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Area Frequency Response through IMC Based PID Controller of Steam Turbine Model

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Abstract: The power system control is to ensure stabilized frequency to the consumers at all times and maintain load frequency control of the power grid by managing generation and distribution services efficiently to maintain reliability of the power system frequency. In an interconnected power system the power load demand varies randomly which impacts both the frequency and tie-line power interchange. Hence, it is necessary to develop a methodology to make decisions synchronously and automatically by all grid connected generating units. The load frequency control address this issue and minimizes the deviations in the power grid frequency and tie-line power interchange bringing the steady state errors to zero maintaining the balance between demand and supply in real time. In order to ensure the same, the precision simultaneous Load Frequency Control is necessary for all the power grid connected generating stations and to define a control strategy which can accurately derive the various parameters for the Load Frequency controller. In this paper, Automatic Load Frequency control of two area power systems using conventional Proportional Integral Derivative (PID) tuning and through internal model based PID control (PID-IMC) technique have been performed using MATLAB simulation. The PID-IMC controller results in quick decision making because of its high adaption for changing conditions. The IMC formulation generally results in only one tuning parameter and the closed loop time constant (Lambda, the IMC filter factor). The PID tuning parameters are then a function of this closed-loop time constant. The selection of the closed-loop time constant is directly related to the robustness (sensitivity to model error) of the closed-loop system. The PID-IMC controller are used to improve the dynamic response as well as to reduce or eliminate the steady-state error. It is much faster, applicable under different nonlinearities and give better stability response as compared to the conventional PID Load Frequency controllers for a two area power system. This paper describe the dynamic analysis of a steam turbo generator model of a typical 660 MW machine and the comparative study of frequency response by conventional PID controller and IMC based PID controller at different MW load condition. The main focus of the work is to determine the area frequency response of two interconnected area based on a realistic mathematical model of turbine generator. The simulated model response for various scenarios are also presented in this paper.

Keywords: HBD, HP, IP, LP, LFC

1. INTRODUCTION

In the power system operation, maintaining the Grid frequency by load frequency control is a challenge and requires necessarily the power load operators and regulators to manage generation and distribution services efficiently to maintain reliability of the power system frequency. In an interconnected power system, as generation and load demand varies randomly, both area frequency and tie-line power interchange vary. The operating point of actual power system changes continuously and randomly with time and experience deviations in nominal system frequency and scheduled power exchanges to other areas that yield undesirable effects. The ability of the generation side to follow the fast changing load is limited due to physical / technical consideration and causes imbalance between the actual and the scheduled generation quantities. This action leads to a frequency variation.. Hence, it is necessary to develop a Synchronous methodology to measure the frequency without measurement delays and make decisions synchronously. For practical purpose it is prudent to consider asynchronous methodology which incorporates frequency measurement delay including boiler-turbine-generator response and asynchronous decentralized decision making. The only way to regulate frequency is to maintain the balance between demand and supply in real time. The load frequency control with free governor or restricted governor mode control address the issue and minimizes the deviations in the area frequency and tie-line power interchange and ensure their steady state errors to be zero by regulating frequency to maintain the balance between demand and supply in real time. In recent years from the year 2010 onwards the Indian Electricity Grid Code has been amended few times to address the governor control as a primary level control which shall act as a first line of defence against sudden frequency rise\fall The system deviates from nominal frequency and generation units deviate from their respective schedules, in response to changes in load. Conventionally, a secondary level control like load frequency control (LFC) is recommended to bring frequency back to nominal value. Implementation of a successful secondary control mechanism is still awaited under present circumstances and various amendments are done to mitigate the issues [2]. Emergency condition arises during transient disturbances due to a tripping of a generator or a loss of load block causing the frequency changes due to the mismatch in load and generation. The drop in operating level of the frequency depends on the instance of starting point of disturbance as well as the system inertia. It is the system inertia, which provides the initial ability of the power system to oppose change in the frequency [28]. A suitable mathematical representation of power units and their controls is required to carry out power system dynamic studies for successful result oriented implementation [25] [29]. The goal of this paper is to illustrate the choice between conventional PID based LFC and Internal model based PID control. The time constants for Steam chest, Reheater and Crossover are calculated at different MW load for this purpose [34]. The parameters for 660 MW turbo generator machine are fed into the mathematical model and the frequency response due to load change is observed. PID Controllers are properly tuned to give the best results. The MW loads considered for the study are being 30%, 50%, 60%, 80%, 100% and 105% of 660 MW. Matlab and Simulink is used in the development of mathematical model and the simulation study.

2. MODELLING OF THERMAL AREAS

2.1. Generator Load Model

The generator model is characterized by the following equation

$$Pg(s) = \frac{1}{2H+D} \quad (1)$$

where power system time constant

$$Tp = \frac{2H}{Df0} \quad (2)$$

and gain of the power system is

$$Kp = \frac{1}{D} \quad (3)$$

2.2. Governor Model

The function of the governing system of steam turbine generator is to regulate or adjust continuously of governing /steam admission control valve, when the turbo-generator is on bars, by controlling the steam inflow to the turbine. The dynamic response of governing control is achieved by various control logics to operate the control valves in the turbine. Stop valves are provided in the governing system before the steam admission control valve to protect the turbine in case of unsafe conditions by blocking the steam flow into the turbine. In an Electro Hydraulic governing system, Halls probes/ Linear variable differential transmitters / pulse generators etc. are used to sense the speed, position of control valves, control circuits to process the signals, computing error and electro hydraulic converters / amplifiers and a hydraulic actuator to drive the control valves.

