in equation (1) and is formulated by using the following parameters;

ITSE= Integral of time multiple of square of error,

T_s = Settling time

Δf_1 and Δf_2 = Frequency deviations, ΔP_{Tie}= Tie line power deviation

x = Minimum Damping Ratio (MDR)

$$J = \omega_1(\text{ITSE}) + \omega_2(1/X) + \omega_3(T_s) \quad (1)$$

ω_1, ω_2 and ω_3 are the suitably chosen weighing factors.

$$\text{ITSE} = \int_0^{t_{sim}} t[(\Delta f_1)^2 + (\Delta f_2)^2 + (\Delta P_{Tie})^2] \; dt$$

$$Ts = Ts_{f1} + Ts_{f2} + Ts_{\Delta Ptie}$$

$Ts_{\Delta Ptie}$, Ts_{f1}, Ts_{f2} = Tie line power variation settling time, frequency variation settling time in area 1 and 2.

IV. SIMULATION AND RESULTS

AGC model is formulated in 'MATLAB/SIMULINK' to find out active output for a step load perturbation (SLP). As the T-T power system is faced to load disturbances, system frequency will be fluctuated and oscillating, affecting the dynamic performance. To fulfill the load variations and fix the area frequency oscillations, the active power flow control of SSSC in coordination with SMES is examined in this work. A coordinated work operation of "SMES" in both the areas is also studied in a comparative manner.

The gains (Ki) of integral controller in AGC, SMES (KSMES, KId), and SSSC (KSSSC, T1 and T3) are optimized in different cases with the help of CSA. At the outset, for the sake of obtaining the objective functions J, the real power loads (Pd) of the control area-1 is perturbed by 1 % SLP. Optimum system response for a SLP and the impacts of SMES and SSSC in that regard, have been explored and discussed in the following section.

4.1 Coordination of SSSC with SMES in different areas for improvement of damping performance

The effectiveness of the SSSC in series with interconnected T-T system, the results is studied with those found with the case without SSSC in the same system. In this analysis, three different cases are considered.

SSSC: Only SSSC is assumed to be present in the tie-line. In this case, the gains of SSSC and integral gains of AGC in both the areas are to be optimized.

SMES-SSSC: In this case, an SMES is placed in the 1st area with an SSSC operating in the tie-line.

SMES-SMES: Both the areas are assumed to be having one SMES each, without the assistance of SSSC in the tie-line.

The gains of the controllers in each case are simultaneously optimized. The tuned controller parameters and optimized value of objective function are presented in Table 2. The active output obtained is shown in Fig. 4. It is observed that the SSSC coordination with T-T system has significantly improved the performance as expected compared to those obtained when SSSC is not operating in the system. However, when the relative advantage of operating the system with two SMES or one SMES in area 1 and SSSC in the tie line is to be examined, their gains are accordingly tuned. In the case of SMES-SMES, the gains (Ki, KSMES, KId) are optimized with CSA using objective function J as done before. Similarly, for SMES-SSSC, their corresponding gains and time constants (KSSSC, T1 and T3) are optimized, using CSA in all the cases, considering the same objective function J.

The optimized controller parameters and objective function values are depicted in Tables 2. The dynamic responses of the systems with the SMES–SMES and SSSC–SMES coordinated operation are given in Fig. 5 after 1 % SLP in area 1. The study revealed that the integration of "SMES–SMES" and "SSSC–SMES" can efficiently be used to suppress the fluctuations in area frequencies and the tie-line power interchange under load variation. Study recorded that the model with SMES presented in both areas gives minimum undershoot and overshoot in frequency fluctuations as well as tie-line power variations, in comparison to "SSSC–SMES" controllers. Further, the fluctuations in frequencies and tie-line power take lesser time to settle.

Keeping the respective optimized gains for all the cases, the result of each damping scheme is studied and compared in terms of several other established time domain performance indices, i.e., IAE, ITSE, ISE and IAE and in terms of the values of the MDRs of their eigen values. All these data are elucidated in Tables 3, from which a clear idea about the efficacy of integrated control and operation of "SMES–SMES" and "SSSC–SMES" can be obtained.From all the above results it may be observed that, among all the schemes of damping controllers, the operation of two numbers of SMES in both the areas has provided the best dynamic response.

