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Improvement of Dynamic Performance of Multi Area System under Load Following Employing FACTS Devices

A. Suresh Babu[1], Ch.Saibabu[2], S.Sivanagaraju[2]
[1] *Department of EEE, SSN Engineering College, Andhra Pradesh, India,*
[2] *Department of EEE, J.N.T University, Kakinada, Andhra Pradesh, India*

Abstract:—The enhancement of dynamic performance of load following based hydrothermal system under open market employing Static synchronous series compensator (SSSC) and Superconducting Magnetic Energy Storage (SMES) is presented in this paper. The SSSC and SMES have been modeled and an attempt has been made to incorporate these devices in the two area system thus improving the dynamic response of the system. The effect of these devices on the system is demonstrated with the help of computer simulations. A systematic method has also been demonstrated for the modeling of these components in the system. Computer simulations reveal that due to the presence of SSSC and SMES, the dynamic performance of the system in terms of settling time, overshoot and peak time is greatly improved than that of the system with SMES only.

Keywords:—Hydrothermal system, Open market system, Load Following, SMES, SSSC.

I. INTRODUCTION

Large scale power systems are normally composed of control areas or regions representing coherent groups of generators. In a practically interconnected power system, the generation normally comprises of a mix of thermal, hydro, nuclear and gas power generation. However, owing to their high efficiency, nuclear plants are usually kept at base load close to their maximum output with no participation in the system AGC. Gas power generation is ideal for meeting the varying load demand. Gas plants are used to meet peak demands only. Thus the natural choice for AGC falls on either thermal or hydro units. Literature survey shows that most of earlier works in the area of AGC pertain to interconnected thermal systems and relatively lesser attention has been devoted to the AGC of interconnected hydro-thermal system involving thermal and hydro subsystem of widely different characteristics. Concordia and Kirchmayer [1] have studied the AGC of a hydro-thermal system considering non-reheat type thermal system neglecting generation rate constraints. Kothari, Kaul, Nanda [2] have investigated the AGC problem of a hydro-thermal system provided with integral type supplementary controllers. The model uses continuous mode strategy, where both system and controllers are assumed to work in the continuous mode.

On the other hand, the concept of utilizing power electronic devices for power system control has been widely accepted in the form of Flexible AC Transmission Systems (FACTS) which provide more flexibility in power system operation and control [3].An attempt was made to use battery energy storage system(BES) to improve the LFC[4]. The problems like low discharge rate, increased time required for power flow reversal and maintenance requirements have led to the evaluation of superconducting magnetic energy storage (SMES) for their applications as load frequency stabilizers[5-7]. Static synchronous series compensator (SSSC) in one of the important member of FACTS family which can be installed in series with the transmission lines [8]. With capability to change its reactance characteristic from capacitive to inductive, the SSSC is very effective in controlling power flow and application of SSSC for frequency regulation by placing it series with tie-line between interconnected two area power system with thermal units is proposed [9-10].

The reported works [11-13] further shows that, with the use of SMES in both the areas, frequency deviations in each area are effectively suppressed. In view of this the main objectives of the present work are:

1. To develop the two area simulink model of hydrothermal system under load following
2. To develop the model of SSSC and SMES
3. To compare the improvement of dynamic performance of the system with SMES only and SSSC with SMES.

The rest of the paper is organized as follows: Section (2) focuses on dynamic mathematical model considered in this work. Section (3) emphasizes on the development of mathematical model of SMES. Section (4) describes the mathematical model of SSSC to be incorporated into the system. Section (5) demonstrates the results and discussions and some conclusions are presented in Section (6).

I. DYNAMIC MATHEMATICAL MODEL

Electric power systems are complex, nonlinear dynamic system. The Load Frequency controller controls the control valves associated with High Pressure (HP) turbine at very small load variations. The system under investigation has tandem-compound single reheat type thermal system. Each element (Governor, turbine and power system) of the system is represented by first order transfer function at small load variations in according to the IEEE committee report [18]. Fig. 1 shows the transfer function block diagram of a two area interconnected network under deregulated scenario .The parameters of two area model are defined in Appendix.

