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RESEARCH ARTICLE

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AUTOMATIC GENERATION CONTROL OF INTERCONNECTED POWER SYSTEM WITH TCSC AND FUZZY LOGIC CONTROLLER UNDER DEREGULATED ENVIRONMENT

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ABSTRACT

This paper presents the automatic generation control (AGC) of an interconnected power system operating under deregulated environment. Simulation of bilateral contracts is reflected in the block diagram with the concept of DISCO participation matrix. The AGC performance is compared with intelligent controllers like fuzzy logic controllers (FLC). FACTS devices like thyristor controlled series capacitor (TCSC) is incorporated in series with tie-lines of interconnected power systems. The dynamic system responses for various system states are obtained considering load perturbation in one of the areas. Comparative analysis of results shows considerable improvement in system performance with FLC. Investigations expose that using TCSC, oscillations and peak overshoot in the responses can be reduced.

Key Words - Interconnected system, automatic generation control, load frequency control, thyristor controlled series capacitor, fuzzy logic controller

I INTRODUCTION

All over the world, there has been continuous progress in transforming the power industry's existing structure to cater to the needs and demand of common consumers to their satisfaction. This is the transition period for the power industry to switch over to a deregulated environment from the existing regulated one. Restructuring of the electricity industries is not a simple but very complex exercise. This exercise is carried out by considering the energy strategies, policies, macroeconomic developments, and national conditions along with strategic relations with other countries. Therefore, its implementation varies from country to country. To date, there is no single solution available that can be adopted worldwide. These structural changes have posed many operational and control difficulties for power engineers. Due to this, the operational and control philosophies that are in use have to be reformulated, keeping the essential ideas the same [1].

In a deregulated environment, the generation and transmission of electrical energy are supposed to be unlimited within the boundaries of local regions or states of the country, but there is a possibility that the power systems may operate globally in the near future, with the sole objective to provide electricity to end users to their utmost satisfaction. One of the major requirements for successful operation of such huge structured power systems to operate locally or globally in a deregulated environment is a suitable net- work of transmission systems capable of transferring electrical power among the control areas of interconnected power system effectively and economically [2, 3].

Since 1980's, the electrical industry supply industry has been undergoing rapid and irreversible changes and an important feature of these changes is to allow competition for competition among generating utilities and to create market conditions in the sector which are seen necessary in reducing the cost of energy production. With the restructuring electrical industry new companies emerged. Many of the ancillary services of a vertically integrated utility will have a different role to play and hence have to be modelled differently. Among these ancillary services is the automatic generation control (AGC). The AGC is based on error signal called area control error (ACE). The main purpose of AGC is to minimise deviations of frequency and tie line power and to reduce their steady state errors to zero. The traditional AGC is well discussed in the papers of Elgerd and Fosha [1],[2].

The duties of area interconnections were fulfilled by extra-high- voltage (EHV) AC transmission lines. With the advent of flexible AC transmission systems technology, few of the problems have been encountered amicably. Therefore, it is able to play an important role in transmission services improvement. Recent decades have seen the rapid development of power electronic technology. Some power electronics based devices have already been widely used in power systems.

The problem of load frequency control has been one of the most emphasises topic discussed in interconnected power systems. The mile stone work on LFC power systems is done by Olle I. Elgerd and Charles E. Fosha. Several strategies to adapt well-tested classical LFC schemes for the changing environment of power system operation under deregulation were reported in [5]. In [3] presented AGC of interconnected power systems in a deregulated environment, where the concept of a distribution company (DISCO) participation matrix (DPM) and area participation factor (apf) to represent bilateral contracts was introduced.

A. RESTRUCTURED SYSTEM

The electrical supply industry in nearly every country for a major part of the last century was a monopoly and so it attracted regulation by the government. The industry was a vertically integrated regulated monopoly that owned the transmission, distribution and generation facilities. In a restructured or deregulated market structure, vertically integrated utilities no longer exist. The utilities no longer have their own generation, transmission, or distribution; instead there are three different entities, viz., generation companies (GENCOs), transmission companies (TRANSCOs), and distribution companies (DISCOs). GENCOs compete with each other to sell the power they produce. TRANSCOs are accessible to any GENCO or DISCO for wheeling of power. As there are several GENCOs and DISCOs in the deregulated structure, a DISCO has the freedom to have a contract with any GENCO for transaction of power. A DISCO may have a contract with a GENCO in another control area. Such transactions are called "bilateral transactions." All the transactions have to be cleared through an impartial entity called an independent system operator (ISO).