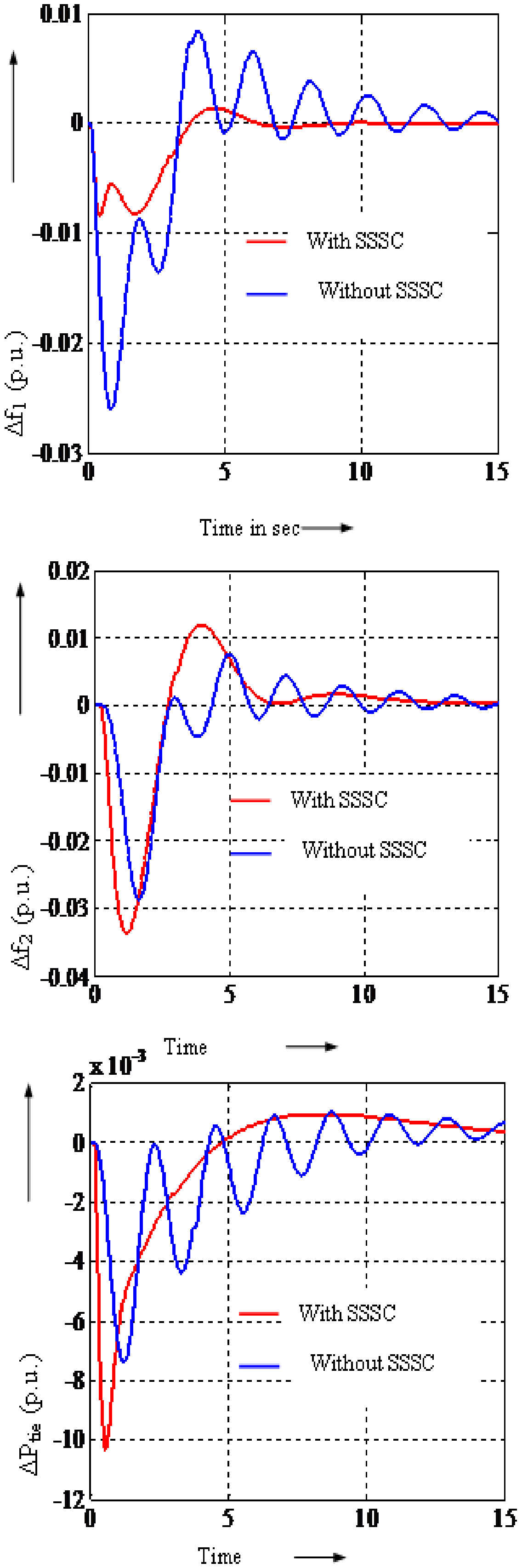

Fig. 4 Δf_1, Δf_2 and ΔP_{tie} in T-T system comparing presence and absence of SSSC with load in area1

