Design of Contract Participation Factor based ALFC with Generator Rate Constraints

J Madhavan[1] and M Devesh Raj[2]
[1] Senior Lecturer, Dept of EEE, Kurinje Polytechnic College,
Cuddalore Main Rd, Kurinjipadi, Tamilnadu, India, 607302,
madhavanphd2023@gmail.com
[2] Associate Professor, Dept of EEE, Sri Sivasubramaniya Nadar
College of Engineering, Kalavakkam, Tamilnadu, India,
603110, deveshraj.m@gmail.com

Abstract: The increasing requirement for the distribution of renewable energy sources into the current power system is causing increased challenges with regards to system stability, specifically frequency response. Current Automatic Load Frequency Control (ALFC) methods developed for a centralized power system do not sufficiently meet the challenges of power system deregulation and the dynamic characteristics of renewable generation. This paper is focused on the development and implementation of an ALFC for a Contract Participation Factor (CPF) based power system with Generation Rate Constraints (GRC) through mathematical modeling of power system blocks. To ensure stable operation is maintained for the power systems, a control methodology is developed so that an equilibrium between generation and demand is maintained while minimizing the frequency deviation of the system. A proportional-integral-derivative (PID) controller is utilized for control actions, while optimizing the controller parameters, so therefore the control design provides improved dynamic performance and frequency stability through better transient response of the generation resource mix.

Keywords: Contract Participation Factor (CPF), Generational Rate Constraints (GRC), Proportional-integral-derivative (PID) controller, Dynamic performance.

1 INTRODUCTION

In an electrical power system, the key element for its reliable performance is the fact that the system operates at a constant frequency and provides a reliable power supply. The fundamental role of Automatic Load Frequency Control (ALFC) is to provide reliability by controlling generators power output based on the loads and the generation capacity of that system. ALFC has traditionally been implemented based on thermal generating units in a centralized power system; however, renewable sources of energy (solar and wind) have introduced unpredictable and intermittent resources that further complicated the frequency control [1].

When the deregulated context began, the structure of the power system transitioned from a centralized operation to that of companies (GENCOs) and market context that contained many DISCOs (Distribution Companies) competing independently with market contracts while affecting the load sharing and control action [2]. This study has the goal of presenting an appropriate ALFC model that considers renewable energy sources in a deregulated context while providing frequency stability and reliability based on variable conditions of load operating [3]. The motivation for this paper derives from the growing need to address serious issues associated with deregulated policies and renewable energy including intermittency, frequency deviation, and contract dispatching [4].

2 AUTOMATIC LOAD FREQUENCY CONTROL

In an electrical power system, the key element for its reliable performance is the fact that the system operates at a constant frequency and provides a reliable power supply. The fundamental role of Automatic Load Frequency Control (ALFC) is to provide reliability by controlling generators power output based on the loads and the generation capacity of that system. ALFC has traditionally been implemented based on thermal generating units in a centralized power system; however, renewable sources of energy (solar and wind) have introduced unpredictable and intermittent resources that further complicated the frequency control [1].

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However, this measure is not sufficient to return system frequency to its nominal frequency in the event of disturbance. To achieve this result after a disturbance, there is also a need for a secondary control, namely Automatic Load Frequency Control (ALFC), which consist of a proportional-integral-derivative (PID) controller with an adaptive control strategy [7]. The relevance of ALFC becomes more important in modern power systems as systems become more complex with deregulation and a more significant reliance on renewable resources [8].

3 THERMAL POWER SYSTEM MODELLING

3.1 Pipeline Overview and TFC Generation

The speed governing mechanism was modelled based on the assumption of small deviations from the steady state conditions. Assume that the system is initially at steady state, pilot valve is closed and linkage mechanism is stationary [9]. The linkage point A moves downwards by small amount due to command ΔPc

$$\Delta y_A = k_c \Delta P_c \tag{1}$$

The net movement of point C contributed by point A and flyball movement

$$\Delta y_C = -k_1 k_c \Delta P_c + k_2 \Delta f \tag{2}$$

Pilot valve opening movement due to point D

$$\Delta y_D = k_3 \Delta y_C + k_4 \Delta y_E \tag{3}$$

Volume of oil admitted to cylinder is proportional to the integral of ΔyD. The movement of Δy_E is given by

$$\Delta y_E = k_5 \int(-\Delta y_D)dt \tag{4}$$

Laplace transform of equations (2 – 4) and eliminating intermediate variables gives the pilot valve displacement $\Delta y_E(s)$ in terms of $\Delta P_c(s)$ and ΔF(s)

$$\Delta Y_E(s) = \frac{-Kg}{1+Tgs}(\Delta Pc(s) - \frac{1}{R}\Delta F(s)) \tag{5}$$