We use speed and frequency interchangeably since they describe proportional quantities. The speed-versus-power output governing characteristic has droop, which means that a decrease in speed should accompany an increase in load, as depicted by the straight line of Figure 1. The per-unit droop or speed regulation of the generating unit is defined as the magnitude of the change in steady-state speed, expressed in per unit of rated speed, when the output of the unit is gradually reduced from 1.00 per-unit rated power to zero. A 5% regulation means that a 5% change in frequency causes a 100% change in power generation. Suppose that the unit is supplying output power P_{g0} at frequency f_0 when the load is increased to $Pg = P_{g0} + \Delta P_g$, as shown in Figure 3. As the speed of the unit decreases, the speed governor allows more steam from the boiler through to the turbine to arrest the decline in speed. Equilibrium between input and output power occurs at the new frequency $f = (fo + \Delta f)$ as shown. According to the slope of the speed-output characteristic given the frequency change (in Hz) is $\Delta f = -R\, \Delta P_g$ where R is called the droop or speed regulation. An isolated turbine generator would continue to operate at the reduced frequency f except for the supplementary control action or the secondary control of the governor. The governor control mechanism can parallel-shift the regulation characteristic to the new position shown by the dashed line of Figure3. Effectively, secondary control of the governor supplements the action of the governor by changing the speed setting to allow more prime-mover energy through to increase the kinetic energy of the generating unit so that it can again operate at the desired frequency f_o while providing the new output P_g. The speed governor has a transfer function

$$G(s)gov = \frac{1}{R\,(1+STgov)} \quad (4)$$

Where T_{gov} is the governor time constant.

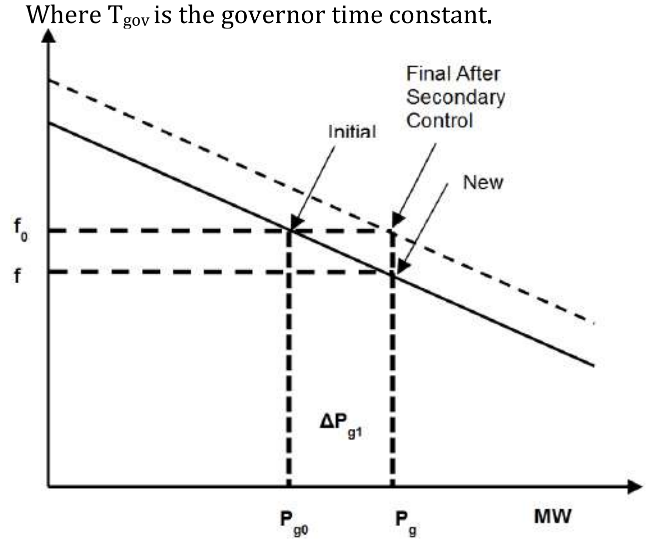

Figure 1. *Governor Characteristics.*

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2.3. Turbine Model

A steam turbine converts stored energy of steam of high pressure and temperature into rotating energy. The source of heat in our case is boiler. A variety of steam turbine configurations have been developed depending on unit size and steam conditions. A turbine with multiple sections may be tandem-compound or cross-compound. In our case tandem-compound single reheat turbine is considered between high pressure exhaust and intermediate pressure turbine, and between the intermediate pressure and low pressure turbine lies the crossover. The steam chest and inlet piping to the first turbine cylinder and re-heaters and crossover piping introduce delays between valve movement and change in steam flow. The reheat turbine model shown in Figure 5 has a transfer function

$$G(s) = \frac{(F_{HP} + F_{IP} + F_{LP}) + S(F_{HP}T_{RH} + F_{IP}T_{CO} + F_{HP}T_{CO}) + S^2(F_{HP}T_{CO}T_{RH})}{(1+ST_{SC})(1+ST_{RH})(1+ST_{CO})} \quad (5)$$

