



COMPARATIVE PERFORMANCE EVALUATION OF FACTS DEVICE CONTROLLERS IN AGC FOR DEREGULATED POWER SYSTEM

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July 23, 2018

Abstract

In this paper, the dynamic performance of two area interconnected Power System consisting of two thermal units in each area under deregulated environment is Analyzed. The implementation of Superconducting magnetic energy storage (SMES), Thyristor controlled phase shifter (TCPS), Unified power flow controller (UPFC) and Electric vehicle (EV) are connected in series with the Tie-line to compensate system frequency and Tie-line power oscillations under load distribution considering different market scenarios. The modeling of these devices are carried out and also the Dynamic Performance characteristics of the deregulated power system in terms of settling time, peak amplitude and overshoots are determined and compared.

Keywords: Automatic generation control (AGC), Disco Participation Matrix (DPM), Deregulated

environment, bilateral transaction, SMES, TCPS, UPFC, EV.

1 INTRODUCTION

In a Power System, Automatic Generation Control (AGC) plays an important and major role to maintain the power system reliability at an appropriate level. The successful operation of deregulated interconnected power systems requires the matching of total power generation with that of total demand load and with association of power losses. For the load perturbations the demand deviates from its nominal value, hence the load frequency oscillations and Tie-line oscillations are appeared. Maintaining bilateral system frequency and tie line power interchanges with neighboring control areas at the scheduled values are the two main objectives of a power system Load Frequency Control (LFC). Deregulated interconnected power system is generally composed of several generating units; these generating units are connected through tie-lines. Thus, the electrical power can be bought and sold between vertically integrated utilities (VIUs) along with these tie lines and such interconnection provides greater reliability in power system. On the other hand, for interconnected two area power system controls the concept of power electronic devices is accepted in the form of Flexible AC transmission system (FACTS) devices. These FACTS devices provide power flow control in the high voltage side of the network at both transient and steady-state conditions. One of the main benefits of utilizing FACTS devices in electrical transmission systems is to Increase transmission system reliability and availability. In this work, Superconducting magnetic energy storage (SMES), Thyristor controlled phase shifter (TCPS), Unified power flow controller (UPFC) and Electric vehicle (EV) are the few important members of FACTS family and they can be installed in series with the tie-line to control the power flow of Automatic Generation Control of deregulated power system.

2 AUTOMATIC GENERATION CONTROL (AGC)

In a two area interconnected power system, if the load deviates the frequency and tie-line power interchange also deviates. To accomplish the objective of deregulating electrical frequency error and tie-line power flow deviation to zero, a control strategy is needed that adjusts the load reference set points of selected generating units. This control process is referred to as Automatic Generation Control (AGC). Automatic Generation Control was mainly introduced to maintain both constant frequency and to regulate tie-line power flows. Load demand on power system increases then speed of the system deviates, hence frequency also changes. Thus, if the load demands of the system changes continuously, then the generation is to be adjusted automatically to restore the frequency to the nominal value in that case Automatic Generation control is majorly considered.

A. Interconnected power Systems

Interconnecting of different power generating systems with Tie-lines can improve the stability in each power system by helping the other generating system and they can also provide additional voltage and frequency support during normal operations. Now, both power generating systems are able to share generation demand and help the other load demand if they experience a generation shortage. Another important benefit of interconnected power systems is to take advantage of lower cost generation sources. In two area interconnected power system, If the generation in Area1 may be more expensive than Area2. So Area1 can draw generation demand from Area2.

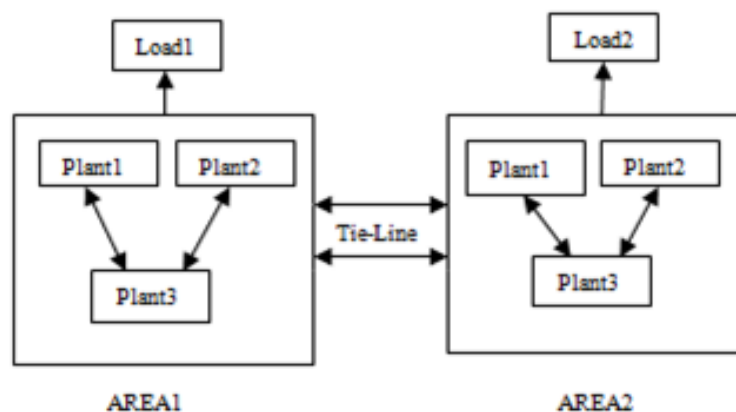


Figure 1. Interconnected power systems

B. Deregulated Environment in power Systems

Initially, traditional power systems are known as vertically integrated utilities (VIUs). This type of power system structures can handle all generation, transmission and distribution within a particular area. The co-ordination and operation of vertically integrated utilities is somewhat simple, where all functioning operations are controllable by a system operator. The main objective of VIUs is to provide good power quality to a consumer.