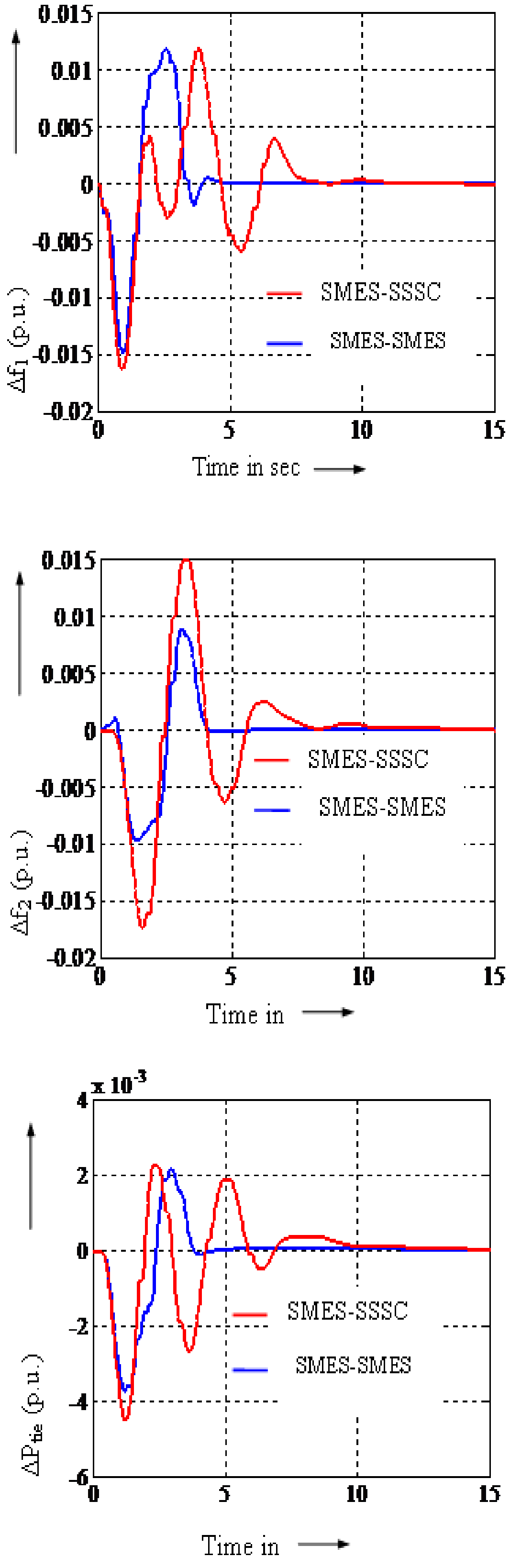

Fig. 5. Δf1, Δf2 and ΔPtie in T-T system with SMES and SSSC with load in area1

Table 2 The CSA optimized values gains and objective function *J* obtained for different schemes of SSSC and SMES.

Controller parameters	Controller parameters						Optimized value of J
	K_i	K_{SMES}	K_{Id}	T_3	T_1	K_{SSSC}	
SSSC	0.7026	-	-	0.4273	3.1191	5.0092	49.8825
SMES(1st)-SSSC	1.7399	50.8156	22.2465	5.7902	32.2239	1.6682	41.7909
SMES-SMES	4.7118	99.1703	14.3716	-	-	-	14.8430
T-T only	0.4986	-	-	-	-	-	76.3698

Table 3 Various PFIs and MDR with different cases of coordinated controllers

Performance Indices		Different FACT devices with SMES.			T-T
		TCPS-SMES	SSSC-SMES	SMES-SMES	
ISE		7.4383×10^{-4}	8.4152×10^{-4}	3.1536×10^{-4}	0.0017
ITSE		0.0015	9.7620×10^{-4}	3.5042×10^{-4}	0.0031
IAE		0.0697	0.0634	0.0324	0.1252
ITAE		0.1965	0.1193	0.0484	0.4510
T_S (sec)	Δf_1	12.24	7.4300	4.9000	25.4900
	Δf_2	14.71	9.6400	4.3400	26.5800
	ΔP_{tie}	13.14	13.2400	3.9800	23.9800
MDR		0.3472	0.6110	0.6954	0.0098
Eigen values		-12.5000 -30.0252 $-1.04\pm2.82i$	-30.3751 $-7.80\pm10.10i$ $-1.77\pm0.29i$	-12.5000 -24.2947 $-3.82\pm3.95i$	-3.3333 -12.5000 $-0.02\pm2.55i$

V. CONCLUSION

The thermal power plants operate with large numbers of operational constraints, particularly in an integrated system. The level of real and reactive power reserve with only contribution from rotor inertia of generators provides a very small margin of maneuverability in system operation. The use of ESS and FACTS devices solves the problem to a large extent particularly in larger interconnected system. Further, the nature of randomness and uncertainty in the availability of renewable resources also require extra storage system for grid reliability.

The 'SMES–SMES' scheme gives the minimum undershoot and overshoot in frequency fluctuations and tie-line power interchanges as compared to 'SSSC–SMES' controller.

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