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IMPROVEMENT OF DYNAMIC PERFORMANCE OF INTERCONNECTED POWER SYSTEMS WITH STATIC SYNCHRONOUS SERIES COMPENSATOR

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ABSTRACT

It is well known that the automatic generation control AGC system is employed to compensate the power system load disturbances which cause power system frequency and tie-line power deviations. The conventional AGC depends essentially of mechanical speed governor system. The speed governor system is slow and it needs maintenance and change. With advent of power electronic switches, Flexible AC Transmission System FACTS devices or controllers are applied to compensate quickly the load disturbances whereupon the frequency and tie-line power deviation can be deleted. The FACTS devices used in this paper is Static Synchronous Series Compensator SSSC. The structure of SSSC involves Voltage Source Inverter VSI and coupling transformer that are connected in series with tie-line between power system areas to inject source voltage of variable magnitude and phase angle. The control system of SSSC device is to modulate and update the exchange power between SSSC circuit and power system to compensate the load disturbance in power system areas. The application of SSSC stabilizer for power system frequency and tie-line power stabilization due to load excursion occurred in power system. The studied power system is simulated using Matlab Simulink Package. The two-area power system performances with SSSC device in terms of area frequency deviations and tie-line power responses are obtained. A comparison between the system performances with SSSC stabilizer in sense of undershoot and settling time.

Keywords: Load Frequency Control,Static Synchronous Series Compensator,Speed Governor, Economic Dispatch, and Load Sharing

I. INTRODUCTION

The concept of load frequency control LFC has been developed to maintain a constant frequency and to regulate the tie line flows. It regulates the frequency deviations and tie line interchanges between different areas that are interconnected with each other. The most widely employed controller is the conventional proportional integral PI controller [1]-[3]. The optimal control is quite often impractical for the implementation because it is a function of all the states of the system but in practice, all the states may not be available in [4]-[5]. The inaccessible states or missing states are required to be estimated. In variable structure or sliding mode control system the structure of the control law may change during the course of action in accordance with the state, output or error measurement in [6]-[7].Stability is the ability of an electric power system, for return the system to steady stat conditions or given initial operating condition after being subjected to small and large different disturbances [8]-[10]. FACTS devices provide strategic benefits for improving transmission system management in terms of better utilization of existing transmission assets, increased transmission system reliability and availability, increased dynamic and transient grid stability, increased quality of supply for sensitive industries, and enabling environmental benefits [11]. The need for more efficient electricity systems management has given rise to innovative technologies in power generation and transmission. The central technology of FACTS involves high power electronics, a variety of thyristor devices, microelectronics, communications and advanced control centers [12-13].

Arrangement capacitive recompense was acquainted decades back with drop a part of the receptive line impedance and there-by expansion the transmittable force [14]. Late advancement of force hardware presents the utilization of adaptable air conditioning transmission framework FACTS controllers in force frameworks [15]. Thusly, inside the FACTS activity, it has been showed that variable arrangement remuneration is profoundly viable in both controlling force stream in the lines and in enhancing dependability [16]. The voltage sourced converter based arrangement compensator, called SSSC gives the virtual recompense of transmission line impedance by infusing the controllable voltage in arrangement with the transmission line. The capacity of SSSC to work in capacitive and also inductive mode makes it exceptionally compelling in controlling the force stream of the framework [17]. SSSC is one of the imperative parts of FACTS family which can be introduced in arrangement in the transmission lines. With the capacity to transform its reactance trademark from capacitive to inductive, the SSSC is exceptionally compelling in controlling force stream in force frameworks [18]. An assistant settling sign can likewise be superimposed on the force stream control capacity of the SSSC in order to enhance power framework wavering steadiness [19]. The applications of SSSC for force wavering damping, steadiness upgrade and recurrence adjustment can be found in a few references [20]-[22]. As of late, new computerized reasoning based methodologies have been proposed to outline a FACTS-based supplementary damping controller. These methodologies incorporate molecule swarm improvement [23]-[25], hereditary calculation [26], differential advancement [27], and multi-objective evolutionary calculation [28].