Where, Kg = governor gain, Tg = governor time constant and R = speed regulation

3.2 Non-Reheat Turbine Modelling

Non-reheat steam turbine has the simplest transfer function, consisting of single time constant (first order lag) block. The change in mechanical power output is related to the change in control valve position by the following transfer function:

$$\frac{\Delta Pm(s)}{\Delta Y_E(s)} = \frac{1}{1+T_t s} \tag{6}$$

Where, T_t = Turbine time constant, it represents the time delay caused by the volume of steam in the steam chest and turbine stages.

3.3 Generator – Load System Modelling

Generator dynamics in a power system are governed by the Swing Equation, which mathematically links the system's electrical power balance to the mechanical inertia of the rotating generator components.

Assume there is a real load change (P_D) for which, generator increases its output by an amount (P_G). The power increment in input to the system is defined in two ways:

Rate of increase of stored kinetic energy in the generator rotor. The kinetic energy stored is,

$$W_{ke} = H * P_r \tag{7}$$

Where, H = Inertia constant and P_r = Rating of the generator

The rate of change of kinetic energy is proportional to the rate of change of frequency given as,

$$\frac{d(Wke)}{dt} = \frac{2HPr}{f0} * (\frac{d(\Delta f)}{dt}) \tag{8}$$

The overall power balance equation relates the change in generated power (ΔP_g) and the change in load demand (ΔP_d) to the energy change in the rotating masses and the frequency-sensitive load component, dividing the equation by the rated power (P_r) converts it to the per-unit system,

$$\Delta P_{G,p.u.} - \Delta P_{D,p.u.} = \frac{2H}{f0}\frac{d(\Delta f)}{dt} + B_{p.u.}\Delta f \tag{9}$$

Taking the Laplace transform of Equation (9) and the transfer function becomes,

$$\Delta F(s) = \frac{\Delta P_G(s) - \Delta P_D(s)}{B(1+\frac{2H}{sBf0})} \tag{10}$$

$$\Delta F(s) = \Delta P_G(s) - \Delta P_D(s)(\frac{kp}{1+ sTp}) \tag{11}$$

Where, $K_P = 1 / B$ = power system gain constant and $T_P = 2H / Bf^0$ = power system time constant

3.4 PID Controller

The secondary Automatic Load Frequency Control (ALFC) loop, known as the integral control loop, is employed in power systems to return the frequency of the system and tie-line power (in areas with multiple area coordination) to its nominal values after a load disturbance occurs. The primary ALFC loop reacts very quickly to stop any deviation of frequency, however; the primary loop does not remove this frequency error. Instead, a small steady state error exists; due to the governor characteristics (R). The secondary ALFC loop removes the steady state error through integral control action [10].

The integral controller in the secondary ALFC loop can remove the steady state frequency error that remains after the primary ALFC loop action. However, the integral controller in the secondary ALFC is not able to improve transient response, meaning that it would not be beneficial for reducing overshoot, settling time, or oscillations. Thus, a Proportional-Integral-Derivative (PID) controller can usually be used for overall better control [11].

The Proportional term provides for a quick response for a frequency deviation, the Integral term removes the steady state frequency error, and the Derivative term improves system stability with prediction of future errors. Thus, the PID controller is able to not only restore the frequency to a nominal value, but also allows for faster and smoother correction with less oscillation and better damping. The mathematical form of PID controller will be,

$$u(t) = K_p e(t) + K_i \int_0^t e(t)\,dt + K_d \frac{de(t)}{dt} \tag{12}$$

Where, K_P = proportional gain, K_i = integral gain (= K_P / T_i if using integral time Ti), and K_d = derivative gain (= K_P * T_d if using derivative time T_d)

Tuning the PID Controller will aid in selecting proper values for proportion, integral, and derivative gains to achieve the desired dynamic performance of control system [12]. Proper tuning will ensure that the system has a quick response to load changes, to minimize overshoot and steady state error, and to ensure overall stability of the system. Tuning methods such as the Ziegler-Nichols method, trial and error, and auto-tuning methods available with some MATLAB commands can help to tune the PID parameters to achieve an optimal speed or frequency regulation [13].