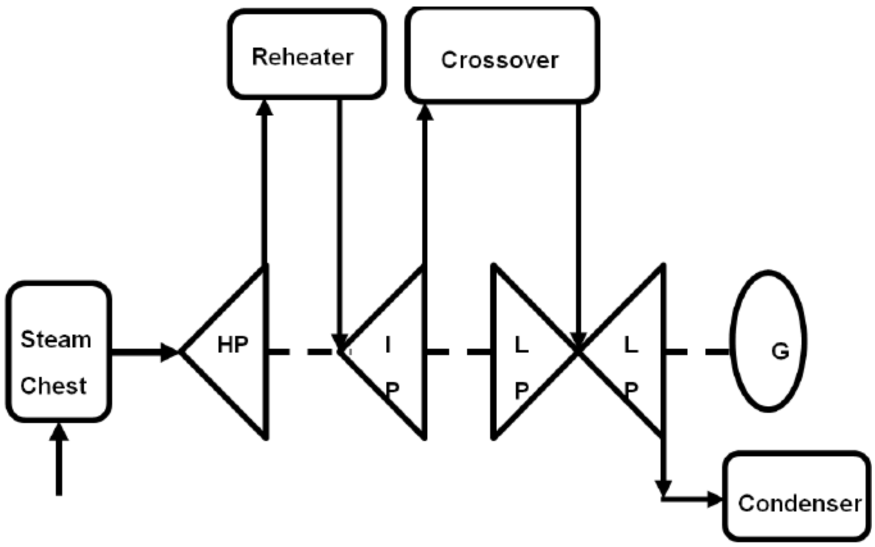

Figure 2. *Tandem Compound Single Reheat turbine.*

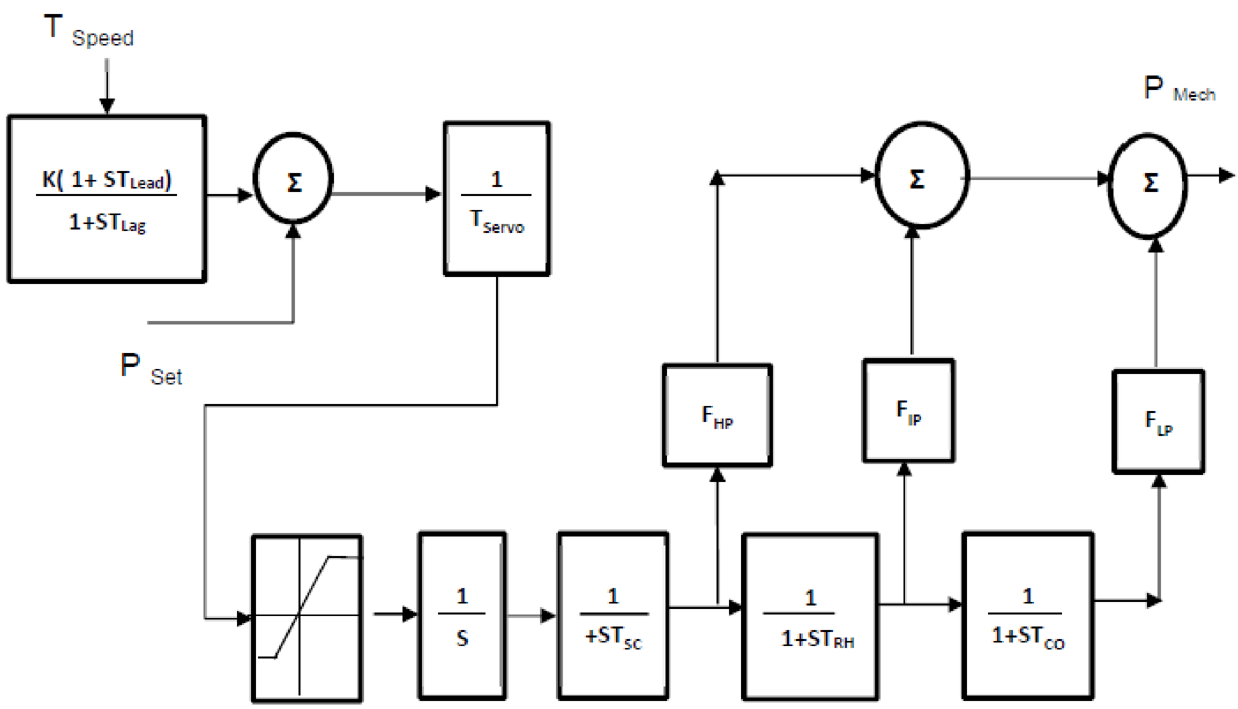

Figure 3. *Turbine Model.*

Where $F_{HP} + F_{IP} + F_{LP} = 1$ and F_{HP}, F_{IP}, F_{LP} are the fraction of the power generated in the high pressure turbine, intermediate pressure and low pressure turbine respectively which can be obtained by using the enthalpy and steam flow data available in the heat balance diagram. T_{RH}, T_{CO}, T_{CH} are the time constant for steam chest, re-heaters and crossovers section of the steam turbine respectively and can be derived from the HBD applicable for this model. T_{Lag} T_{Lead}, T_{Servo} are controller lag, lead compensation and servo time constant respectively of a 660 MW tandem compound single reheat machine. The HBD represents the heat balance map of the unit cycle. In this map, thermodynamic data including pressure (kgf/cm2), enthalpy (kcal/kg), mass flow (T/h), and temperature (DegC) of nearly all sections of the cycle are given. Temperature control loop maintains the input steam of HP and IP turbines to have constant temperature. Also, there are three extraction outlets in the HP turbine, five in the IP turbine, and six in the LP turbine. There are also gland steam fed into some sections. The heat regenerative cycle consists of one gland steam condenser, five low-pressure feed water preheaters and three high-pressure feed water preheaters . In this relatively complex cycle, we are interested in the thermodynamic data of the reheater, HP, IP, LP turbines, and extraction pipes for calculating the turbine model parameters.

3.1. Derivation of Steam Chest Time Constant

We can calculate the time constant of turbine steam chest for different MW load conditions from other HBD as shown in Table 1 and Table 2.

Table 1. *660 MW Steam Turbine Parameters.*

Steam Turbine Parameters				
Turbo Generator Load		Pressure	Flow	Temperature
(MW)	(%)	(Kgf/cm²)	(Kg/Hr)	(Celcius)
198	30	108	625911	565
330	50	139.4	917165	600
396	60	164.9	1093233	600
528	80	216.7	1459346	600
660	100	270	1849134	600
693	105	270	1960251	600

Table 2. *660 MW Steam Chest Time Constant at different Loads.*

Steam Chest Time Constant			
Turbo Generator Load		Ksc	Time Constant t_{SC}
(MW)	(%)	(Kg/m³)/Kpa	(Seconds)
198	30	0.002956529	0.819933708
330	50	0.002816499	0.688034571
396	60	0.002972196	0.720561091
528	80	0.003236127	0.772345396
660	100	0.003236127	0.759462444
693	105	0.003236127	0.716412249

3.2. Derivation of Reheater Time Constant

The Reheater section in the boiler under consideration covers the area starting from the HP turbine outlet, cold reheat pipe, primary re-heater inlet header, primary re-heater bank, terminal, outlet header, primary re-heater to secondary re-heater, secondary re-heater inlet header, secondary re-heater bank, outlet header and hot reheat pipe up to IP turbine inlet.

The time constant of re-heater for different MW load conditions are calculated from the HBD as shown in Table 3 and Table 4.

Table 3. *660 MW Steam Turbine Reheater Parameters.*

Reheater Steam Parameters				
Turbo Generator Load		Pressure	Flow	Temperature
(MW)	(%)	(Kgf/cm2)	(Kg/Hr)	(Celcius)
198	30	17.3	545611	530
330	50	26.1	789568	600
396	60	30.7	932193	600
528	80	40	1220920	600
660	100	49.6	1518342	600
693	105	52.4	1610421	600

Table 4. *660 MW Steam turbine Reheater Time Constant.*

Reheater Time Constant			
Turbo Generator Load		K_{RH}	Time Constant t_{RH}
(MW)	(%)	(Kg/m3) / Kpa	(seconds)
198	30	0.002911205	14.67890699
330	50	0.002797203	14.70390995
396	60	0.00256179	13.43408491
528	80	0.00256179	13.36436518
660	100	0.002591757	13.46369583
693	105	0.002627575	13.54406349

3.3. Derivation of Turbine Crossover Time Constant

The crossover pipe is located between the IP and LP turbine.

The time constant of crossover area for different MW load conditions are calculated from the as shown in Table 5 and Table 6.

Table 5. *660 MW Steam turbine Crossover Steam Parameters.*

Crossover Steam Parameters				
Turbo Generator Load		Pressure	Flow	Temperature
(MW)	(%)	(Kgf/cm2)	(Kg/Hr)	(Celcius)
198	30	3.09	470251	289.8
330	50	4.54	673655	338.1
396	60	5.42	783924	334.8
528	80	6.19	1006356	329.6
660	100	8.23	1225821	324
693	105	8.64	1287558	323.3

Table 6. *660 MW Steam turbine Crossover Time Constant.*

Crossover Time Constant			
Turbo Generator Load		K_{CO}	Time Constant t_{CO}
(MW)	(%)	(Kg/m3) / Kpa	(seconds)
198	30	0.004036285	1.00187911
330	50	0.003846242	0.979173618
396	60	0.003708024	0.968439662
528	80	0.00373245	0.867236969
660	100	0.003766075	0.955138868
693	105	0.003766075	0.954642316

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4. DERIVATION OF POWER FRACTIONS OF TURBINE

Power fractions determination of HP, IP and LP turbine section requires calculating each turbine's thermodynamic work.