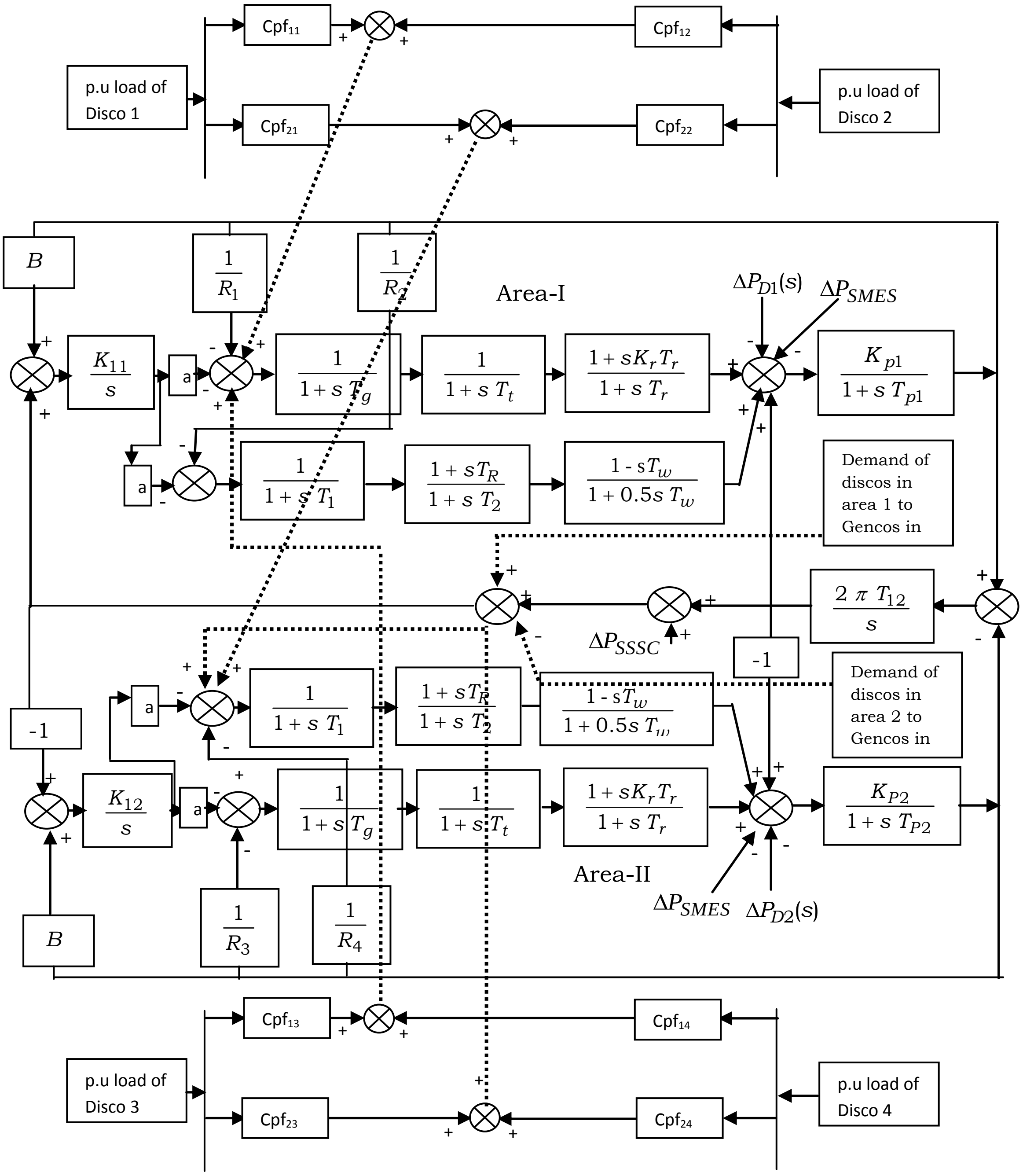


Fig. 1. Two Area load following Hydrothermal system with SSSC and SMES

II. DESIGN OF SMES

Either frequency deviation or Area Control Error (ACE) can be used as the control signal to the SMES unit. In this work the frequency deviation of area 1 is employed as input to the SMES device. It can be seen from Figure 3 that the structure of SMES consists of gain block K_{SMES}, time constant T_{SMES} and two stage phase compensation blocks having time constants T_1, T_2, T_3, T_4 respectively. A performance index considered in this work to compare the performance of proposed method is given by $J = \int_0^t \left(\alpha \cdot \Delta f_1^2 + \beta \cdot \Delta f_2^2 + \Delta P_{tie12}^2\right)$

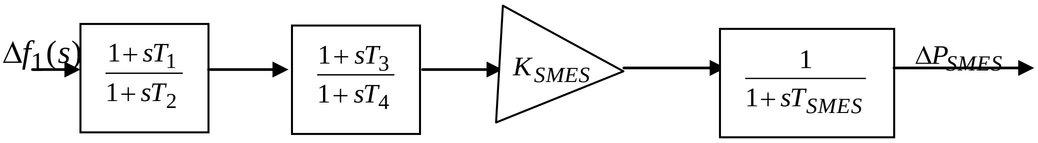


Fig. 3. Schematic diagram of SMES applied to system

III. DESIGN OF SSSC

A SSSC employs self-commutated voltage-source switching converters to synthesize a three-phase voltage in quadrature with the line current, emulates an inductive or a capacitive reactance so as to influence the power flow in the transmission lines. The schematic of an SSSC, located in series with the tie-line between the interconnected areas, can be applied to stabilize the area frequency oscillations by high speed control of the tie-line power through interconnection as shown in Fig. 4. The equivalent circuit of the system can also be represented by a series connected voltage source V_S along with a transformer leakage reactance X_S as shown in Fig 5. The SSSC controllable parameter is V_S, which in fact represents the magnitude of injected voltage. Fig 6 represents the phasor diagram of the system taking into account the operating conditions of SSSC.