4 DEREGULATION OF POWER SYSTEM

In a traditional power system, the generation, transmission, and distribution components are all overseen by one utility. This setup creates reliability but typically has no competition and no efficiencies either. With the intention for increased efficiencies, deregulation was born. Deregulation involves restructuring the power sector so that generation, transmission, and distribution are performed by separate entities. This opens the market to many power producers to come in and compete for business - achieving efficiencies, reducing power costs and improving service [14].

In this model, GENCOs are the producers of electricity, DISCOS deliver the electricity to end-use customers who have the ability to choose their power supplies, and an Independent System Operator (ISO) oversees the bidding process, manages the flow of power across the network, and ensures fair access to the network.

4.1 Operation of Deregulation

The operation of deregulation in power systems involves three main types of flows namely Power flow, Money flow and Information Flow, which together define how the system functions both physically and economically. The process starts with the information flow, in which data about bidding, demand, generation capacity and market prices are shared among GENCOs, DISCOs and the ISO. By this information, the power flow happens where electricity is produced and transmitted from the GENCOs through the transmission and distribution networks to reach consumers. Finally, the money flow goes in the opposite direction from consumers to DISCOs, and then to GENCOs as payment for the electricity they provided [15].

4.2 Contract Participation Factors (CPFs)

A Contract Participation Factor defines how much of a particular DISCO's demand is supplied by each GENCO. It indicates the economical contribution of every generator to meet the total contracted demand of each distribution company. CPFs are generally represented in the form of a participation matrix, where each cpfij specifies the portion of power that the ith GENCO provides to the jth DISCO [16].

For example, if there are two GENCOs (G1, G2) and two DISCOs (D1, D2), the contract participation matrix can be written as,

$$\begin{bmatrix} cpf11 & cpf12 \\ cpf21 & cpf22 \end{bmatrix}$$

Where, cpf11, cpf12 - fraction of D1's and D2's demand supplied by G1

cpf21, cpf22 – fraction of D1's and D2's demand supplied by G2

The sum of all participation factors for a DISCO should be equal to unity, ensuring that the total demand of each DISCO is completely met by the available GENCOs:

$$\sum_{i=1}^{n} cpf_{ij} = 1 \tag{13}$$

Through these CPFs, the load demand of each DISCO is distributed among multiple GENCOs as per contractual agreements. This helps in modelling load allocation, power-sharing and frequency control under deregulated conditions.

4.3 Generational Rate Constraints (GRC)

In practical power systems, the output power of a generator cannot change suddenly. Every generating unit has physical and mechanical limits on how fast its output can increase or decrease due to the thermal and mechanical factors of the turbine and governor. These limits are known as Generation Rate Constraints (GRC).

The GRC defines the maximum allowable rate of change of generation (in MW per second). It explains how quickly a generator can respond to changes in load demand or frequency deviation. This limitation plays a major role in ALFC studies, especially during transient conditions, as it affects how fast the system can come back to its nominal frequency.

$$-DR \leq \frac{dPg(t)}{dt} \leq UR \tag{14}$$

Where, dPg(t) / dt = rate of change of generation, UR= maximum upward generation rate limit (pu MW/s or MW/min) and DR = maximum downward generation rate limit (pu MW/s or MW/min)

5 CALCULATION AND RESULTS

The design of single area thermal power system has been made by modelling the transfer function of governor, non-reheat turbine, generators through calculation of power system gain and time constant, inertia constant, damping constant, speed regulation. To make this design into deregulated power system, we have calculated contract participation factors (CPF), DISCO Participation matrix (DPM) and Generational rate constraints (GRC).

For designing and calculation of single area thermal power system, parameters are taken from Elgerd book. Total rated area capacity (Pr) = 2000 MW (4 generators each of 500 MW), Total Operating Load (PD) = 1000 MW, Governor time constant (Tg) = 0.08 s, Turbine time constant (Tt) = 0.3 s, Rated Frequency = 60 Hz and Stored kinetic energy = 10000 MJ. DISCO Participation Matrix (DPM) has been designed for 4 GENCOs and 2 DISCOs with load demand of 250 MW and 300 MW respectively.

5.1 Simulation of Single Area Centralized Thermal Power System with Non-Reheat Turbine

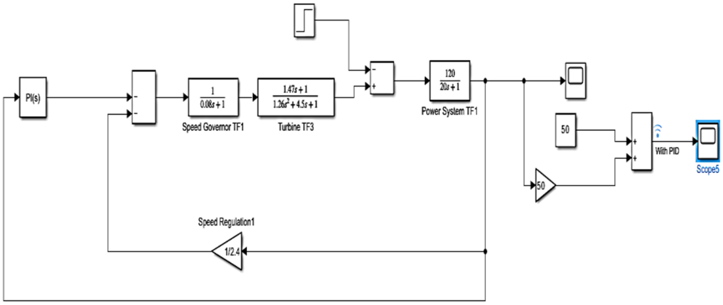

Fig. 1. Simulation of Single Area Centralised Thermal Power System

The simulation diagram of single area centralized thermal power system with ALFC is shown in Fig.1. Here, the primary and secondary ALFC loop were designed in the centralized thermal power system. The scope shows the frequency deviations of the centralized ALFC. The comparison of frequency regulation with respect to time, without controller, with P, I, PI and PID controller is shown in Fig.2.