Table 7. *660 MW HP turbine Power Fraction Parameters.*

HP Turbine Power				
Turbo Load	Generator	Power	Power Fraction	Power Fraction
(MW)	(%)	(MW)		(%)
198	30	86.846972	0.422730994	42.2730994
330	50	129.002877	0.381040337	38.1040337
396	60	151.846029	0.374792441	37.4792441
528	80	198.256714	0.367568149	36.7568149
660	100	245.268053	0.363925968	36.3925968
693	105	245.68811	0.347677815	34.7677815

Table 8. *660 MW IP turbine Power Fraction Parameters.*

IP Turbine Power				
Turbo Generator Load		Power	Power Fraction	Power Fraction
(MW	(%)	(MW)		(%)
198	30	62.858208	0.305964758	30.5964758
330	50	102.10129	0.301580173	30.1580173
396	60	121.300953	0.299399864	29.9399864
528	80	160.108616	0.296841536	29.6841536
660	100	200.773283	0.297905131	29.7905131
693	105	220.40398	0.311897764	31.1897764

Table 9. *660 MW LP turbine Power Fraction Parameters.*

LP Turbine Power				
Turbo Generator Load		Power	Power Fraction	Power Fraction
(MW)	(%)	(MW)		(%)
198	30	55.737461	0.27134248	27.134248
330	50	107.450218	0.31737949	31.737949
396	60	132.000006	0.325807695	32.5807695
528	80	181.008701	0.335590315	33.5590315
660	100	227.909067	0.338168901	33.8168901
693	105	240.56247	0.340424421	34.0424421

The correct transfer function of the turbine under consideration is derived under various MW load condition in the form as

$$G(s) = \frac{As^2+Bs+1}{(Xs^3+Ys^2+Zs+1)} \tag{6}$$

Where at 30% load and 100% load of the 660 MW turbine under consideration the values of the parameters A, B, X, Y and Z can be calculated from the equation (5) and Table 2, 4, 6, 7, 8, 9 as shown in the Table 10. It implies that the dynamic model of the turbine varies with the MW load of the machines as shown in Table 10.

Table 10. *Turbine Transfer Function Parameters.*

Turbo Generator Load						
MW	198	330	396	528	660	693
%	30	50	60	80	100	105
A	6.2092	5.4861	4.8761	4.2601	4.67998	4.4954
B	6.9382	6.2712	5.6879	5.4885	5.53193	5.3386
X	12.022	9.9061	9.3746	8.9515	9.76646	9.263
Y	27.52	25.188	23.388	22.582	23.8103	23.317
Z	16.498	16.371	15.123	15.004	15.1783	15.215

5. LOAD FREQUENCY CONTROL RESPONSE

In power systems, frequency is dependent on active power and and voltage depends on reactive power limit.The control of frequency through active power is called load frequency control. There are many load frequency control methods developed for controlling Frequency of power system. This include flat frequency control (FFC), tie-line bias control (TBC) and flat tie-line control (FTC). In FFC, some generators absorb load change and other generators are operated at base load. The reason is that the operating efficiency at base load is maximum but the disadvantage is the power system becomes more prone to transient disturbances due to lesser number of generating station for load change absorbers. The widely used methods are in TBC, where all the power systems in the interconnected areas regulate the frequency regardless of where the frequency change originates. In FTC, the change in frequency is of a particular control area is taken care of by the generators of that control area thereby maintaining the tie-line loading and frequency thereof. In a single area power system consists of a electrohydraulic governor, a steam turbine, and a generator with feedback of regulation. System also includes step load change input to the generator. The objective of load frequency controller is to exert the control of frequency response and at the same time real power exchange through outgoing transmission line. The load frequency control strategies is based on the conventional linear Control theory. These controllers may be unsuitable in some operating conditions due to the complexity of the power systems such as nonlinear load characteristics and variable operating points. The power system static and dynamic properties must be well known to design an efficient controller. The change in frequency is detected by a reliable and accurate frequency sensor. The load frequency controller amplify error frequency error signal corresponding to the change in load and send command signal to the electro-hydraulic governor of the turbine-generator set to control the steam admission valve mechanism. Any increment or decrement in torque because of any frequency change balances the output of governor, which will compensate the value of frequency error signal. The process continues till the steady state error of frequency or load becomes zero with the help of a simple proportional-integral controller. In order to reduce the frequency deviation to zero a reset action in proportional-integral controller sets the load reference point to change the speed set point which forces the final frequency deviation to zero. The controller parameters are tuned to achieve a satisfactory transient response of the system.

6. TWO AREA INTERCONNECTED POWER SYSTEM

A power system consists of several generating units connected together; these generating units are inter-connected through tie-lines to become fault tolerant. In case of two control areas, the two areas are interconnected through Transmission line which allow flow of active power from one area to another as and when needed. Such Transmission Lines are known as tie lines and the power Transmitted through them is known as Tie Line Power. In case there is any load change in one of the areas, active power from the other system is supplied to the system with load change to help restore the system frequency. Each control area as for as possible should supply its own load demand and power transfer through tie line should be on mutual agreement. The control objective is to regulate the frequency of each area and to simultaneously regulate the tie line power as per inter-area load dispatch schedule. This use of tie-line power creates a new error in the control problem, which is the tie line power exchange error. Area controller error (ACE) play major role in interconnected power system and also minimizing error functions of the given system. To correct the steady state errors of frequency and tie line power following load change, supplementary control must be given in both the areas such that change in area1 provides supplementary control only in that area and not in area2.This control signal is known as Area Control Error(ACE) and is achieved using Tie-line Bias Control(TBC).