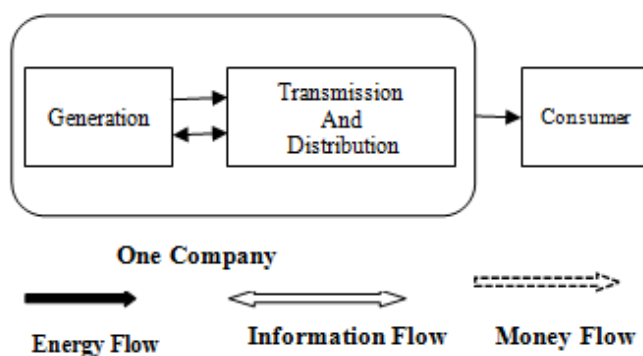


Figure 2. Vertical Integral Utility

Further, instead of vertical integral utility, Deregulated Utility structure is come into exists due to its satisfying operations. In Deregulated utility structure the power system consists of number of generating and distributing stations in a single area and they have freedom to access of power exchange from any generating Station in its own area or from neighboring area depending upon the reliability, quality and economic factors. Two area interconnected power system under deregulated environment is shown in below figure.

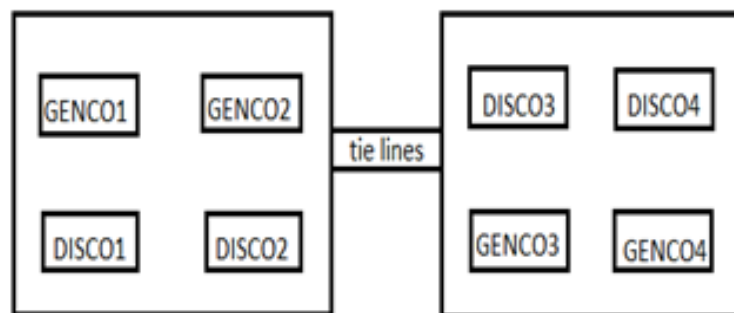


Figure 3. Two-area interconnected Power system under Deregulation

C. Disco Participation Matrix (DPM)

The DISCO participation factor indicates that the amount of participation of a generator unit in the Automatic Generation Control (AGC) system. In two area interconnected power system under deregulation environment, two generators are considered in each area for this act and each generating system participates in Automatic Generation Control (AGC) as it was defined by Area participation factors (apfs). Area participation factors (apfs) are the coefficients that distribute Area control error (ACE) to several generating systems. Each distributing system contract with the generating system as per the Disco Participation Matrix.

For this work Disco Participation Matrix (DPM) is taken as follows:

$$DPM(DiscoParMatrix) = \begin{bmatrix} cpf_{11} & cpf_{12} & cpf_{13} & cpf_{14} \\ cpf_{21} & cpf_{22} & cpf_{23} & cpf_{24} \\ cpf_{31} & cpf_{32} & cpf_{33} & cpf_{34} \\ cpf_{41} & cpf_{42} & cpf_{43} & cpf_{44} \end{bmatrix}$$

D. Bilateral Transactions

In this work, each control area consists of two generating stations and distribution stations with two area interconnected power system. Any distribution station (DISCO) can access power from any of the generating station (GENCO).