B. DISCO Participation Matrix

In the restructured environment, GENCOs sell power to various DISCOs at competitive prices. Thus, DISCOs have the liberty to choose the GENCOs for contracts. They may or may not have contracts with the GENCOs in their own area. This makes various combinations of GENCO-DISCO contracts possible in practice. We introduce the concept of a "DISCO participation-matrix" (DPM) to make the visualization of contracts easier. DPM is a matrix with the number of rows equal to the number of GENCOs and the number of columns equal to the number of DISCOs in the system. Each entry in this matrix can be thought of as a fraction of a total load contracted by a DISCO (column) toward a GENCO (row). Thus, the *ij*th entry corresponds to the fraction of the total load power contracted by DISCO from a GENCO. The sum of all the entries in a column in this matrix is unity. DPM shows the participation of a DISCO in a contract with a GENCO; hence the name "DISCO participation matrix."

$$\text{DPM} = \begin{bmatrix} cpf_{11} & cpf_{12} & cpf_{13} & cpf_{14} \\ cpf_{21} & cpf_{22} & cpf_{23} & cpf_{24} \\ cpf_{31} & cpf_{32} & cpf_{33} & cpf_{34} \\ cpf_{41} & cpf_{42} & cpf_{43} & cpf_{44} \end{bmatrix} \quad (1)$$

Where cpf refers to "contract participation factor. The block diagonals of DPM correspond to local demands. Off diagonal blocks correspond to the demands of the DISCOs in one area to the GENCOs in another area. It is noted that $\sum cpf_{ij} = 1$.

C. Block Diagram Formulation

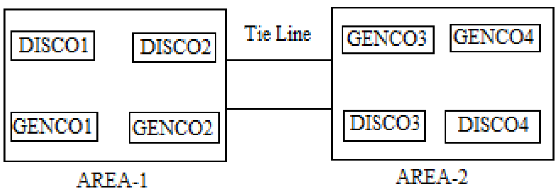

Fig 1.Power system model with AC and DC tie-line

In this model, the expressions for actual and scheduled steady-state power flows on the tie-line are given as

$$\Delta P_{tie\ 12,schedul} = \sum_{i=1}^{2}\sum_{j=3}^{4} cpf_{ij}\,\Delta P_{L} - \sum_{i=3}^{4}\sum_{j=1}^{2} cpf_{ij}\,\Delta P_{Lj}$$

$\Delta P_{tie12,schedule}$ =(cpf$_{13}$ +cpf$_{23}$)ΔP_{L3}+ (cpf$_{14}$ +cpf$_{24}$)ΔP_{L4} -(cpf$_{31}$ +cpf$_{32}$)ΔP_{L1} − (cpf$_{32}$ +cpf$_{42}$)ΔP_{L2}, (2)

$$\Delta P_{tie\,12,actual} = \frac{2\pi T_{12}}{s}(\Delta f_1 - \Delta f_2) \quad (3)$$

The tie-line power error ($\Delta Ptie_{12,error}$) is defined by

$$\Delta P_{tie\,12,error} = \Delta P_{tie\,12,actual} - \Delta P_{tie\,12,scheduled} \,. \quad (4)$$

The area control errors (ACEs) in a deregulated power system in both areas are defined as

$$ACE_1 = B_1\,\Delta f_1 + \Delta Ptie_{12,error} \quad (5)$$

$$ACE_2 = B_2\,\Delta f_2 + \alpha_{12}\,\Delta Ptie_{12,error} \quad (6)$$

D. State Space Characterization of the Two Area system under Deregulation

The closed loop system in Fig.2 is characterized in state space form as

$$\dot{X} = A^{cl}x + B^{cl}u$$
$$Y = Cx + Du$$

Where X is the state vector, u is the vector of power demands of the Discos, Y is the output vector. A^{cl} is the system matrix and B^{cl} is the input distribution matrix are constructed from state space equations.