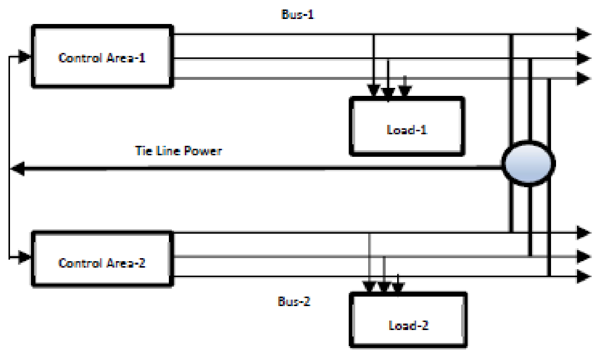

Figure 3. *Two Area Schematic.*

The power transfers from area 1 to area 2 are

$$P_{tie\ 12}= \frac{|V1||V2|}{X12} Sin(\delta\ 1\text{-}\ \delta\ 2) \quad (7)$$

If the change in load demands of two areas there will be incremental change in power angle.Δδ1 and Δδ2 be the incremental changes in δ 1 and δ. The change in load demands of two areas there will be incremental change in power angle Δδ1 and Δδ2 and will be

$$P_{tie\ 12} + \Delta P_{tie\ 12}= \frac{|V1||V2|}{X12} Sin[(\delta 1 + \Delta\delta 1)\text{-}(\delta 2 + \Delta\delta 2)] \quad (8)$$

$$Ptie12 = \frac{|V1||V2|}{X12} Cos(\delta 1\text{-}\ \delta 2)(\ \Delta\delta 1\text{-}\Delta\delta 2) \quad (9)$$

$$T12 = \frac{|V1||V2|}{X12*P1} Cos(\delta 1\text{-}\ \delta 2) \quad (10)$$

Here, the new quantities which is not present in the isolated power system model is T_{12}, called synchronizing torque coefficient.

$$\Delta P_{tie12\ (p.u)} = T12(\ \Delta\delta 1\text{-}\Delta\delta 2) \quad (11)$$

$$Pmax12 = \frac{|V1||V2|}{X12} (\ \Delta\delta 1\text{-}\Delta\delta 2) \quad (12)$$

$$T12 = \frac{Pmax\ 12}{P1} Cos(\delta 1\text{-}\ \delta 2) \quad (13)$$

$$2\pi\Delta f = d\delta/dt \quad (14)$$

Incremental tie line power output of area1

$$\Delta P_{tie12\ (p.u)}= 2\pi T_{12}\{(\ \Delta f_1\text{-}\ \Delta f_2)/s\} \quad (15)$$

Laplace transform of both sides give

$$\Delta P_{tie21\ (p.u)}= \{2\pi T_{12}(\ \Delta f_{2(s)}\text{-}\ \Delta f_{1(s)}\ )\}/s \quad (16)$$

$$T_{21}=a_{12}T_{12} \quad (17)$$

$$\Delta P_{tie21\ (p.u)}= \{-2\pi T_{21}(\ \Delta f_{1(s)}\text{-}\ \Delta f_{2(s)}\ )\}/s$$

If ΔPd is increase in load at area 1 then by Swing equation power balance is

$$\Delta P_g\text{-}\Delta P_d = 2H/f^0\ d/dt\ (\ \Delta f) + B(\ \Delta f) \quad (18)$$

Where H is the system inertia, f0 is the system nominal frequency, Δf is the cange in frequency and B is the area parameter. For the two Area power systems

$$\Delta P_g\text{-}\Delta P_d = 2H/f^0\ d/dt\ (\ \Delta f) + B(\ \Delta f) + \Delta P_{tie12} \quad (19)$$

Taking Laplace transform of both sides

$$\Delta P_{g(s)}\text{-}\Delta P_{d\ (s)} = 2H(s)/f^0\ d/dt\ \{\Delta f(s) + B\Delta f(s)\} + \Delta P_{tie12(s)} \quad (20)$$

$$\Delta f_{1(s)} = [\Delta P_{g1(s)}\text{-}\Delta P_{d1\ (s)}\text{-}\Delta P_{tie12(s)}]/[B_1(2H_{1s}\ /f^0\ B_1 + 1] \quad (21)$$

$$\Delta f_{1(s)} = [\Delta P_{g1(s)}\text{-}\Delta P_{d\ 1(s)}\ \text{-}\ \Delta P_{tie12(s)}]\{\ K_p\ /(\ 1+ sT_P)\} \quad (22)$$

Where $K_p = 1/B_1$ and $T_p = 2H\ /\ B_1 f^0$ (23)

Similarly, for area 2,

$$\Delta f_{2(s)} = [\Delta P_{g2(s)}\text{-}\Delta P_{d\ 2(s)}\ \text{-}\ \Delta P_{tie21(s)}]\{\ K_p\ /(\ 1+ sT_P)\} \quad (24)$$

For n number of interconnected control areas Pij is the power deviation between areas i and j to maintain the frequency f

$$ACEi= \sum_{j=1}^{n} \Delta\ \boldsymbol{Pij} + \boldsymbol{Bi}\ \Delta\ \boldsymbol{fi} \quad (25)$$

ACE consists of a tie line flow deviation added to a frequency deviation weighted by a bias factor to accomplish the desired objectives.

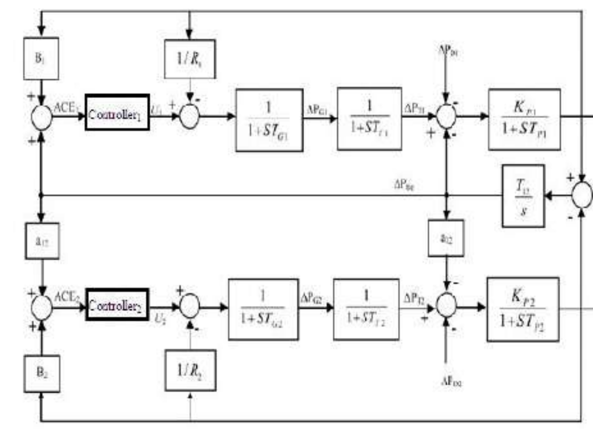

Figure 4. *Two Area Model*

Two area models are studied here where each area consists of three identical steam turbine and generators of 660 MW each having speed droop of single unit on machine base 2 Hz/MW leading to total 1980 MW area capacity in each area. The inter area tie line power exchange is assumed to be 200 MW with a power angle difference of 30 degrees.