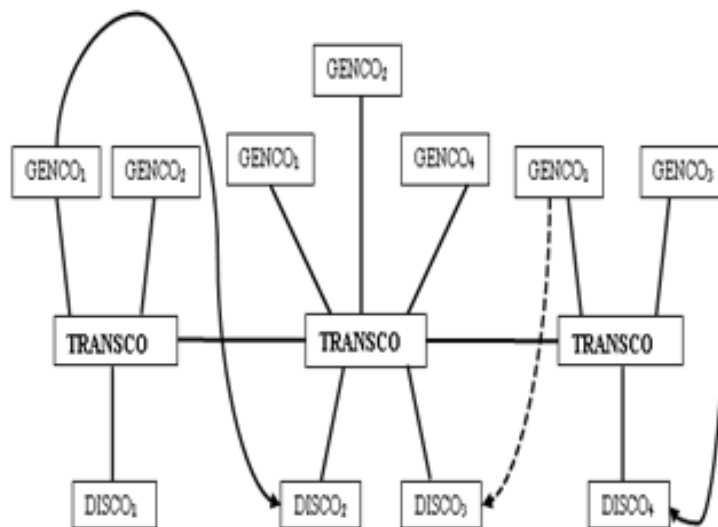


Figure 4. Bilateral transactions

3 DYNAMIC MODEL OF INTERCONNECTED POWER SYSTEM

State-space representation of AGC dynamically inter connected power system is a useful representation for the application of modern control theory. For this study, the system state space vector, control vector and disturbance vectors are selected as follows:

$$\begin{aligned}\bar{X} &= AX + BU + W \\ Y &= CX + DU\end{aligned}$$

Where X is state space vector, U is control vector, Y is output vector, W is disturbance vectors and A, B, C are system, control and output matrices respectively.

State space vector:

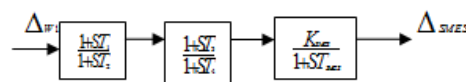
$$X = [\Delta\omega_1 \ \Delta\omega_2 \ \Delta P_{GV1} \ \Delta P_{GV2} \ \Delta P_{GV3} \ \Delta P_{GV4} \ \Delta P_{M1} \ \Delta P_{M2} \ \Delta P_{M3} \ \Delta P_{M4} \ \int ACE_1 dt \ \int ACE_2 dt \ \Delta P_{tie1-2} \ \Delta x_{15} \ \Delta x_{16} \ \Delta P_{dc}]^T$$

$$\text{Control Vector: } U = [\Delta P_{L1} \ \Delta P_{L2} \ \Delta P_{L3} \ \Delta P_{L4}]^T$$

$$\text{Disturbance Vector: } W = [\Delta P_{D1} \ \Delta P_{D2}]^T$$

A. Dynamic Model of SMES Applicable for AGC

Superconducting magnetic energy storage (SMES) is a member of FACTS family which having the ability to control both Active and Reactive powers simultaneously. It is one of the most significant and effective stabilizer of frequency oscillations and also dynamic performance of system is improved.



Structure of SMES

The Deregulated power system considering SMES connected with

Tie- line is defined by the state space model as follows.

State space vector,

$$X = [\Delta\omega_1 \ \Delta\omega_2 \ \Delta P_{GV1} \ \Delta P_{GV2} \ \Delta P_{GV3} \ \Delta P_{GV4} \ \Delta P_{M1} \ \Delta P_{M2} \ \Delta P_{M3} \ \Delta P_{M4} \ \int ACE_1 dt \ \int ACE_2 dt \ \Delta P_{tie1-2} \ \Delta x_{15} \Delta x_{16} \Delta P_{dc}]^T$$

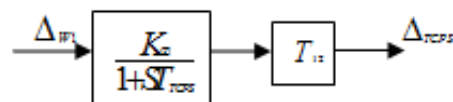
The SMES based controller can be represented in AGC as follows:

$$X_{SMES} = \frac{K_{SMES}}{1+ST_{SMES}} \left[\frac{1+ST_1}{1+ST_2} \right] \left[\frac{1+ST_3}{1+ST_4} \right] X_1$$

Where K_{SMES} is gain and T_{SMES} is time constant of SMES in seconds.

B. Dynamic Model of TCPS Applicable for AGC

Thyristor controlled phase shifter (TCPS) is a FACT device that control real power transfers between two area interconnected power systems. TCPS can reduce the frequency oscillations in the tie-line power flow and fastest responses of phase shifters make them more useful for stability improvement. The dynamic and transient stabilities of two area deregulated power system are improved with utilization of TCPS.