State vector:

$\dot{X}$ = [$\Delta\omega_1$ $\Delta\omega_2$ ΔP_{G1} ΔP_{G2} ΔP_{G3} ΔP_{G4} ΔP_{M1} ΔP_{M2} ΔP_{M3} ΔP_{M4} $\int ACE_1$ $\int ACE_2$ $\Delta P_{tie\ 1-2}$ ΔP_{DC}]^T

Control vector:

U = [ΔP_{L1} ΔP_{L2} ΔP_{L3} ΔP_{L4}]^T

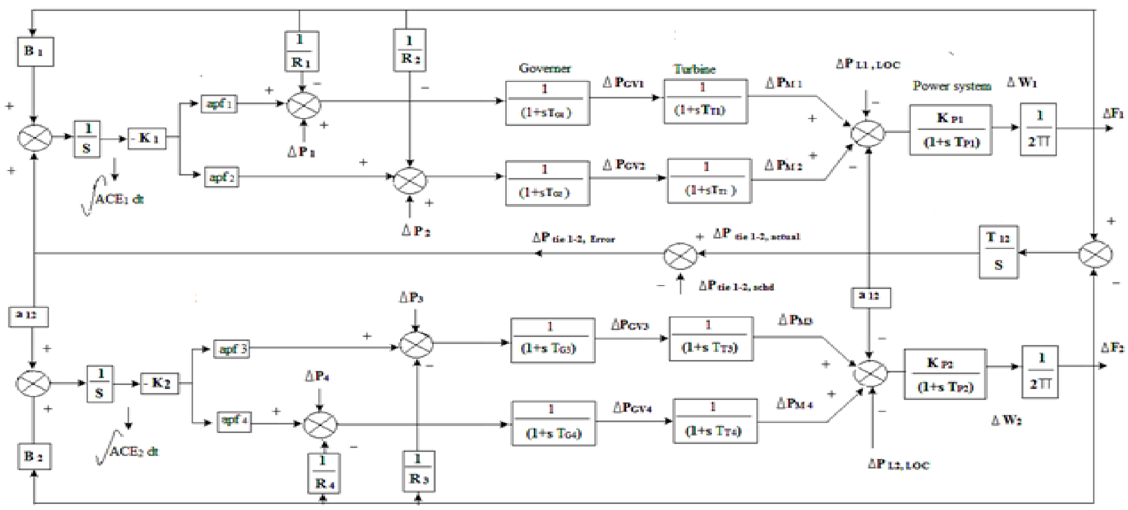

Fig 2 Transfer function Model with HVDC Tie line parallel with EHVAC tie line

From Fig.2 ΔP_{L1} ,$\Delta P_{L2,}\Delta P_{L3,}\Delta P_{L4}$ are the market signals from power market where

$\Delta P_{L1,Loc} = \Delta P_{L1} + \Delta P_{L2}$,

$\Delta P_{L2,Loc} = \Delta P_{L3} + \Delta P_{L4}$ (7)

$\Delta P_1 = cpf_{11}\Delta P_{L1} + cpf_{12}\Delta P_{L2} + cpf_{13}\Delta P_{L3} + cpf_{14}\Delta P_{L4}$,

$\Delta P_2 = cpf_{21}\Delta P_{L1} + cpf_{22}\Delta P_{L2} + cpf_{23}\Delta P_{L3} + cpf_{24}\Delta P_{L4}$, (8)

$\Delta P_3 = cpf_{31}\Delta P_{L1} + cpf_{32}\Delta P_{L2} + cpf_{33}\Delta P_{L3} + cpf_{34}\Delta P_{L4}$,

$\Delta P_4 = cpf_{41}\Delta P_{L1} + cpf_{42}\Delta P_{L2} + cpf_{43}\Delta P_{L3} + cpf_{44}\Delta P_{L4}$ (9)