The speed droop of single unit on power system area base is R $=\frac{2}{(\frac{660}{1980})}$=6.06 Hz/Mw(pu)

Equivalent speed droop characteristic for area-1 and area-2

Speed droop for 3 generating stations in an area

$Reqv = \frac{1}{\frac{3}{R}} = \frac{R}{3} = 2.02$ Hz/MW(pu)

If the inertia constant of a single identical generating unit of capacity G=660 MW is H= 5s then the equivalent inertia constant of each identical area is found to be

$H_{eq}=(H_1G_1+H_2G_2+H_3G_3)\,/\,G_{System} =\frac{5*660*3}{1980}$=5 sec

Then for $P_{maxtie\ 12}$ = 200MW and (δ 1- δ 2) =30 degrees

$2\pi T12 = \frac{Pmax12}{P1} Cos(\delta 1- \delta 2)$ = 0.5496

Table 11. *Two Area System Parameter*

Parameters	Area 1	Area 2
Inertia Constant(H)	5	5
$2\pi T_{12}$	0.5496	0.5496
Load Change	0.2	0
β(Gain Constant)	0.049896	0.049896
Speed Droop	4%	4%
Tie Line Power P_{12}(MW)	200	200

7. Simulation Results

The MATLAB simulation is done with turbine model corresponding to two different MW load of 100% and 50% with parameters as shown in Table 10 for the dynamic analysis of the model as defined in equation. A step load variations are applied in any one of the two identical interconnected area model with system parameters corresponding to 100% and 50% MW load and the simulation results are shown below in the following figures. The area frequency response has been studied for using basic PID controller tuning method as also using IMC based PID Controller so as to minimize deviation and create an ideal system.

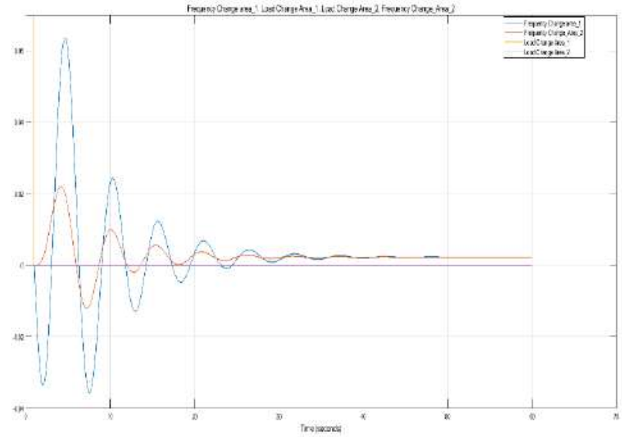

Fig 5*. Two Area Frequency Response Characteristics at 100% Load*

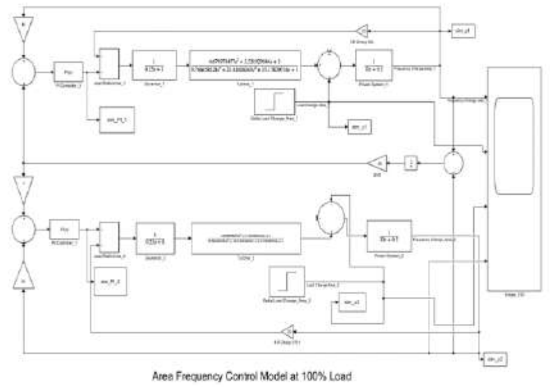

Fig 6. *Two Area Inter Connected Power System Model for 100% Load*

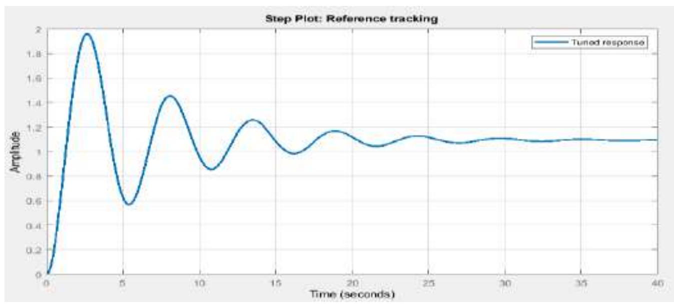

Fig 7. *Ideal tuned response for a PID controller at 100% load*

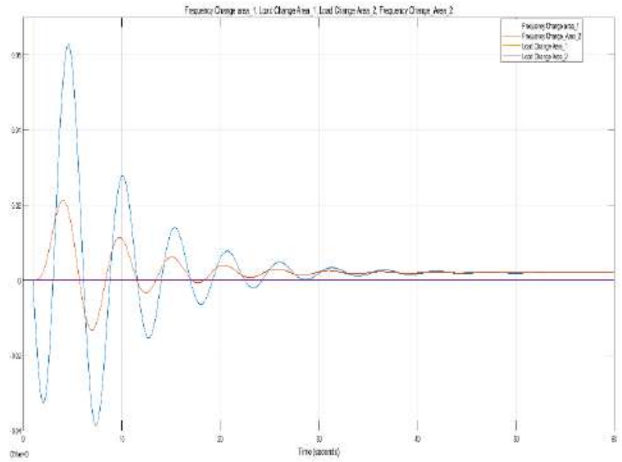

Fig 8. *Two Area Frequency Response Characteristics of 50% Load*

Table 12. *Two Area PID Tuning Parameter*

Parameters	AREA 1		AREA 2	
	50% load	100% Load	50% load	100% Load
P	354.05	248.36	50	50
I	128.41	78.17	10	10
D	242.81	194.68	100	100
N	143.09	111.61	100	100
	50% Load		100% Load	
Δf	2.479x10-3		4.301×10^{-3}	
Settling Time	37.139		36.180	
Peak Overshoot	5.541×10^{-2}		7.732×10^{-2}	

8. INTERNAL MODEL BASED CONTROL

Till now we have used the basic and conventional PID tuning method so as to minimize deviation and create an ideal system but another method of Load Frequency Control is by using Internal Model based PID Controller known as IMC. The response of the Single area and Two area Power System model using IMC based PID Controller is being analyzed also and compared to the conventional PID control. The response of IMC based PID controller results in increased damping of oscillation, reduced steady state error of the tie line exchange in a Multi area interconnected Power system and also higher rise time.