The applications incorporate sparing burden dispatching, force framework stabilizers PSS, and so forth. The proposed controller has been connected and tried under diverse aggravations for a multi-machine power framework. The framework comprises of three generators partitioned into two subsystems and are joined through an intertie. For the outline reason, MATLAB/Simulink model of the force framework with SSSC controller is created. Reproduction results are exhibited at diverse working conditions and under different unsettling influences to demonstrate the viability of the proposed controller. The results demonstrate that the proposed SSSC-based controller can enhance the voltage profile and transient solidness of the test framework more productive than the ordinary lead-slack controller of above gadgets [29]-[31]. In view of this the main objectives of the present work are: To develop the two area Simulink model of hydrothermal system under load following. To develop the model of SSSC, andto compare the improvement of dynamic performance of the system with SSSC. The rest of the paper is organized as follows: A general overview on FACTS systems is given firstly. Dynamic mathematical model considered in this work. Describes the mathematical model of SSSC to be incorporated into the system. Demonstrates the results and discussions and some conclusions are presented finally.

II. STUDIED SYSTEM

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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. (1). Also, represent by a series connected voltage source V_s along with a transformer leakage reactance X_s. The SSSC controllable parameter is V_s, which in fact represents the magnitude of injected voltage. Fig. (2) represents the phasor diagram of the system taking into account the operating conditions of SSSC.

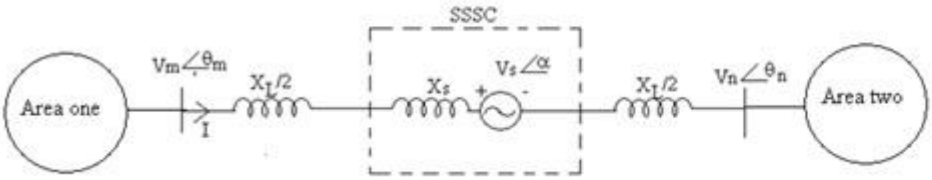

Fig. 1.Simplified Two-Area Studied System with SSSC Device

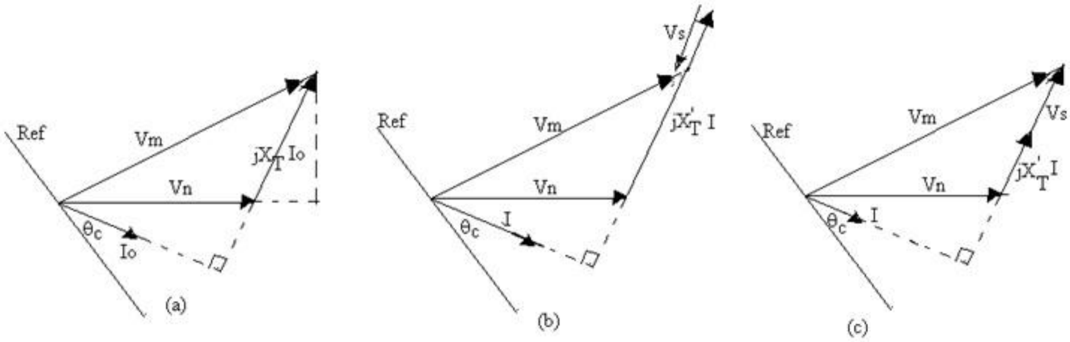

Fig. 2. Phasor Diagram (a) V_s=0, (b) V_s Lagging I by 90^o (c) V_s Leading I by 90^o

The voltage phasor diagram is drawn in the three states without SSSC, with lagging, and leading). The effect of connecting SSSC in tie line power flow is formulated and derived in mathematical form as when $V_s=0$, the current I_o of the system can be written as:

$$I_o = \frac{V_m - V_n}{jX_T} \tag{1}$$

Where $X_T=X_L+X_S$.