Structure of TCPS

For TCPS,

State space vector,

$$X = [\Delta\omega_1 \ \Delta\omega_2 \ \Delta P_{GV1} \ \Delta P_{GV2} \ \Delta P_{GV3} \ \Delta P_{GV4} \ \Delta P_{M1} \ \Delta P_{M2} \ \Delta P_{M3} \ \Delta P_{M4} \ \int ACE_1 dt \ \int ACE_2 dt \ \Delta P_{tie12} \ \Delta P_{TCPS} \ \Delta x_{15} \Delta x_{16} \Delta P_{dc}]^T$$

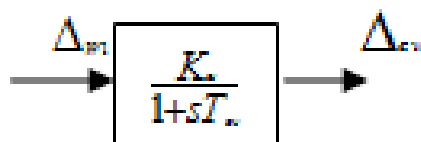
The TCPS based controller can be represented in AGC as follows:

$$X_{TCPS} = \frac{K_{\phi} T_{12}}{1+ST_{TCPS}} X_i$$

Where K_ϕ is gain and T_{TCPS} is time constant of TCPS in seconds.

C. Dynamic Model of EV Applicable for AGC

Electric vehicle (EV) consisting of its own battery with V2G technology, a number of EV can be used as controllable energy storage devices participated in power system operation. EV participation in the AGC to assist power system units to rapidly suppress the load fluctuations. EV is very effective in stabilizing of load and compensates frequency fluctuations due to its fast response characteristics.



Structure of Electric vehicle

For Electric Vehicle,
State space vector,

$$X = [\Delta\omega_1 \ \Delta\omega_2 \ \Delta P_{GV1} \ \Delta P_{GV2} \ \Delta P_{GV3} \ \Delta P_{GV4} \ \Delta P_{M1} \ \Delta P_{M2} \ \Delta P_{M3} \ \Delta P_{M4} \ \int ACE_1 dt \ \int ACE_2 dt \ \Delta P_{tie12} \ \Delta P_{EV} \ \Delta x_{15} \ \Delta x_{16} \ \Delta P_{dc}]^T$$

The EV based controller can be represented in AGC as follows:

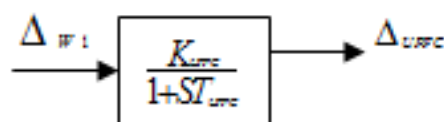
$$X_{ev} = \frac{K_{ev}}{1 + sT_{ev}} X_1$$

Where K_{ev} is gain and T_{ev} is time constant of EV in seconds.

D. Dynamic Model of UPFC Applicable for AGC

The UPFC is the most resourceful FACTS controller which having the Capabilities of Phase Shifting, voltage regulation and series compensation. The UPFC is under the family of compensators and power flow controllers. The UPFC is able to control

simultaneously or selectively all the parameters affecting power flow patterns in a transmission network, including voltage magnitudes and phases, and real and reactive powers. The latter utilize the synchronous voltage source (SVS) concept to provide a unique comprehensive capability of transmission system control. These basic flexibilities are making the UPFC the most powerful device in the present day transmission and control systems.



Structure of UPFC

For UPFC,
State space vector,

$$X = [\Delta\omega_1 \Delta\omega_2 \Delta P_{GV1} \Delta P_{GV2} \Delta P_{GV3} \Delta P_{GV4} \Delta P_{M1} \Delta P_{M2} \Delta P_{M3} \Delta P_{M4} \int ACE_1 dt \int ACE_2 dt \Delta P_{tie12} \Delta P_{UPFC} \Delta x_{15} \Delta x_{16} \Delta P_{dc}]^T$$

The UPFC based controller can be represented in AGC as follows:

$$X_{UPFC} = \frac{K_{UPFC}}{1 + sT_{UPFC}} X_1$$

Where K_{UPFC} is gain and T_{UPFC} is time constant of UPFC in seconds

Table 1. Demands of Discos

CASES	DISCOs Demands	Disco Participation Matrix
Case1	$\Delta P_{d1} = 0.1$ $\Delta P_{d2} = 0.1$ $\Delta P_{d3} = 0$ $\Delta P_{d4} = 0$	$\begin{bmatrix} 0.5 & 0.5 & 0 & 0 \\ 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$
Case2	$\Delta P_{d1} = 0.1$ $\Delta P_{d2} = 0.1$ $\Delta P_{d3} = 0.1$ $\Delta P_{d4} = 0.1$	$\begin{bmatrix} 0.5 & 0.25 & 0 & 0.3 \\ 0.2 & 0.25 & 0 & 0 \\ 0 & 0.25 & 1 & 0.7 \\ 0.3 & 0.25 & 0 & 0 \end{bmatrix}$
Case3	$\Delta P_{d1} = 0.2$ $\Delta P_{d2} = 0.1$ $\Delta P_{d3} = 0.1$ $\Delta P_{d4} = 0.1$	$\begin{bmatrix} 0.5 & 0.25 & 0 & 0.3 \\ 0.2 & 0.25 & 0 & 0 \\ 0 & 0.25 & 1 & 0.7 \\ 0.3 & 0.25 & 0 & 0 \end{bmatrix}$