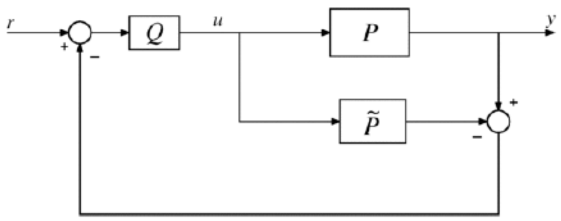

Fig 9. *IMC Configuration*

It is one of the most popular methods for Load Frequency Control (LFC).Here P stands for the plant to be controlled. P~ stands for the plant model and Q stands for the IMC Controller to be designed.

The two area LFC transfer function model comprises of two third order turbine model (Eqn 6). It is reduced to First Order Plus Dead Time (FOPDT) model using process reaction curve method .The IMC based PID is designed for the FOPDT model. From the process reaction curve the third order system is reduced to: follow where K is process gain, θ is delay time and s is the slope of the tangent line of step response:

$$P(s)=\frac{Kp}{\tau ps+1}e^{-\theta s} \tag{26}$$

Using a first-order Padé approximation for dead time and the IMC based PID parameters are obtained with the following

equation: $$Kc=\frac{\tau p+(0.5)\theta}{Kp(\lambda+(0.5)\theta)} \tag{27}$$

Where $\tau i=\tau p+\theta(0.5)$ (28)

$$\tau D=\frac{\tau p\theta}{2\tau p+\theta} \tag{29}$$

The λ is called the closed loop time constant and value of is chosen in such a way that it's value is always less than 2τp for IMC based PID with FOPDT.

$$F(s)=\frac{1}{\lambda s+1} \tag{30}$$

8.1 Single area power system at 100% load

The turbine transfer function is as follows:

$$P(s)=\frac{4.6799s^{2\wedge}+5.5319s+1}{9.7664s^3+23.8102s^2+15.1762s+1} \tag{31}$$

In order to reduce this to a FOPDT system we use mathematical approximations by breaking down P(s) into its factors

$$P(s)=\frac{(s+0.22)(s+0.95)}{(s+0.074)(s+1.046)(s+1.316)}=\frac{0.487(1+4.5s)(1+1.05s)}{(1+13.51s)(1+0.965s)(1+0.759s)} \tag{32}$$

The important property to remember here is that $e\theta s=1+\theta s$.

Putting this approximation in equation (32) we get the FOPDT system as:

$$P(s)=\frac{0.487}{13.998s+1}e^{-4.313s}$$

$Kp=0.487$ $\tau p=13.998$ $\theta = 4.313$

As a result, using the formulas for IMC Tuned PID the Parameters are calculated as follows:

$Kc=1.22$ $\tau i=16.1545$ $\tau D=1.868$

Simulation result

All the turbine parameters and power system parameters like inertia Constant, area capacity, tie line

Power remain the same as shown in the conventional PID Tuning Case.After further tuning the new parameters obtained are as follows

Table 13. *Single Area IMC-PID Tuning Parameter at 100% Load*

P	9791.8872
I	7202.0044
D	3315.3905
N	590.4126
Δf	2.912×10^{-5}
Settling Time(t_s)	23.66
Peak Overshoot(M_p)	1.54×10^{-3}

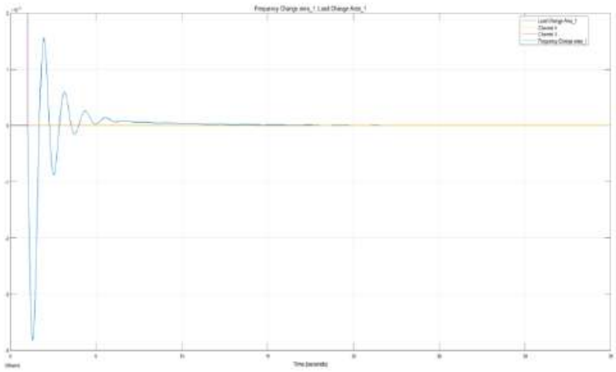

Fig 10. *Area Frequency Response for Single Area Power System Model with 100% Load*

8.2 Single area power system at 50% load

$$P(s)=\frac{4.6799s^{2}+5.5319s+1}{9.7664s^{3}+23.8102s^{2}+15.1762s+1} \quad (34)$$

In order to reduce this to a FOPDT system we use mathematical approximations by breaking down P(s) into its factors

$$P(s)=\frac{(s+0.191)(s+0.951)}{(s+0.068)(s+1.02)(s+1.45)}=\frac{0.556(1+5.23s)(1+1.05s)}{(1+14.705s)(1+0.98s)(1+0.68s)} \quad (35)$$

Putting this approximation $e\theta s=1+\theta s$ in equation (33) we get the FOPDT system as:

$$P(s)=\frac{0.556}{15.195s+1}e^{-5.11s} \quad (36)$$

Kp=0.556 , τp=15.195, $\theta = 5.11$

As a result using the formulas for IMC Tuned PID the Parameters are as follows:

Kc=1.158 τi=17.745τD=2.187

After further tuning the new PID parameters are obtained as follows

Table 14. *Single Area IMC-PID Tuning Parameter at 100% Load*

P	2798.253
I	2356.0528
D	820.2015
N	298.147
Δf	2.008×10^{-5}
Settling Time(t_s)	25.478
Peak Overshoot(M_p)	4.028×10^{-3}

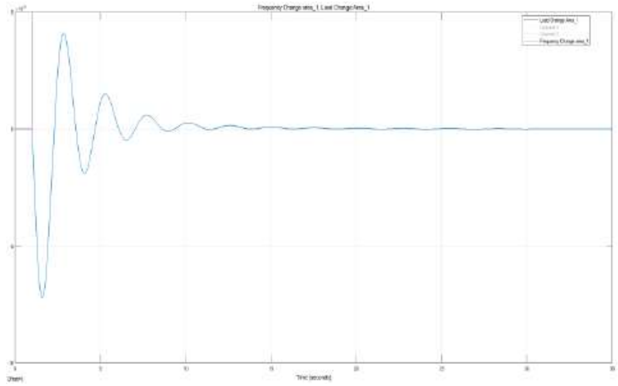

Fig 11. *Area Frequency Response for a Single area Power System Model wit 50% Load*

8.3 Two area interconnected power system at 100% load

The turbine transfer function is as follows:

$$P(s)=\frac{4.6799s^{2}+5.5319s+1}{9.7664s^{3}+23.8102s^{2}+15.1762s+1} \quad (37)$$