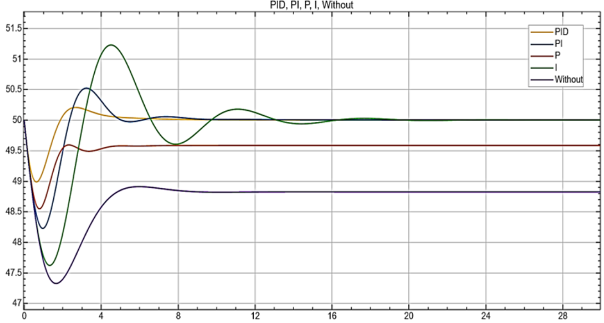

Fig. 2. Comparison of Frequency Regulation using different PID controllers

Table 1 shows the comparison of parameters for centralized ALFC which include rise time, settling time, maximum frequency deviation, peak time, steady state frequency of P, I, PI, PID and without PID respectively. This comparison is helpful in choosing proper PID controller to get the expected frequency regulation.

Table 1: Comparison Table of Results of different controllers for centralized ALFC

Controller	Rise time (ms)	Settling Time (sec)	Maximum Frequency Deviation (Hz)	Peak Time (sec)	Steady State Frequency (Hz)
Without	2.07	4.52	2.68	5.98	48.82
P	846.34	3.03	1.46	2.32	49.59
I	1157.7	10.4	2.38	4.52	50
PI	930.37	6.34	1.78	3.23	50
PID	846.53	4.99	1.02	2.68	50

From the Table 1, it is clear that PID controller works effectively on frequency regulation in the single area centralized thermal power system, it shows less peak and settling time in bringing back the frequency to nominal value.

5.2 Simulation of Single Area Contract Participation Factor based ALFC with Generator Rate Constraints

The simulation diagram of single area contract participation factor based ALFC with Generational Rate Constraints is shown in Fig.3. Here, the primary and secondary ALFC loop were designed in the deregulated thermal power system along with contract participation factor. The scope shows the frequency deviations of the deregulated ALFC. The comparison of frequency regulation with respect to time, with P, I, PI and PID controller is shown in Fig.4.

Table 2 shows the comparison of parameters for decentralized power system like rise time, settling time, maximum frequency deviation, peak time, steady state frequency of P, I, PI, PID respectively. This comparison is helpful in choosing proper PID controller to get the expected frequency regulation.

Table 2: Comparison Table of Results of different controllers for Contract Participation Factor based ALFC

Controller	Rise time (ms)	Settling Time (sec)	Maximum Frequency Deviation (Hz)	Peak Time (sec)	Steady State Frequency (Hz)
P	698.34	15.905	2.23	1.71	59.73
I	255.34	15.451	1.75	1.74	60
PI	322.72	15.512	2.52	1.93	60
PID	443.94	4.995	2.012	1.34	60

From the Table 2, it is clear that PID controller works effectively on frequency regulation in the single area deregulated thermal power system also, it shows less peak and settling time in bringing back the frequency to nominal value, comparing to other controllers.