4 RESULTS AND DISCUSSION

Case1:

Consider a case where the GENCOs in each area participate equally in AGC; i.e., ACE Participation factors are $apf1=0.5$, $apf2= 0.5$, $apf3= 0.5$, $apf4=0.5$.

It is assumed that the load change occurs only in area I. Thus, the load is demanded only by DISCO1 and DISCO2. Let the value of this load demand be 0.1 Pu MW for each of them. The corresponding Disco Participation Matrix will become,

$$DPM = \begin{bmatrix} 0.5 & 0.5 & 0 & 0 \\ 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Disco Participation Matrix for Case1

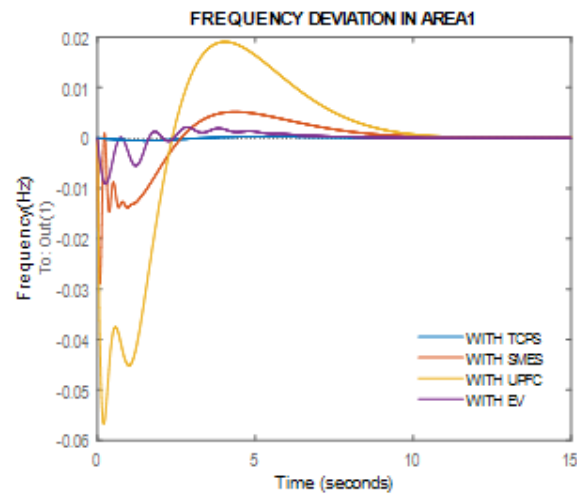


Figure 1. (a) Plot of Frequency deviation in Area1

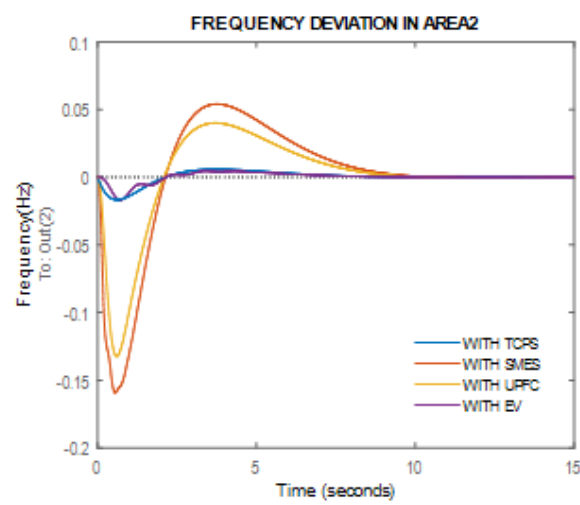


Figure 1. (b) Plot of Frequency deviation in Area2

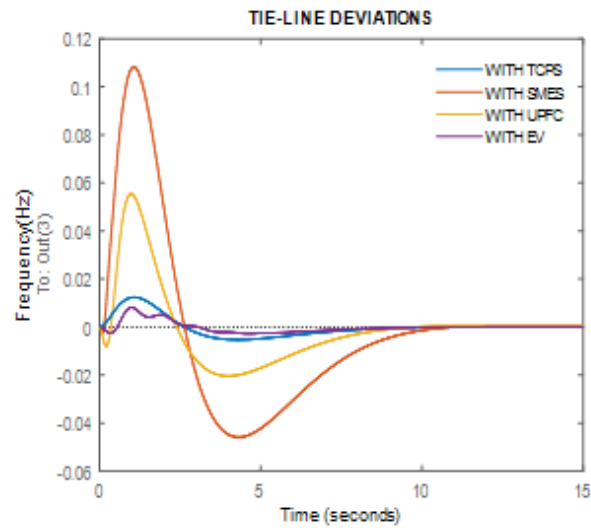


Figure 1. (c) Plot of Tie-line deviation

Table 2. (a) Comparison of dynamic response for Area1

CASE1	Settling time	Peak amplitude
WITH SMES	9.49	3.98e+15
WITH TCPS	9.1	1.02e+15
WITH UPFC	10.9	5.48e+17
WITH EV	8.1	2.33e+18

