PID controller design for load frequency control: Past, Present and future challenges

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Abstract: In this paper, a brief literature review for the design of a PID controller for load frequency control (LFC) in power systems is presented. The transfer function models for various configurations of power systems are developed. For a systematic presentation of the review, the PID tuning schemes are categorised into soft computing techniques, robust control schemes, fractional order based PID design and internal model control (IMC) based PID design approaches. Due diligence has been taken to include all the design schemes. Further, the paper also enlists various future challenges that are still unresolved and can form the basis of future research work.

Keywords: PID control, Disturbance rejection, Fractional order PID, Robust control, Mathematical models

1. INTRODUCTION

We know that both the active and reactive power requirements of a power system are never steady since the consumer load and industrial load are continuously varying. Consequently, input supply, i.e., steam input to turbo-generators or water input to hydro generators must be regulated properly, else there can be variation in machine speed and hence a change in frequency which is highly undesirable in the power system operation. Theoretically, one can make the change in frequency as zero, but, in practice, it is not possible. Thus, there is a certain permissible limit for the variation in frequency. Larger deviations in frequency will have a detrimental effect on the consumer end and may lead to an extensive damage of the costly equipments in the industry. Today, all the systems are interconnected in nature. Therefore, power system problem is nothing but a multi-area system problem. Thus, it is highly challenging task to maintain frequency constant. In a modern large scale interconnected system, manual regulation is not effective, leading to the need for automatic digital control which has its own set of problems like communication delays.

The deviations in frequency call for the need to design a controller which should be robust and most importantly simpler in nature. It is known, that more than 90% of industries still employ PID controllers owing to their simplicity, clear functionality and ease of use. But, many control practitioners pointed out that a PID controller tuned via conventional approaches was not robust. Therefore, there was a need for advanced control techniques such as sliding mode control, H-infinity, Quantitative feedback theory(QFT), Linear matrix inequality (LMI) based techniques, etc. At the first glance, it appeared that these techniques are better than the PID control design but subsequently it was observed that these controllers are complex and encounter problems of robustness in an uncertain environment.

The widespread use of PID and the drawbacks of optimal control techniques made the researchers feel that there was a need to combine the simplicity of PID controllers with optimal tuning approaches. It was observed that such a controller yields better results in case of parametric uncertainties, disturbance rejection and also in the case of non-minimum phase behaviour. In this paper, a brief review of various PID based control schemes is presented. The main purpose of this paper is to summarize various controller designs for LFC problem that have been proposed in the recent past. The paper is organized into a number of sections as follows: section 2 discusses the motivation behind LFC and section 3 emphasises on the importance and the need for LFC. Section 4 presents the mathematical modelling of a power system. In section 5, the overall transfer function models are developed for systems consisting of different types of turbines. A brief summary of the various PID based control schemes is presented in section 6. Finally, the future challenges of LFC are presented and the conclusions are drawn in section 7.

2. MOTIVATION

It has been reported in various publications about the increasing number of power grid blackouts observed in the recent years. For example, in 1999, there was a blackout in Brazil, in August, 2003, in Northeast USA-Canada, and in 2005, in Russia. In fact, as recently as in July 2012, India suffered the largest ever power outage in the history affecting over 620 million people, which is equivalent to 9% of the world population. In order to avoid these issues, there is need for the load frequency to be constant. The frequency deviation can directly impact the power system operation. The large deviation can

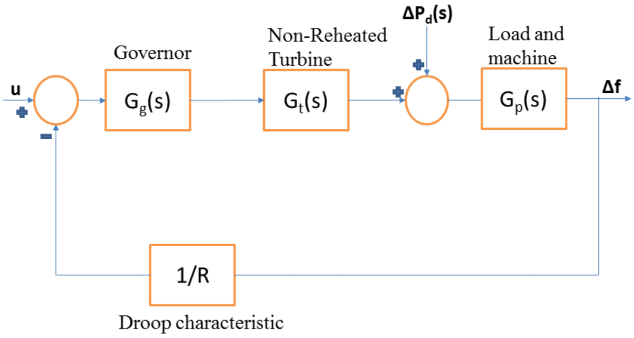

Fig. 1. Linear model of a single-area power system

damage the equipments, demean the load performance, affect the various protection schemes in power systems and sometimes lead to a system collapse. Thus, it is important to keep the system frequency within allowable tolerance range. In order to handle the issues related to frequency variations, effective robust control strategies are needed which can improve the performance of the system as well as system security. It is found that the most important and simple controller to handle these issues is PID type controller. Therefore, there is need to explore various PID and its variants such as two degree freedom PID type controller, fractional order PID controller, IMC based PID controller, etc. Along with this, there is a need to make PID a robust controller which can handle parametric uncertainty, disturbance rejection, effect of noise and the effect of communication delay.

3. AIMS OF LFC

The performance of a complex power system unit deteriorates due to degradation in power quality caused by load perturbation which results in deviation in tie-line power interchange and fluctuation in area frequency. Thus, the use of LFC is paramount to withstand the undesirable effects on the system due to load disturbances, parametric uncertainties, non-linearities, etc.