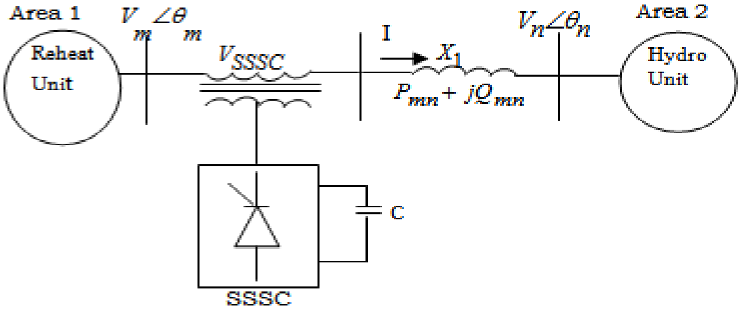


Fig 4: Schematic of SSSC applied to two- area interconnected system

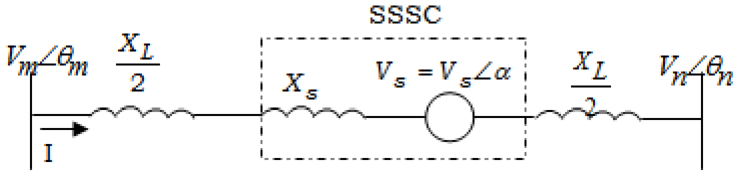


Fig 5: Equivalent circuit of SSSC

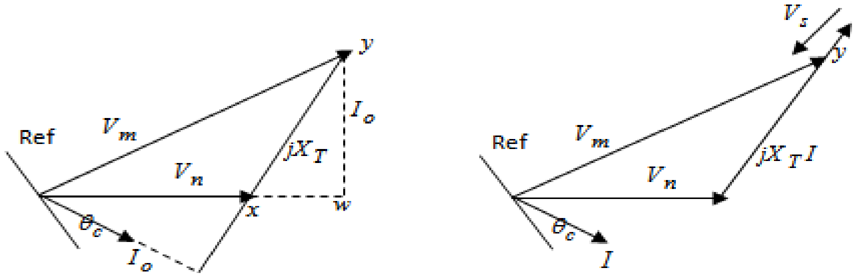


Fig 6: Phasor diagram at (a)V_s=0; (b) V_s lagging I by 90°

Based on the above figure when $V_S = 0$, the current I_o of the system can be written as

$$I_o = \frac{V_m - V_n}{jX_T} \qquad (1)$$

Where $X_T = X_L + X_S$. The phase angle of the current can be expressed as

$$\theta_c = \tan^{-1}\left[\frac{V_n \cos\theta_n - V_m \cos\theta_m}{V_m \sin\theta_m - V_n \sin\theta_n}\right] \qquad (2)$$

But Eqn (1) can be expressed in a generalized form as

$$I = \frac{V_m - V_s - V_n}{jX_T} = \left[\frac{V_m - V_n}{jX_T}\right] + \left[\frac{-V_s}{jX_T}\right] = I_o + \Delta I \qquad (3)$$

The term ΔI is an additional current term due to SSSC voltage V_s. The power flow from bus m to bus n can be written as $S_{mn} = V_m I^* = S_{mno} + \Delta S_{mn}$ which implies

$$P_{mn} + jQ_{mn} = (P_{mno} + \Delta P_{mn}) + j(Q_{mno} + \Delta Q_{mn}) \qquad (4)$$

Where P_{mno} and Q_{mno} are the real and reactive power flow respectively when $V_s = 0$. The change in real power flow caused by SSSC voltage is given by

$$\Delta P_{mn} = \frac{V_m V_s}{X_T} \sin(\theta_m - \alpha) \qquad (5)$$

When V_s lags the current by 90^o, ΔP_{mn} can be written as

$$\Delta P_{mn} = \frac{V_m V_s}{X_T} \cos(\theta_m - \theta_c) \qquad (6)$$

From Eqn (2) the term $\cos(\theta_m - \theta_c)$ can be written as

$$\cos(\theta_m - \theta_c) = \frac{V_n}{V_m} \cos(\theta_n - \theta_c) \qquad (7)$$

Referring to Fig 3 it can be written as

$$\cos(\theta_n - \theta_c) = \frac{yw}{xy} \qquad (8)$$

And it can be seen as $yw = V_m \sin\theta_{mn}$ (9)

Also $xy = \sqrt{V_m^2 + V_n^2 - 2V_m V_n \cos\theta_{mn}}$ and $\theta_{mn} = \theta_m - \theta_n$ (10)

Using these relationships Eqn (6) can be modified as follows

$$\Delta P_{mn} = \frac{V_m V_n}{X_T} \sin\theta_{mn} \times \frac{V_s}{\sqrt{V_m^2 + V_n^2 - 2V_m V_n \cos\theta_{mn}}} \qquad (11)$$

From Eqn (4) it can be written as $P_{mn} = P_{mno} + \Delta P_{mn}$ which implies

$$P_{mn} = \frac{V_m V_n}{X_T} \sin\theta_{mn} + (\frac{V_m V_n}{X_T} \sin\theta_{mn} \times \frac{V_s}{\sqrt{V_m^2 + V_n^2 - 2V_m V_n \cos\theta_{mn}}}) \qquad (12)$$

Linearizing Eqn (12) about an operating point it can be written as

$$\Delta P_{mn} = \frac{V_m V_n}{X_T} \cos(\theta_m - \theta_n)(\Delta\theta_m - \Delta\theta_n) + (\frac{V_m V_n}{X_T} \sin\theta_{mn} \times \frac{\Delta V_s}{\sqrt{V_m^2 + V_n^2 - 2V_m V_n \cos\theta_{mn}}}) \qquad (13)$$

$\Delta P_{mn} = \Delta P_{tie} + \Delta P_{SSSC}$ which implies

$$\Delta P_{SSSC} = (\frac{V_m V_n}{X_T} \sin\theta_{mn} \times \frac{\Delta V_s}{\sqrt{V_m^2 + V_n^2 - 2V_m V_n \cos\theta_{mn}}}) \qquad (14)$$

Based on Eqn (14) it can be observed that by varying the SSSC voltage ΔV_s, the power output of SSSC can be controlled which will in turn control the frequency and tie line deviations. The structure of SSSC to be incorporated in the two area system in order to reduce the frequency deviations is provided in Figure 5 shown below. The frequency deviation of area 1 can be seen as input to the SSSC device.