Table 2. (b) Comparison of dynamic response for Area2

CASE1	Settling time	Peak amplitude
WITH SMES	8.93	3.35e+16
WITH TCPS	8.94	5.55e+16
WITH UPFC	8.7	1.78e+17
WITH EV	8.83	1.69e+17

Table 2. (c) Comparison of dynamic response for Tie-line

CASE1	Settling time	Peak amplitude
WITH SMES	9.64	4.58e+16
WITH TCPS	9.67	7.61e+16
WITH UPFC	8.85	5e+17
WITH EV	9.78	9.19e+16

Case2: It is assumed that each DISCO demands 0.1 pu MW power from GENCOs as defined by Contract Participation Factor in DPM matrix and each GENCO participate in AGC as defined by following ACE Participation Factors (apfs) are, apf1=0.75, apf2= 0.25, apf3= 0.5, apf4=0.5.

$$\text{DPM} = \begin{bmatrix} 0.5 & 0.25 & 0 & 0.3 \\ 0.2 & 0.25 & 0 & 0 \\ 0 & 0.25 & 1 & 0.7 \\ 0.3 & 0.25 & 0 & 0 \end{bmatrix}$$

Disco Participation Matrix for Case2

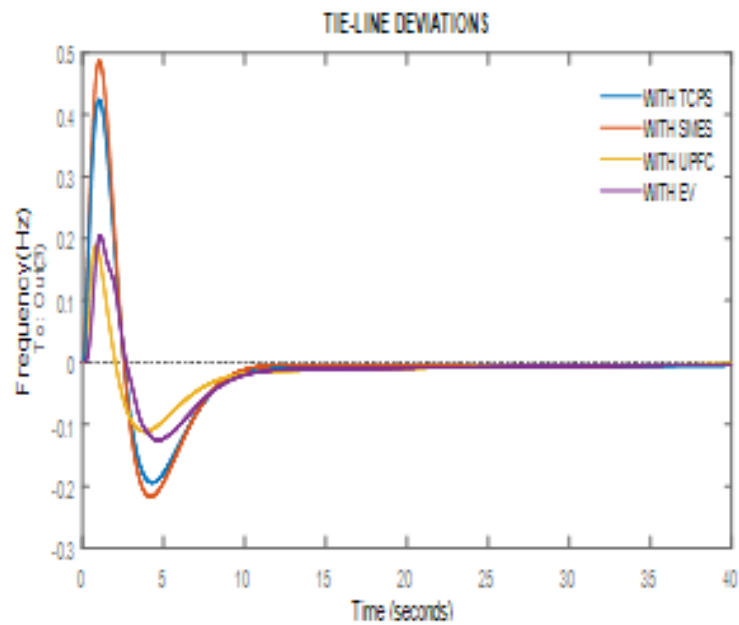


Figure 2. (a) Plot of Frequency deviation in Area1

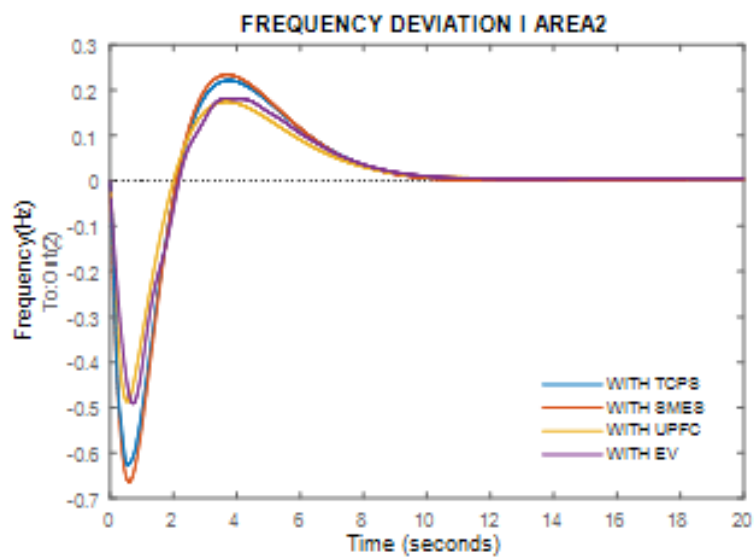


Figure 2. (b) Plot of Frequency deviation in Area2

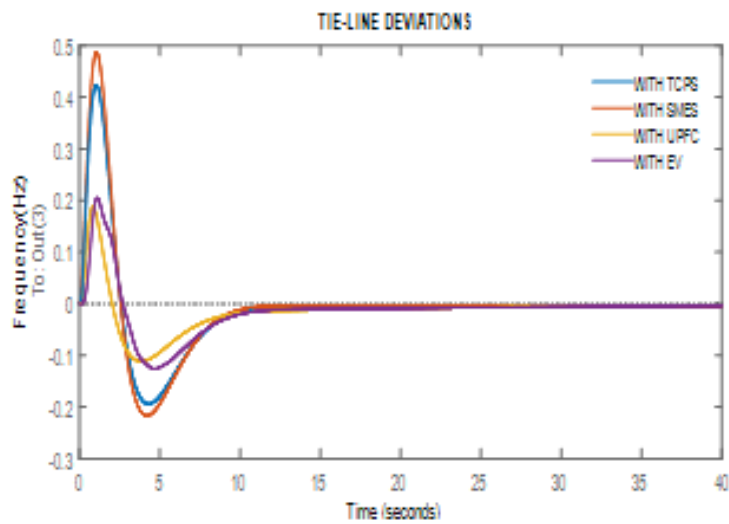


Figure 2. (c) Plot of Tie-line deviation

Table 3. (a) Comparison of dynamic response for Area1

CASE2	Settling time	Peak amplitude
WITH SMES	122	1.8e+16
WITH TCPS	72.8	2.33e+15
WITH UPFC	19.9	4.14e+16
WITH EV	16.9	3.6e+16

Table 3. (b) Comparison of dynamic response for Area2

CASE2	Settling time	Peak amplitude
WITH SMES	9.12	7.418e+16
WITH TCPS	9.31	1.36e+16
WITH UPFC	10.0	1.1e+16
WITH EV	10.1	1.04e+17

Table 3. (c) Comparison of dynamic response for Tie-line

CASE2	Settling time	Peak amplitude
WITH SMES	11.0	2.5e+17
WITH TCPS	10.2	3.85e+17