The phase angle of the current can be expressed as:

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

From the Eqn. (1) can be expressed in a generalized form as:

$$I = \frac{V_m - V_s - V_n}{jX_T} = \frac{V_m - V_n}{jX_T} + \frac{-V_s}{jX_T} = I_o + \Delta I \tag{3}$$

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

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

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

$$P_{SSSC} = \frac{V_m V_s}{X_T} \sin(\theta_m - \alpha) \tag{5}$$

When $V_s$lags the current by 90^o, ($\alpha=\theta_c-90^o$) ΔP_m can be written as:

$$P_{SSSC} = \frac{V_m V_s}{X_T} \cos(\theta_m - \theta_c) \tag{6}$$

From fig (1) the term *cos* $(\theta_m-\theta_c)$ in eqn (6) can be written as:

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

Then:

$$\cos(\theta_n-\theta_c)=\frac{V_m\sin(\theta_{mn}}{\sqrt{V_m^2+V_n^2-2V_mV_n\cos(\theta_{mn})}} \tag{8}$$

Where $\theta_{mn}=\theta_m-\theta_n$

Also, using the above Equations can be modified as follows:

$$P_{SSSC}=\frac{V_mV_n}{X_T}sin\theta_{mn}\frac{V_s}{\sqrt{V_m^2+V_n^2-2V_mV_n cos\theta_{mn}}} \tag{9}$$

At last the power flow between buses m and n in both senses are given by:

$$P_{mn}=-P_{mn0}\frac{V_mV_n}{X_T}sin\,\theta_{mn}\left(1+\frac{V_s}{\sqrt{V_m^2+V_n^2-2V_mV_n cos\,\theta_{mn}}}\right)=P_{tie}+P_{SSSC} \tag{10}$$

Linearizing Eqn. (10) about an operating point it can be written as:

$$\Delta P_{mn}=\frac{V_mV_n}{X_T}\cos\theta_{mn}(\Delta\theta_m-\Delta\theta_n)+\frac{V_mV_n}{X_T}sin\theta_{mn}*\frac{\Delta V_s}{\sqrt{V_m^2+V_n^2-2V_mV_n cos\theta_{mn}}} \tag{11}$$

$$\Delta P_{mn}=\Delta P_{tie}+\Delta P_{SSSC} \tag{12}$$

Where:

$$\Delta P_{tie}=\frac{V_mV_n}{X_T}cos\,\theta_{mn}(\Delta\theta_m-\Delta\theta_n) \tag{13}$$

$$\Delta P_{SSSC}=\frac{V_mV_n}{X_T}sin\theta_{mn}*\frac{\Delta V_s}{\sqrt{V_m^2+V_n^2-2V_mV_n cos\theta_{mn}}} \tag{14}$$

Based on Eqn. (14) it can be observed that by varying the SSSC voltage V_s, the output power of SSSC can be controlled which will in turn control the frequency and tie line deviations.

The two-area power system model consists of two of one area systems connected through tie line. Each area consists of three first-order transfer functions, modeling the system turbine, governor, and generator power system. However, the incremental tie line power is calculated as follows:

$$\Delta P_{tie}=\frac{2\pi T_{12}}{s}\left(\Delta F_1(s)-\Delta F_2(s)\right) \tag{15}$$

Where: $T_{12}=\frac{V_1V_2}{X_{12}}\cos(\delta_1-\delta_2)$T (16)

X_{12} is tie line reactance, V_1, V_2, δ_1 and δ_2 are voltages and angles of area buses