. It can be seen from Fig 5 that the structure of SSSC consists of gain block K_{SSSC}, time constant T_{SSSC} and two stage phase compensation blocks having time constants T_1, T_2, T_3, T_4 respectively.

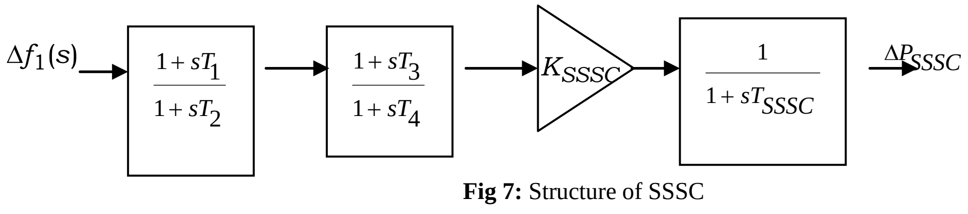


Fig 7: Structure of SSSC

IV. RESULTS AND DICUSSIONS

Simulation studies are performed to investigate the performance of the two-area hydrothermal system under deregulated Environment. Here in the two-area hydrothermal system three Gencos and two Discos are considered in each area. It is assumed in this work that one Genco in each area is under AGC only and the remaining Gencos participate in the bilateral contracts. It is assumed that there is 0.2% step load disturbance of each Disco, as a result of which the total step load disturbance in each area and accounts to 0.4% and each Genco participates in AGC as defined by following area participation factors (apfs): apf_1=0.25, apf_2=0.25, apf_3=0.5, apf_4=0.25, apf_5=0.25, apf_6=0.5 and the Discos contract with the Gencos as per the following Disco Participation Matrix

$$\text{DPM} = \begin{bmatrix} 0.25 & 0.3 & 0.1 & 0.3 \\ 0.25 & 0.1 & 0.4 & 0.4 \\ 0 & 0 & 0 & 0 \\ 0.25 & 0.4 & 0.3 & 0.1 \\ 0.25 & 0.2 & 0.2 & 0.2 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

A nominal value of 0.5 is considered for the gain setting of integral controller in both the areas. Table 1 shows the comparison between the dynamic performance of the system with and without SMES. It can be observed that the system with SMES has better dynamic performance than the system without SMES. Contract violation case has also been considered in this work. In this case it is considered that Disco_1 demands additional load of 0.3% after 30 sec and Disco_4 in area 2 demands additional load of 0.3% after 60 sec. It can be seen that the uncontracted power is supplied by the Gencos in the same area as that of the Disco which has demanded for additional power.

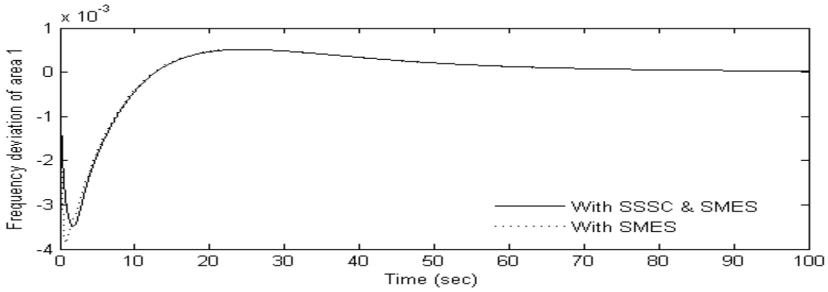
TABLE 1 COMPARISON OF SYSTEM PERFORMANCE WITH AND WITHOUT SMES

	Area-I			Area-II		
	Peak time (sec)	Overshoot	Settling Time (sec)	Peak time (sec)	Overshoot	Settling Time (sec)
With SSSC & SMES	1.77	0.003483	4.68	0.785	0.005696	3.9
With SMES	0.75	0.003856	4.345	0.825	0.004707	4.0

TABLE 2 COMPARISON OF PERFORMANCE INDEX VALUES

	Performance Index Value (Base case)	Performance Index Value (contract violation)
With SSSC& SMES	7.801×10^{-6}	2.747×10^{-5}
With SMES	8.199×10^{-6}	3.332×10^{-5}

Fig.8 shows the comparison between the frequency deviations and tie line power error deviations for both the cases. Fig 9 and 10 shows the generation of gencos of both areas. Fig.11 shows the comparison of frequency deviations and tie line power error deviations during the contract violation. Fig.12 and 13 depict the various generation of gencos during contract violation. The comparison of both the system in terms of performance index has been carried out in Fig.14 and 15. It can be observed from the figures that the system with SSSC and SMES has less performance index than the system with SMES only which indicates that the system has less error in the presence of SSSC and SMES.