WITH UPFC	36.4	6.47e+17
WITH EV	38.9	3.77e+16

5 CONCLUSION

The present paper deals with the study of dynamic performance of two area interconnected Power System equipped with different FACTS devices. Implementation of SMES, TCPS, UPFC and EV in series with the Tie-line the performance of the system is investigated. This paper also investigated the dynamic response of the systems with FACTS devices with respect to reduction of Tie-line power and frequency deviations during a load change on a two area bilateral system. The simulation results of frequency deviation in Area1 and Area2 and also Tie-line deviations are actually shown for FACTS devices connected power system. Thus, the application of UPFC device may be successfully implemented for dynamic stabilization for dynamically unstable two area interconnected power system. Further investigations on performance of the system considering coordination of FACTS devices with best optimized algorithm have to be done.

6 APPENDIX

System parameters are:

$B1=B2=0.439\text{p.u.MW/Hz}$; $T12=0.0433\text{s}$, $a12=-1$, $TP1=TP2=20.008\text{s}$, $KP1=KP2=120.048\text{Hz/p.u.Mw}$, $Tt1=Tt2=0.3\text{s}$, $TG1=TG2=0.08\text{s}$, $R1=R2=2.4048\text{Hz/p.u.Mw}$, $K1=K2=0.6588$, $Kdc=1.0$, $Tdc=0.5\text{s}$.

SMES:

$Ksmes=0.3$, $Tsmes=0.04\text{s}$, $T1=0.3\text{s}$, $T2=0.02\text{s}$, $T3=0.65\text{s}$, $T4=0.3\text{s}$;

TCPS: $K\phi=1.5\text{rad/sec}$, $T12=0.0866\text{s}$, $Ttcs=0.1\text{s}$;

UPFC: $Kupfc=1$, $Tupfc=0.01\text{s}$; EV: $Kev=2$, $Tev=1\text{s}$.

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