The block diagram of two-area power system is built and illustrated as fig. (3). From the above equations it is shown that there are his steady state errors of frequency deviations ΔF_1, ΔF_2 and tie power deviation ΔP_{tie} following a change in loads.. In other words, if there is a change in area-1 load, there should be supplementary control action only in area-1 and not in area-2. The control signal is known as Area Control Error ACE. The ACE for area-1 and area-2 can be defined as:

$$ACE_1=B_1\Delta F_1+\Delta P_{tie} \tag{17}$$

$$ACE_2=B_2\Delta F_2+a_{12}\Delta P_{tie} \tag{18}$$

Where B_1 and B_2 are frequency biases for area-1 and area-2 respectively

Application of tie line frequency bias control in terms of ACE in two-area power system is depicted in fig. (3). AC interconnected power system is subjected to a large load rapid change, system frequency may be severely disturbed and becomes oscillatory. To stabilize the frequency oscillations, application of the SSSC to stabilize the frequency of oscillations in an interconnected power system is investigated. The SSSC is located in series with the tie-line between any interconnected areas as shown in fig (3). Application of SSSC to provide an active power control facility for stabilization of frequency oscillations in an interconnected power system is proposed. The control system of SSSC device for LFC system stabilization due to load disturbance in terms of damping of frequency deviations of two areas and tie-line power. The SSSC is superior to the conventional frequency control system, i.e. governor, in terms of a high-speed performance. The control signal to SSSC device is scaled frequency deviation of one area summed with scaled tie-line power deviation. However, the SSSC is modeled by first order transfer function ($1/(1+t_{SSSC}s)$). The output signal from SSSC device is the active power deviation summed with tie-line power deviation and sent to two areas at summation junction of power system model as shown in fig. (3). It is noted that the output signal from SSSC stabilizer is the active power injected to tie-line to compensate the load deviation disturbance.