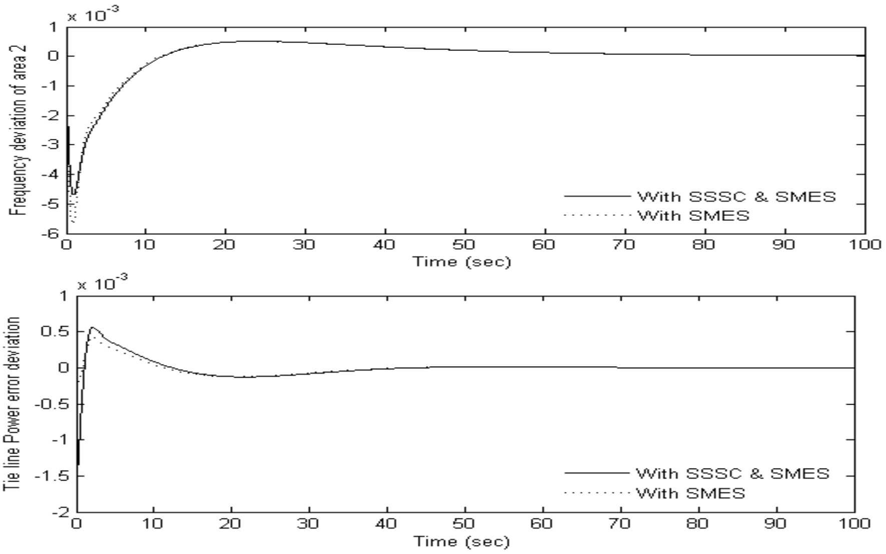


Fig 8: Comparison of Frequency deviations and tie line power error deviations

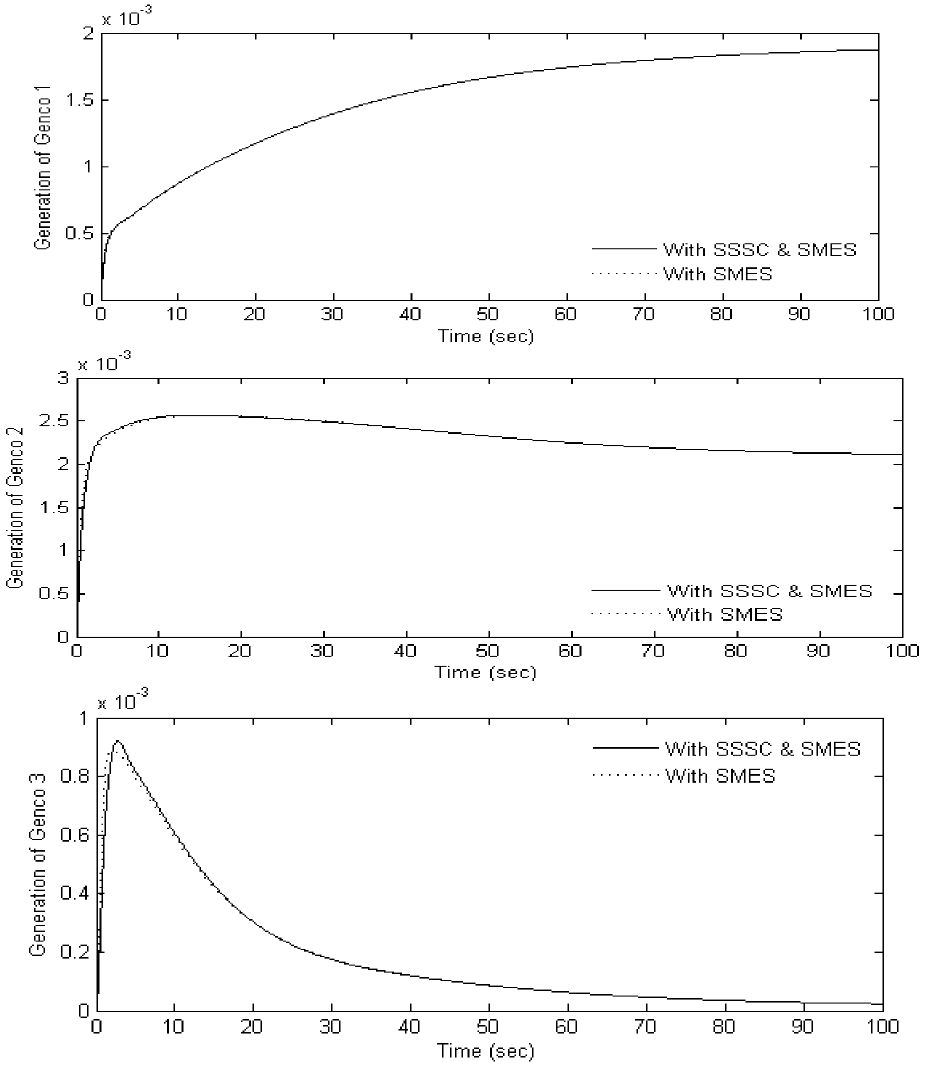


Fig 9: Generation of Gencos of Area I

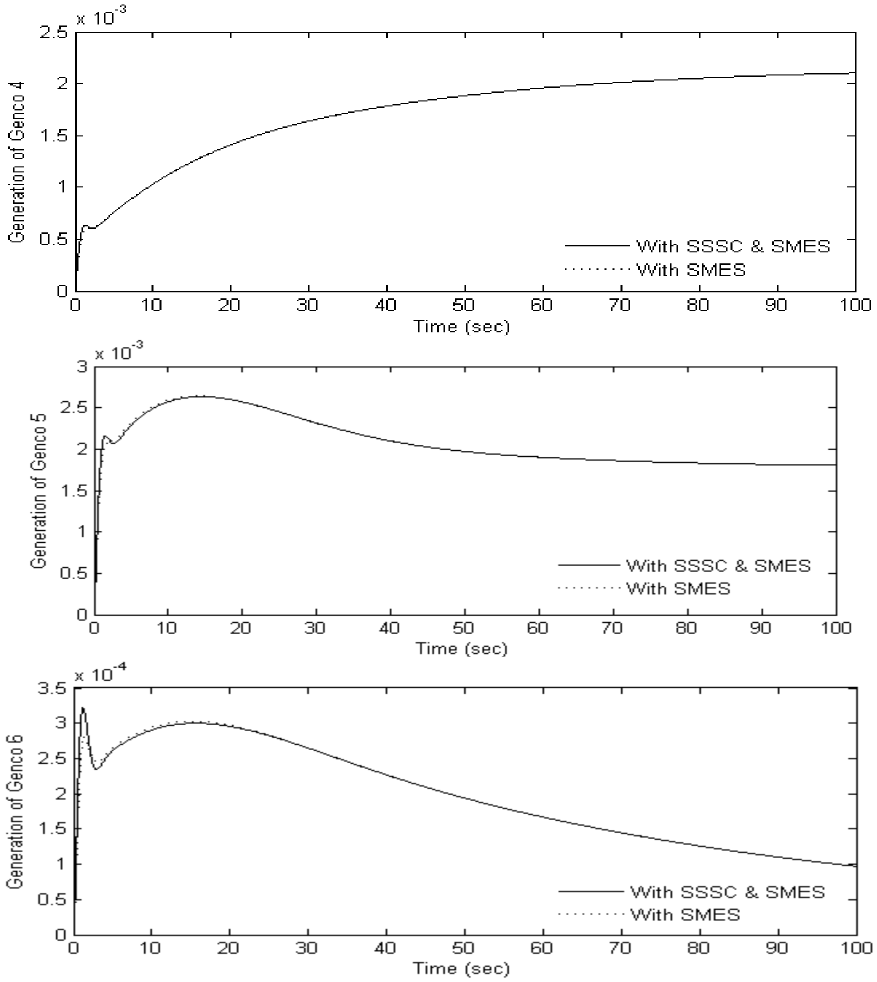