II .*CASE STUDIES:*

Table I: ACE participation factors and demands of DISCOs

Case study	Type of contracts	apf	Demand of DISCOs (in p.u. MW)	DPM	Change in demand of DISCOs(in p.u. MW)
1	DISCOs in each area participate equally	apf_1=0.5 apf_2=0.5 apf_3=0.5 apf_4=0.5	ΔP_{L1}=0.1 ΔP_{L2}=0.1 ΔP_{L3}=0 ΔP_{L4}=0	$\begin{vmatrix} 0.5 & 0.5 & 0 & 0 \\ 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{vmatrix}$	$DISCO_1$ and $DISCO_2$ demand 0.1 p.u MW power
2	DISCOs contract with GENCOs	apf_1=0.75 apf_2=0.25 apf_3=0.5 apf_4=0.5	ΔP_{L1}=0.1 ΔP_{L2}=0.1 ΔP_{L3}=0.1 ΔP_{L4}=0.1	$\begin{vmatrix} 0.5 & 0.25 & 0 & 0.3 \\ 0.2 & 0.25 & 0 & 0 \\ 0 & 0.25 & 1 & 0.7 \\ 0.3 & 0.25 & 0 & 0 \end{vmatrix}$	All the DISCOs demand 0.1 p.u MW power
3	Contract violation of DISCO by demanding more power	apf_1=0.75 apf_2=0.25 apf_3=0.5 apf_4=0.5	ΔP_{L1}=0.2 ΔP_{L2}=0.1 ΔP_{L3}=0.1 ΔP_{L4}=0.1	$\begin{vmatrix} 0.5 & 0.25 & 0 & 0.3 \\ 0.2 & 0.25 & 0 & 0 \\ 0 & 0.25 & 1 & 0.7 \\ 0.3 & 0.25 & 0 & 0 \end{vmatrix}$	$DISCO_1$ demands excess $0.1\ p.u$ and remaining DISCOs demand 0.1 p.u MW

III. THYRISTOR CONTROLLED SERIES CAPACITOR

The schematic of an interconnected power system considering a TCSC [7] in series with the Tie-line is shown in Fig 3 where TCSC is placed near Area 1.

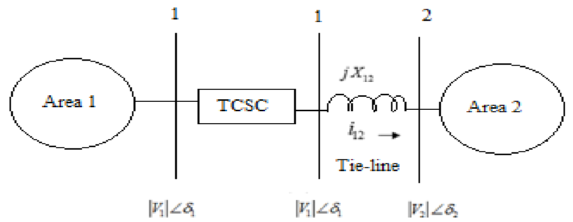

Fig 3 Schematic of interconnected power system with TCSC in series with Tie-line

The power flow through the tie lines connecting areas i and area j with TCSC is given by

$$P^n_{tiei-j} - jQ^n_{tiei-j} = V_i^* i_{ij}\ |V_i| \angle(\delta_i^n) \frac{|V_i|\angle\delta_i^n - |V_j|\delta_j^n}{j(X_{ij} - X_c^n)}$$

Where X_{ij} is the line reactance and X_c^n is the impedance of TCSC.P is the active power and Q is the reactive power and the superscript n represents the nominal values. In AGC we are concerned with active power. When the equation is simplified for active power P is simplified, the tie-line power in the connecting area I and j is given by

$$P^n_{tiei-j} = \frac{|V_i||V_j|\sin(\delta_i^n - \delta_j^n)}{X_{ij}(1 - X_c^n / X_{ij})} = \frac{|V_i||V_j|\sin(\delta_i^n - \delta_j^n)}{X_{ij}(1 - K_c^n)}$$

Where K_c^n is the % compensation of the TCSC.

In transfer function model, the change in percentage compensation ΔK_c is given by

$$\Delta K_c(s) = \frac{K_{TCSC}}{1 + sT_{TCSC}} \Delta Error(s) \quad (11)$$

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Where $\frac{K_{TCSC}}{1+sT_{TCSC}}$ is the transfer function of TCSC. K_{TCSC} is the gain and T_{TCSC} is the time constant of TCSC. The change in frequency in area 1 is taken as $\Delta Error(s)$ in our present work.