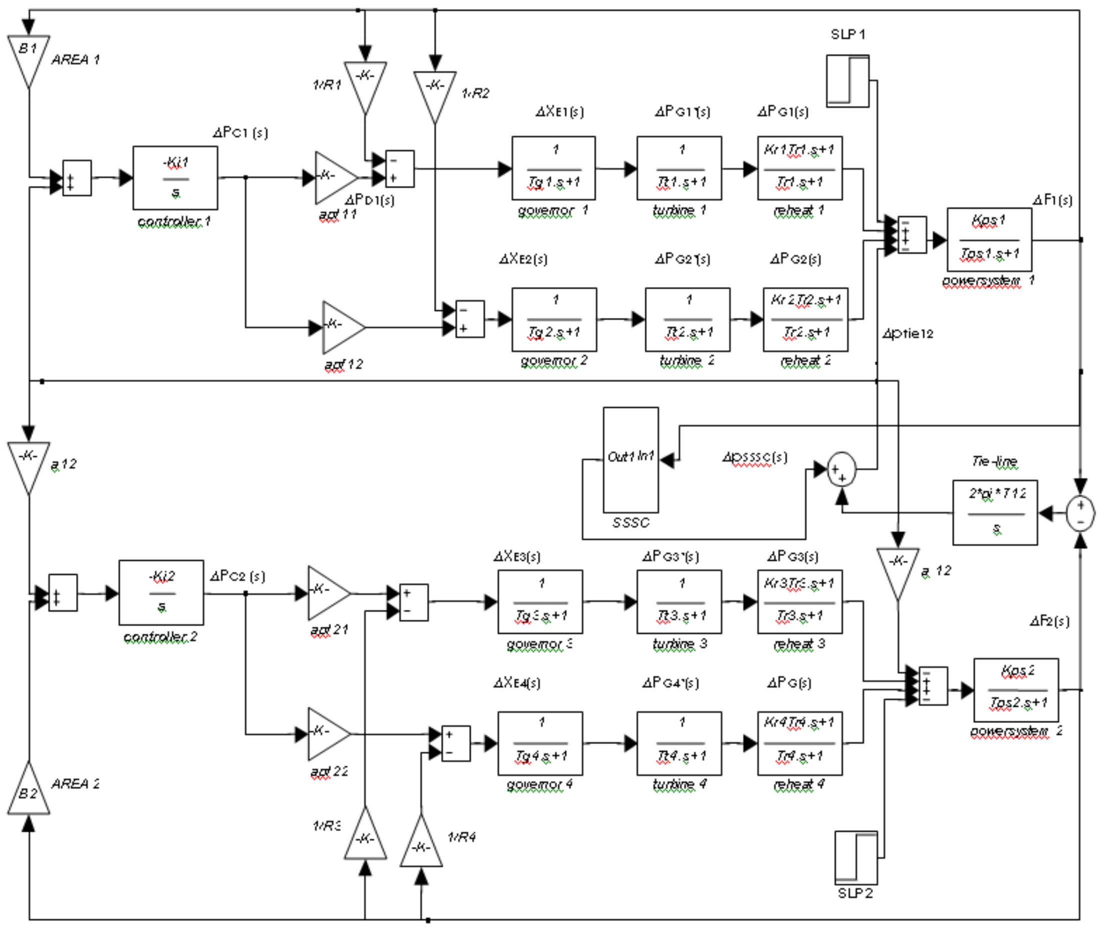

Fig. 3 Two-Area Studied System with SSSC Device Controls

III. RESULTS AND DISCUSSIONS

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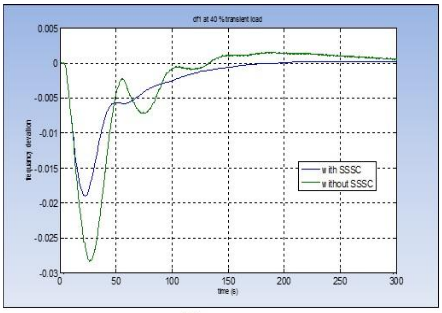
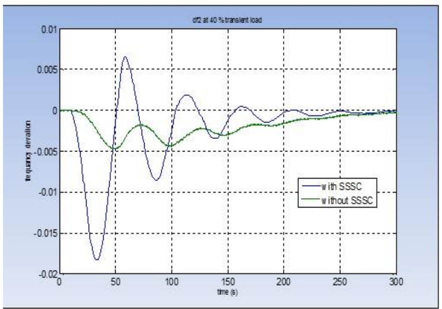
The above two-area power system with SSSC stabilizer is simulated using Matlab Simulink software Package. However the values of gains of SSSC stabilizer of frequency and tie-line power deviations G_1 and G_2 are selected as -10 and 0.5 respectively. Also the time constant of SSSC block $T_{sssc}$is 0.03 sec. The studied system is subjected to different disturbances which can be described as follows: The step load perturbation ΔP_D of 10% is applied in area #1 the frequency oscillations and tie-line power flow deviations are obtained in fig. (4). System performances with and without SSSC stabilizer in terms of deviations of frequencies of each area and deviations of tie-line power flows i.e. dF_1, dF_2, and dP_{tie}. It is noted that with SSSC stabilizer, the system response in terms of frequency deviations of two areas and tie-line power deviations are better in sense of overshoot, settling time.' Also, the Effect of load disturbance ΔP_D of area-1 of 40% value: With and without SSSC stabilizer, the two-area power system states responses are shown in fig. (5) in terms of deviations of frequencies of each area and deviations of tie-line power flows. It is noticed that the system responses in terms of frequency deviations of two areas and tie-line power deviations are better with SSSC stabilizer in sense of overshoot, settling time.