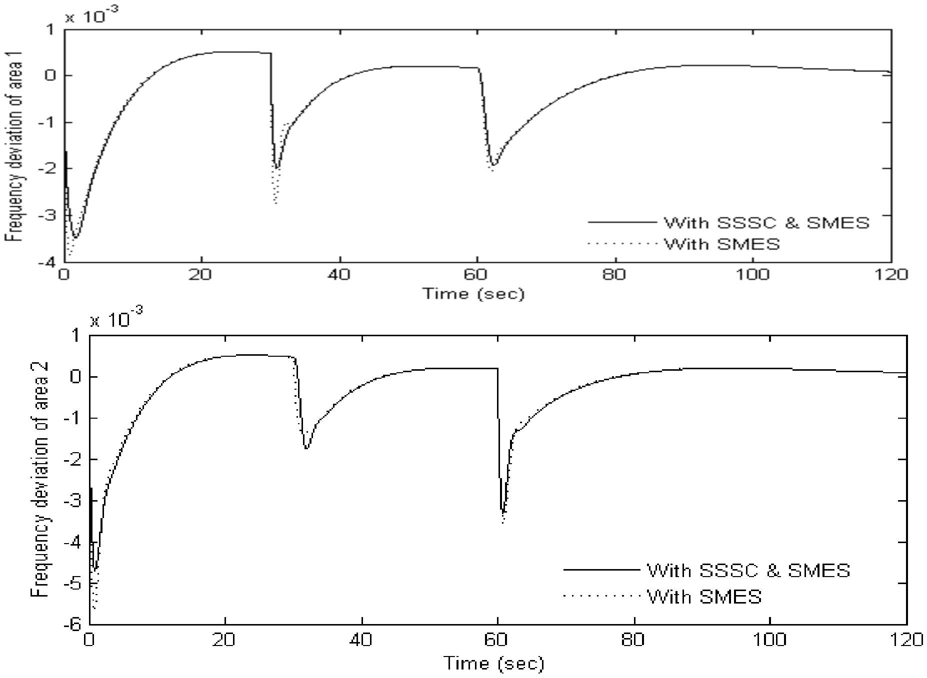


Fig 10: Generation of Gencos of Area II



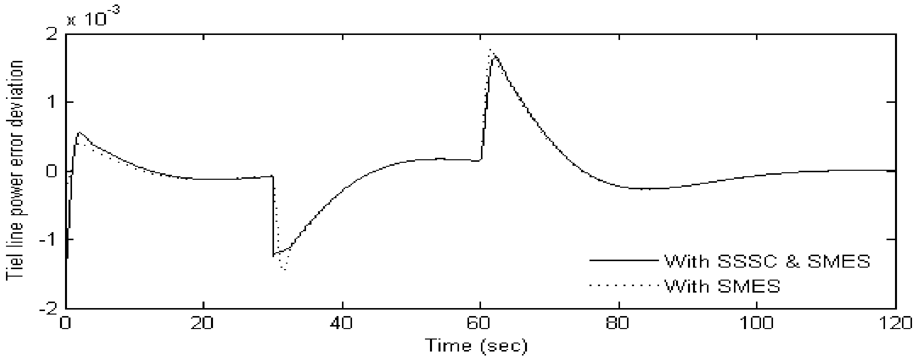


Fig 11: Comparison of Frequency deviations and tie line power error deviations during contract violation