III *FUZZY LOGIC CONTROLLER:*

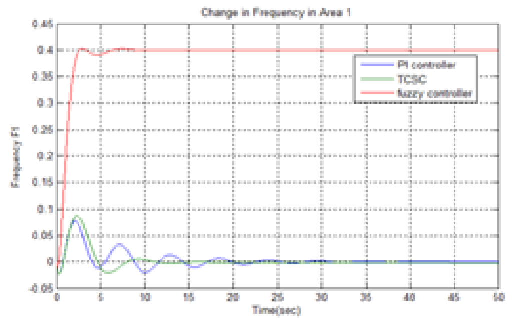
Fuzzy set theory and fuzzy logic establish the rules of a nonlinear mapping. There has been extensive use of fuzzy logic in control applications. One of its main advantages is that controller parameters can be changed very quickly depending on the system dynamics because no parameter estimation is required in designing controller for nonlinear systems. Many conventional control strategies have been proposed for AGC, which exhibit poor dynamic response in the presence of uncertainties and non-linearity's. The real world power system contains different kinds of uncertainties due to unpredictable load variations, system modelling errors and change of the power system structure. As a result, the conventional control strategies certainly are not adequate for the AGC problem. Consequently, it is required that a flexible controller be developed to improve the performance of the system. In recent years, the advent and application of intelligent control techniques for AGC in power systems have overcome the problems associated with conventional control techniques to a reasonable extent.

In this paper, the fuzzy logic controller is implemented. [6] The inputs of the proposed fuzzy controller are ACE and rate of change in ACE. The appropriate fuzzy rule base is given in Table ii , where NB, NM, NS, Z, PS, PM, and PB represent negative big, negative medium, negative small, zero, positive small, positive medium, and positive big, respectively. The designed fuzzy controller will behave like a parameter time varying PID controller. The Mamdani-type fuzzy inference system has been used and the defuzzification technique used is centre of gravity.

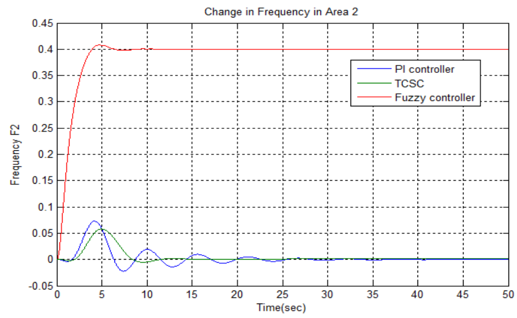
	Change in ACE {d(ACE)/dt}							
		NB	NM	NS	Z	PS	PM	PB
	NB	NB	NB	NB	NB	NM	NS	Z
	NM	NB	NB	NB	NM	NS	Z	PS
	NS	NB	NB	NM	NS	Z	PS	PM
	Z	NB	NM	NS	Z	PS	PM	PB
	PS	NM	NS	Z	PS	PM	PB	PB
ACE	PM	NS	Z	PS	PM	PB	PB	PB
	PB	Z	PS	PM	PB	PB	PB	PB

V.*RESULTS COMPARISON FOR THE TWO-AREA POWER SYSTEM WITH PI CONTROLLER, FUZZY CONTROLLER AND TCSC FOR DIFFERENT CASE STUDIES*

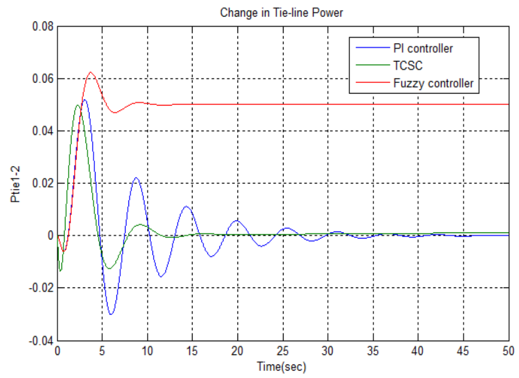
A. Case 1: Change in frequency in Area 1