(a)



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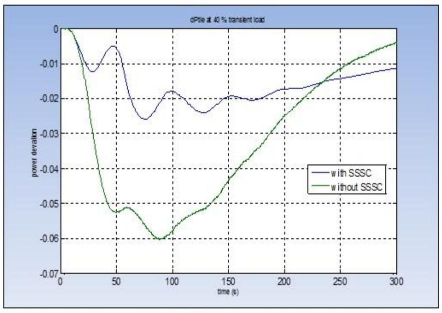
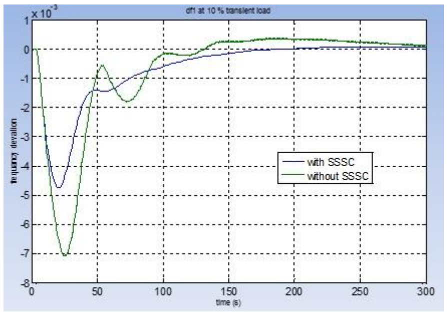
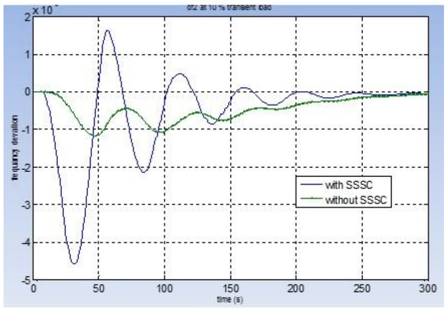


(c)_

Fig. 4 Effect of load disturbance ΔP_D at area-1 of 10% on variable system parameters (ΔF_1, ΔF_1, and ΔP_{tie}) with and without SSSC device



(a)



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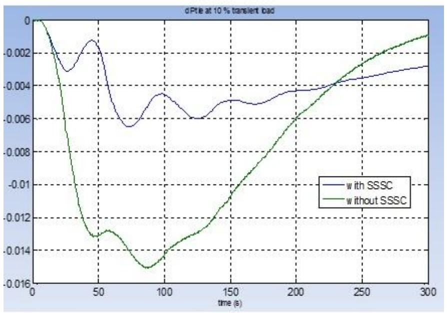
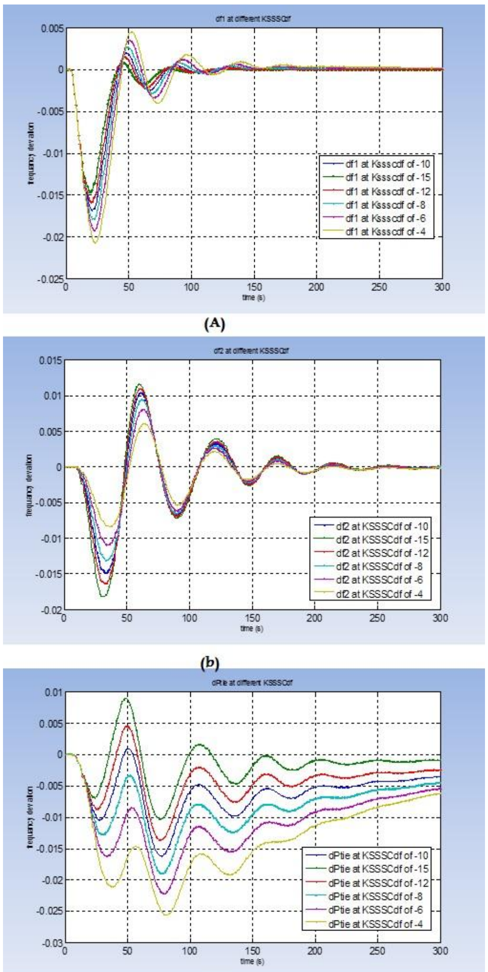


(c)