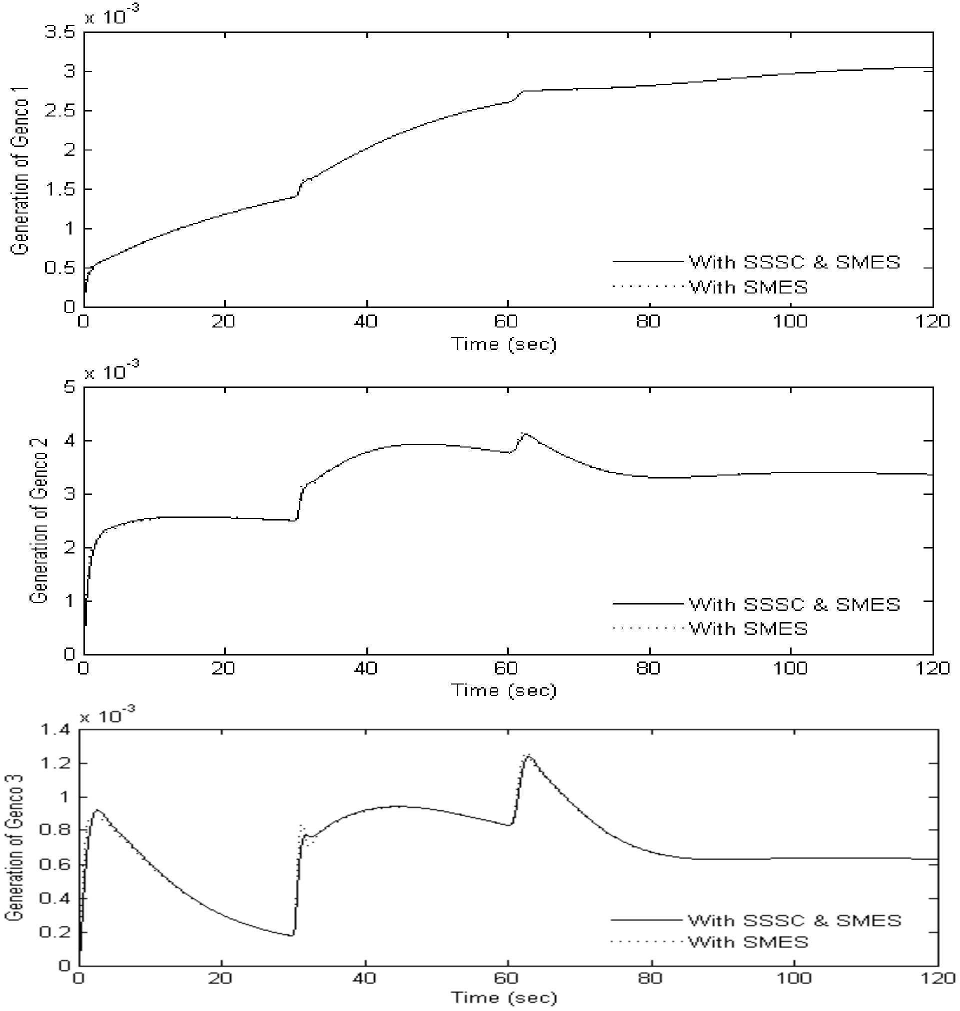
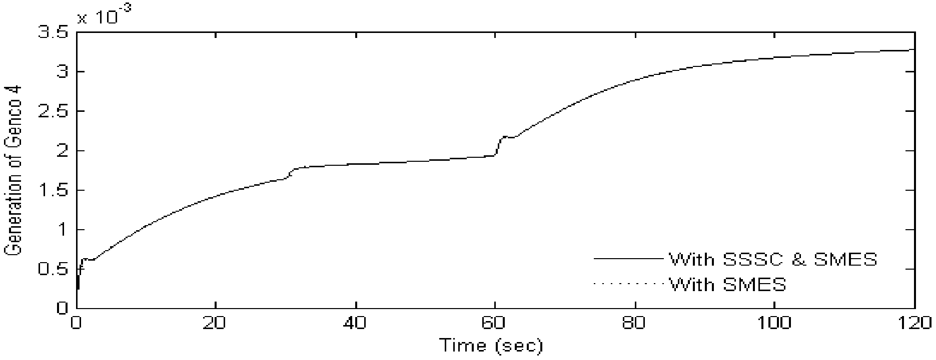