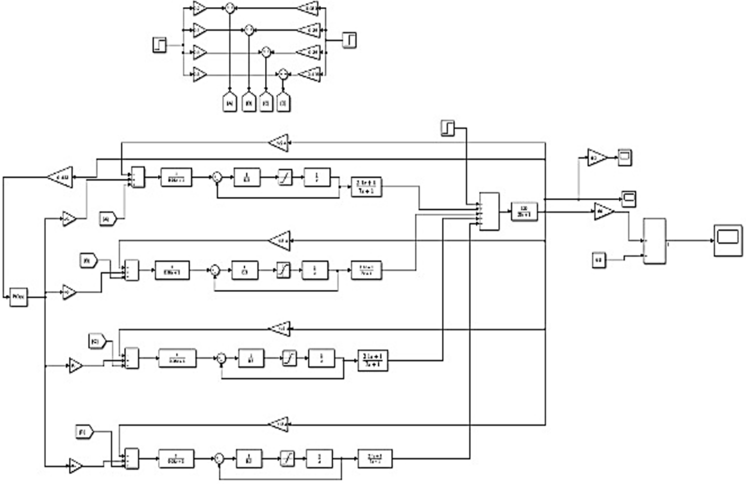

Fig. 3. Simulation of Contract Participation factor based ALFC

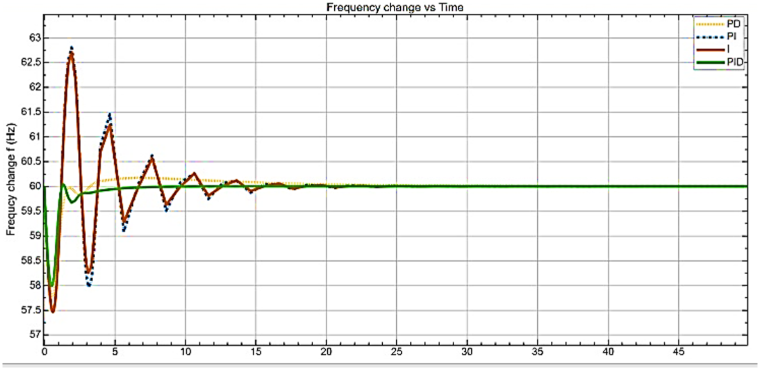

Fig. 4. Comparison of Frequency Regulation using different PID controllers

Simulation results prove frequency regulation to be effective using both Centralized and Deregulated CPF/GRC-based configurations. As expected, the Centralized System PID controller produced the fastest disturbance rejection of any controller with the least amount of overshoot and quickest settling time. Without control, the highest frequency deviation peaked at ~2.68 Hz; however, the PID loop reduced the highest peak frequency deviation to approximately 1.02 Hz and returned the frequency to nominal much faster (rise time ≈846 ms, settling time ≈ 4.5 seconds). This is consistent with typical ALFC behaviour; adding integral and derivative actions to controllers significantly improves the transient damping of the system. In the Deregulated (CPF/GRC-based) case, similar results occurred, with the PID Controller completely restoring the frequency to its nominal value (60Hz) with a settling time of approximately 5 seconds. When used in place of the PID, both PI and PD controllers took approximately 15 seconds to settle and had slightly greater residual frequency deviations. Realistic generation rate constraints (GRC) and contract participation factors (CPF) can be imposed on the system without causing the system to destabilise. Both the unconstrained contract and the GRC-constrained contract produce stable and comparable simulation results. In particular, as noted in [8], The PID Controller consistently generated the best dynamic response in both cases and this is confirmed here. The CPF matrix (DPM) represents how much total generated load will be shared among generators, with each CPF entry representing how much of a DISCO's demand is fulfilled.

6 CONCLUSION

In this paper, we have successfully simulated and analyzed a single area contract participation factor based Automatic Load Frequency Control (ALFC) under a deregulated environment for thermal power system, which was our main objective. The paper findings showed that the PID controller successfully minimized the frequency deviation and overall, even though slightly improved system stability, compared to simple proportional or integral control.

Decentralization and Multi-Agent Control: Future research could also be directed at developing a decentralized scheme for automatic frequency load control (ALFC). In this approach, all generating companies (GENCOs) or areas would have local or individual controllers, with only minimal coordination required between them. Decentralized or distributed schemes would help to improve the reliability (by eliminating single-point failures) and expand the capacity of deregulated networks. The multi-agent system concept may also be applicable to AGC frequency regulation in a continuous power flow (CPF) model.

Dynamic Contract-Based Dispatch: A variation of the CPF model would be to create a more dynamic contract market that allows for dynamic pricing and other contract options. Dynamic contracts may require automatic or real-time changes in CPF parameters and controller set points. The potential for developing smart contracts or blockchain technology as platforms for automatic execution of contracts also exist. Researching how to integrate the AGC and market systems will create a synergy between both systems, allowing compliance with power purchase agreements (PPAs) while maintaining stable operating conditions.

Practical Challenges of Implementing CPF: There are several practical challenges to be addressed in order to implement CPF-based load frequency control (LFC). These challenges include communication delays, uncertainties in LFC parameters, and varying renewable generation capabilities. Future research should address LFC's ability to cope with CPF uncertainties through robust, adaptive control methods. In addition, future research could also develop algorithms capable of accommodating both contract violations (where schedule areas dispatch in excess of contract management) and resistance from competitors to comply with agreements (for example, disputes between independent system operators (ISOs) or OSI).

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