In order to reduce this to a FOPDT system we use mathematical approximations by breaking down P(s) into its factors

$$P(s)=\frac{(s+0.22)(s+0.95)}{(s+0.074)(s+1.046)(s+1.316)}=\frac{0.487(1+4.5s)(1+1.05s)}{(1+13.51s)(1+0.965s)(1+0.759s)} \quad (38)$$

The important property to remember here is that

$e\theta s=1+\theta s$

Putting this approximation in equation (1) we get the FOPDT system as: $P(s)=\frac{0.487}{13.998s+1}e^{-4.313s}$ (39)

Kp=0.487 τp=13.998 $\theta = 4.313$

As a result using the formulas for IMC Tuned PID the Parameters are obtained as follows with Kc=1.22

$Kc = 1.22\ \tau i = 16.1545 \tau D = 1.868$

Table 15. *Two Area IMC-PID Tuning Parameter at 100% Load*

Parameters	Area 1	Area 2
P	692.8135	50
I	196.9505	10
D	606.0845	100
N	224.9483	100
Δf	1.581×10^{-3}	
Settling Time(t_s)	22.6	
Peak Overshoot(M_p)	2.57×10^{-2}	

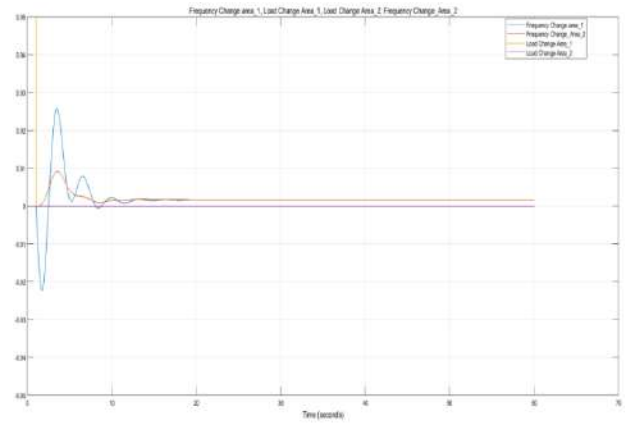

Fig 12. *Area Frequency Response for Two Area Power System Model with IMC-PID at 100% Load*

8.4 Two are interconnected power system at 50% load

$$P(s)=\frac{4.6799s^{2^{\wedge}}+5.5319s+1}{9.7664s^{3}+23.8102s^{2}+15.1762s+1} \quad (40)$$

In order to reduce this to a FOPDT system we use mathematical approximations by breaking down P(s) into its factors

$$P(s)=\frac{(s+0.191)(s+0.951)}{(s+0.068)(s+1.02)(s+1.45)}=\frac{0.556(1+5.23s)(1+1.05s)}{(1+14.705s)(1+0.98s)(1+0.68s)} \quad (41)$$

Putting this approximation $\theta s=1+\theta$in eqn(1) we get the FOPDT system as

$$P(s)=\frac{0.556}{15.195s+1}e^{-5.11S} \quad (42)$$

Kp=0.556 τp=15.195 $\theta = 5.11$

As a result using the formulas for IMC Tuned PID the Parameters are as follows:

Kc=1.158 τi=17.745 τD=2.187

After further tuning the new PID parameters are

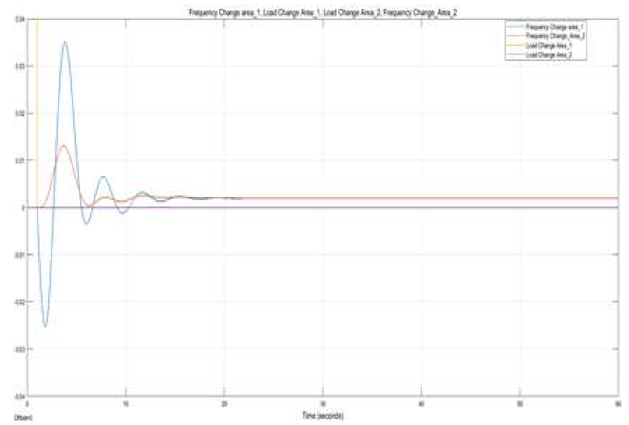

Fig 13. *Area Frequency Response for Two Area Power System Model with IMC-PID at 50% Load*

Table 16. *Two Area IMC-PID Tuning Parameter at 50% Load*

Parameters	Area 1	Area 2
P	51,32,497	50
I	166.417	10
D	392.868	100
N	188.629	100
Δf	1.917x10-3	
Settling Time(t_s)	20.202	
Peak Overshoot(M_p)	3.505x10-2	

9 CONCLUSION

The paper describes the methodology to derive the turbine model using dynamic parameters like the turbine time constants and power fractions of steam turbine generators obtained from the heat balance diagram data of a typical 660 MW steam turbine and finding the load dependent frequency response. Steam turbine time constant depends on the MW generation of the machine. The time constant for steam chest varies in the range of 0.688–0.819 s, for re-heater the range is 13.364-14.678 s, and that for the crossover is 0.867-1 s for a typical 660 MW machine. The power output of HP, IP and LP turbines at 100% rated condition are contributing 36.39, 29.79 and 33.81% of total power output respectively. As the MW load decreases, contribution of LP turbine in total power output decreases while that of HP and LP turbines increases. At 30% load HP, IP and LP turbine contributions are 42.27, 30.59 and 27.13% which means that LP turbine contribution has been decreased by 6.68% while that of HP and IP turbine have been increased by 5.88% and 0.8% respectively. Hence, the value of the turbine time constant should be selected based on the MW generation of the machine instead of arbitrarily selecting within the any defined range [34].

The PID controllers are well known and are widely used in power system and control systems to damp system oscillations, increase stability and reduce steady state error as they are simple to realize and easily tuned. It is seen that if the proper tuning of parameter of PID controller is done, the area frequencies could brought back to its predefined value or very nearer to its predefined value with acceptable tolerance so as the tie line power in minimum time, when there is sudden change in load occurs .

The area frequency response results show the comparison between conventional PID tuning and IMC based PID tuning and clearly differentiate that the frequency deviation for the IMC based data is less as compared to the Normal tuning method and even the settling time is also reduced. Simulation also results that for two area system IMC based PID controller is easy to implement and damping is improved when compared with the conventional PID controller.

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