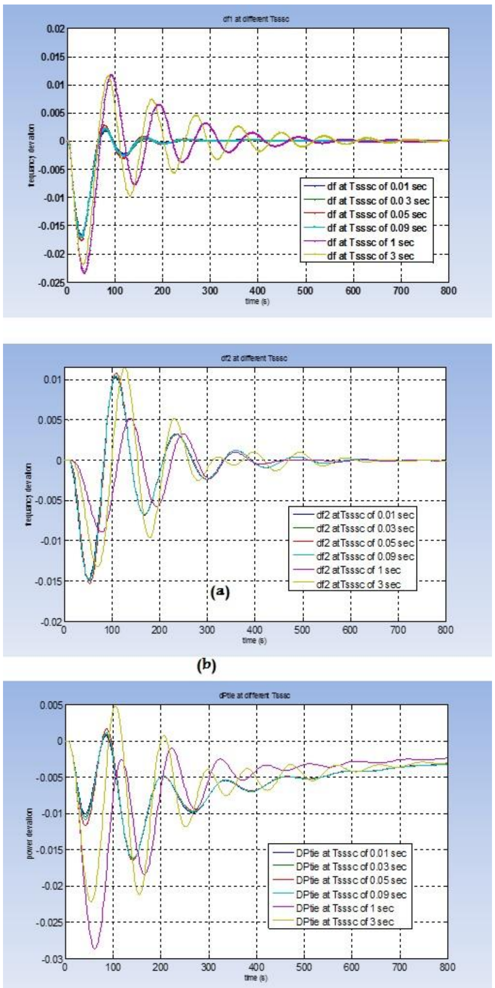
Fig. 5 Effect of load disturbance ΔP_D at area-1 of 40% on variable system parameters (ΔF_1, ΔF_1, and ΔP_{tie}) with and without SSSC device

To study the robustness of the proposed SSSC devices with system parameters variations, the effect of system parameters change on the system performance. The scale factor G_1 of frequency deviation used to generate the input signal with scaled tie-line power deviation for SSSC block is changed to study the robustness of SSSC stabilizer to restore the system states after load disturbances. The values of frequency deviation scale factor is changed from -4 to -15 and the system responses in terms of frequency deviation of each area and tie-line power deviation due to load disturbance in area one of 40% value are shown in fig. (6). From the above response figures it is noticed that the system responses in terms of frequency deviations of two areas and tie-line power deviations due to system parameters variations in terms of frequency deviation scale factors are robust with SSSC stabilizer in sense of overshoot, settling time. The values of SSSC time constant T_{sssc} is changed from .01 to 1 sec and the system responses in terms of frequency deviation of each area and tie-line power deviation due to load disturbance in area one of 40% value are shown in fig. (7). The system responses in terms of frequency deviations of two areas and tie-line power deviations due to system parameters variations in terms of SSSC stabilizer block time constant T_{sssc} are compared in sense of overshoot, settling time.



(c)

Fig. 6 Effect of scale factor K_{sssc} parameters at area-1 of 40% on variable system parameters (ΔF_1, ΔF_1, and ΔP_{tie}) with SSSC device



(c)

Fig. 7 Effect of time constant T_{sssc} parameters at area-1 of 40% on variable system parameters (ΔF_1, ΔF_1, and ΔP_{tie}) with SSSC device

IV. CONCLUSIONS

Modeling of AGC system in block diagram is established in one-area and two-area interconnected thermal plant power system. Also the construction of SSSC devices are described. Application of SSSC controller for stabilization of AGC system is investigated. The two-area interconnected power system model including the control system of SSSC controller is developed. The studied system is tested using Matlab Simulink package. The digital simulation results due to different load disturbances of 10% to 40% value in terms of area frequency and tie-line power deviations proves the effectiveness and powerful of SSSC device via quickly damping the oscillations and restoring the normal power system frequency and tie-line power. Also, the effect of control parameters variation of SSSC control system gain block value and time constant of SSSC block on system performance shows that the proposed system with SSSC device is robustness and system performance still better. The results indicate that the SSSC controller improves effectively the damping of the oscillations and reduces the settling time and overshoot as compared to PI controller only. Therefore, the two-area power system with SSSC stabilizer is preferred and is fast compared to governor speed controller only. Where the governor speed is a mechanical system whereupon it needs large time to response and make an action to restore and stabilize the system states. The effect of system parameters and SSSC time constant variations are studied and obtained. The results show that the proposed load frequency control system with SSSC is robust for system parameters variations.

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