Fig 12: Generation of Gencos of Area I during contract violation



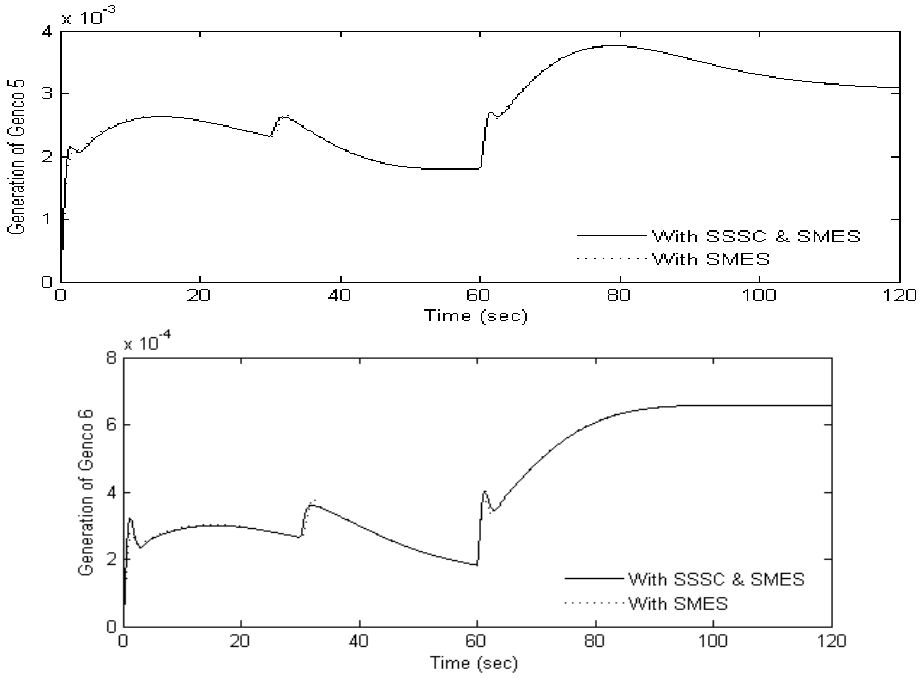


Fig 13: Generation of Gencos of Area II during contract violation

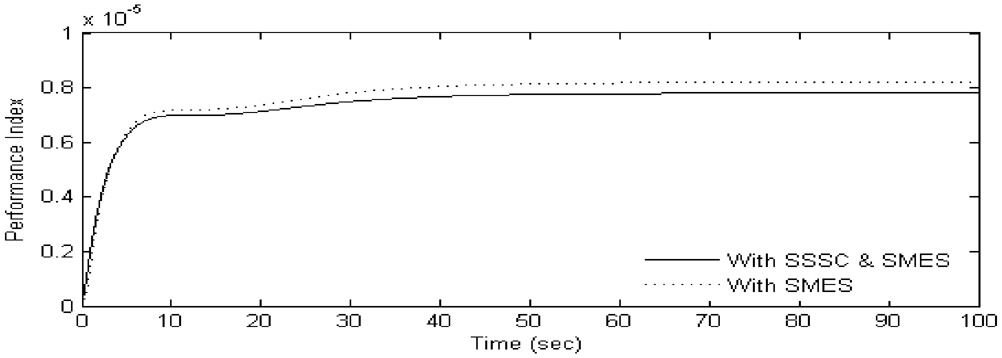


Fig 14: Comparison of performance index values during normal case

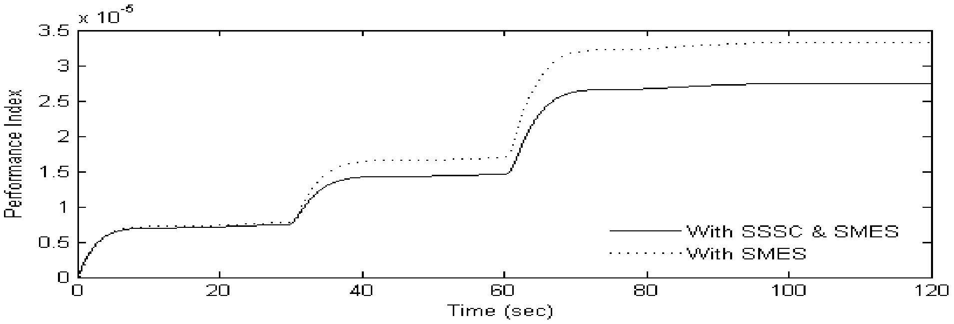


Fig 15: Comparison of performance index values during contract violation

V. CONCLUSIONS

A systematic method has been suggested for the design of a Superconducting Magnetic Energy Storage and SSSC for a multi area system under deregulated scenario. This paper has also investigated the performance of the system with SSSC and SMES, and with SMES only with respect to reduction of frequency deviations and tie line power deviations during a load change on a multi area system. The simulation results indeed show that the proposed method indeed successfully mitigates the frequency and tie line power deviations during a load change and also it can be seen that the performance index of the system with SSSC and SMES is less than the system only with SMES which indicates the superiority of the proposed method.

Appendix

(a) System data

T_{p1}, T_{p2} = 20s; K_{p1}, K_{p2} = 120 Hz/p.u.Mw; P_{r1}, P_{r2} = 1200 Mw; T_t = 0.3s; T_g = 0.08s, T_w = 1s; $T_r = 5s, T_1 = 41.6s, T_2$ =0.513s; R_1, R_2 = 2.4Hz/pu Mw; T_{12} = 0.0866s; B_1, B_2 =0.4249p.u Mw/Hz;

(b) CES data: $T_1 = 0.279; T_2 = 0.026; T_3 = 0.411; T_4 = 0.1; K_{CES} = 0.3; T_{CES} = 0.0352$

(c) SSSC data: $T_1 = 0.188; T_2 = 0.039; T_3 = 0.542; T_4 = 0.14; K_{SSSC} = 0.292; T_{SSSC} = 0.030$

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