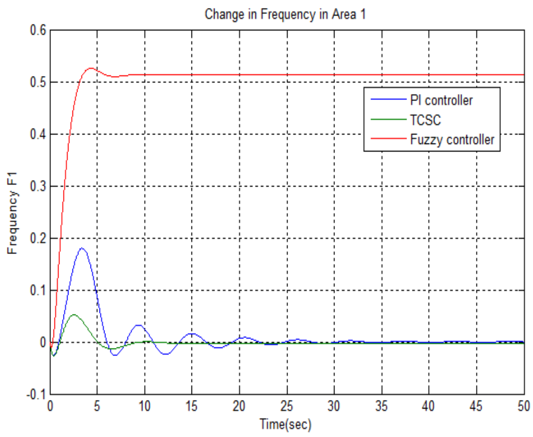
Change in frequency in Area 2



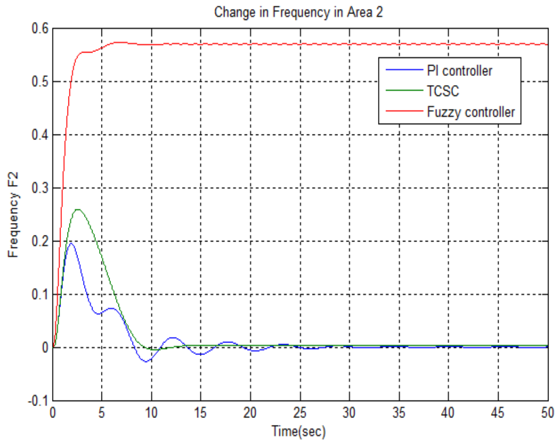
Change in Tie-line Power



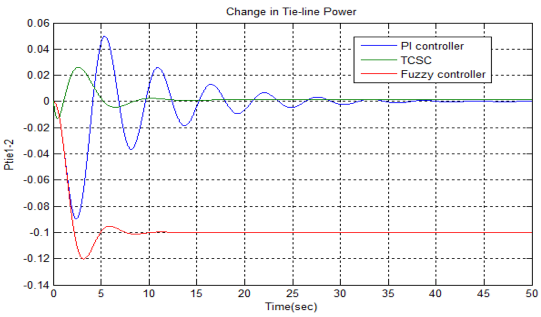
B. *Case 2: Change in frequency in Area 1*



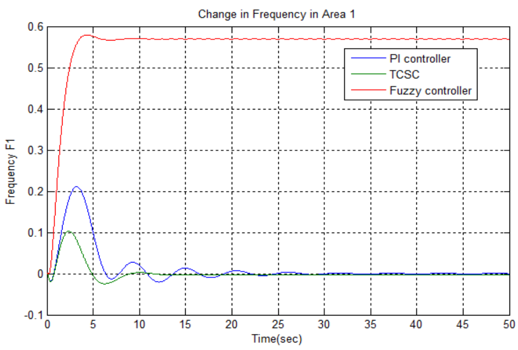
Change in frequency in Area 2



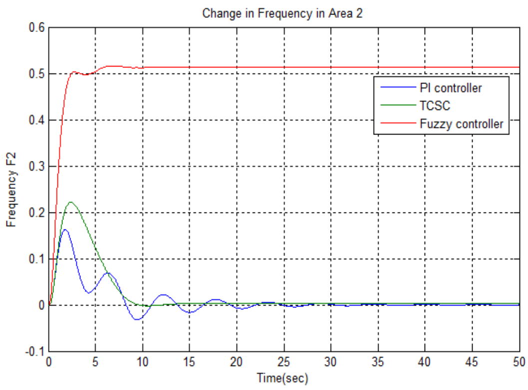
Change in Tie-line Power



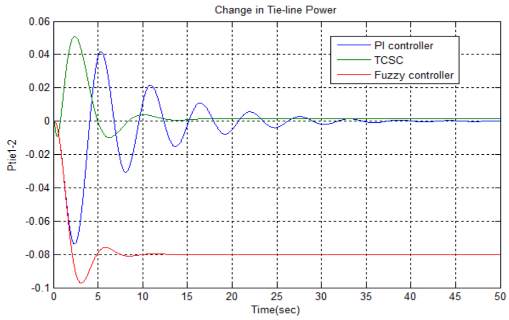
C. Case 3: Change in frequency in Area 1



Change in frequency in Area 2



Change in Tie-line Power



VI .CONCLUSION

In all the case studies, the settling time of the power system model with FLC is less compared with TCSC and PI controller but the peak over shoot is less with TCSC than FLC. When TCSC is used, the frequency oscillations and change in tie line power flow are reduced. The oscillation's and peak over shoot is more with considering only PI controller. In the case of contract violation, the tie line peak overshoot of PI controller is less than TCSC. The responses generally depend upon cpf's and apf's.

VII. APPENDIX

K_{P1} = 120 Hz/p.u MW, T_{P1} = 20.008 sec, T_{G1} = T_{G2}= 0.08 sec, T_{T1}= T_{T2} = 0.3 sec, B_1 = B_2 = 0.425 Pu Mw/Hz, R_1 = R_2 = 2.4 Hz/PuMW, $-\alpha_{12} = -1$, K_{TCSC} =1.0, T_{TCSC} =0.02.

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