The principle aims of LFC are:

(1) Maintaining a constant frequency (zero steady state error in a minimum time from the onset of disturbance)
(2) To withstand load disturbance and counteract it.
(3) To minimise unscheduled power flow between neighbouring areas.
(4) To make a power system robust to parametric uncertainties and non-linearities.
(5) To maintain acceptable time response specifications within a specified margin of error.

4. TRANSFER FUNCTION MODELS OF LFC

A power system is normally a large scale system with complex nonlinear dynamics. But, for the purpose of load frequency control, it can be approximated by a linear model, linearized about the operating point. The major components of a single area power systems (Kundur et al. (1994), Shayeghi et al. (2009)) are alternator, turbine, governor and load. Fig. 1 depicts the linear model of a single area power system consisting of various components as discussed herein. The nomenclature of different system parameters is given in Table 1. The dynamics of different components of the power system are given as follows:

Table 1. Nomenclature: Power system parameters

c	Percentage power generated in reheat portion
Δf	Incremental frequency deviation (Hz)
K_p	Electric system gain
ΔP_d	Load disturbance (p.u.MW)
R	Speed regulation due to governor action (Hz/p.u.MW)
T_g	Governor time constant (s)
T_p	Electric system time constant (s)
T_r	Reheat turbine constant (s)
T_t	Turbine time constant (s)
T_w	Time constant of hydro turbine (s)
u	Input to the power system

Governor

$$G_g(s) = \frac{1}{T_g s + 1} \tag{1}$$

Turbine : A turbine could be classified into non- reheated turbine, reheated turbine and a hydro turbine. Depending on its type, its transfer function models are given as follows:

Non Reheated turbine

$$G_{t1}(s) = \frac{1}{T_t s + 1} \tag{2}$$

Reheated turbine

$$G_{t2}(s) = \frac{cT_r s + 1}{(T_r s + 1)(T_t s + 1)} \tag{3}$$

Hydro turbine

$$G_{t3}(s) = \frac{1 - T_w(s)}{1 + 0.5T_w(s)} \tag{4}$$

Load and machine

$$G_p(s) = \frac{K_p}{T_p s + 1} \tag{5}$$

The transfer function of the overall system without droop characteristics can be computed as follows:

$$G_{wd}(s) = G_g(s)G_p(s)G_{ti}(s) \tag{6}$$

where, $i = 1, 2, 3$.

On the other hand, the transfer function of the overall system with droop characteristics is given as

$$G_d(s) = \frac{G_g(s)G_p(s)G_{ti}(s)}{1 + \frac{G_g(s)G_p(s)G_{ti}(s)}{R}} \tag{7}$$

where, $i = 1, 2, 3$.

5. TRANSFER FUNCTION MODELS OF SINGLE AREA SYSTEMS

The overall transfer functions of power system comprising of non-reheated turbine, reheated turbine and hydro turbine with and without droop characteristics are elucidated below.

Non-reheated turbine: The transfer function of a non-reheated turbine is a third order model which can be formulated as follows:

$$G_1(s) = \frac{K_p}{as^3 + bs^2 + cs + d} \tag{8}$$

where a, b, c, d depend on the parameters of the turbine.

Without droop characteristics: The transfer function for the system having no droop characteristics is given by (8) and computed via (6), resulting in the following values of a, b, c and d.

$a = T_g T_p T_t$, $b = T_g T_p + T_g T_t + T_p T_t$, $c = T_g + T_p + T_t$, $d = 1$

With droop characteristics: The transfer function for the system with droop characteristics is of the form given in (8) wherein the following values of a, b, c and d are obtained using (7).

$a = T_g T_p T_t$, $b = T_g T_p + T_g T_t + T_p T_t$, $c = T_g + T_p + T_t$,

$d = 1 + \frac{K_p}{R}$

Reheated turbine: The transfer function of a reheated turbine is a fourth order model which can be expressed as follows:

$$G_2(s) = \frac{as + b}{cs^4 + ds^3 + es^2 + fs + g} \quad (9)$$

where a, b, c, d, e and f depend on the parameters of the turbine.

Without droop characteristics: The transfer function for the power system in the absence of droop characteristics is given by (9) with the following values of a, b, c, d, e, f and g.

$a = K_p c T_r$, $b = K_p$, $c = T_g T_p T_r T_t$,

$d = T_g T_p T_t + T_p T_r T_t + T_g T_p T_r + T_g T_r T_t$,

$e = T_g T_p + T_g T_t + T_g T_r + +T_p T_t + T_p T_r + T_t T_r$,

$f = T_g + T_p + T_r + T_t$, $g = 1$

With droop characteristics: The transfer function for the power system with droop characteristics is of the form of (9) with the values of a, b, c, d, e, f and g given as:

$a = RK_p c T_r$, $b = RK_p$, $c = RT_g T_p T_r T_t$,

$d = R(T_g T_p T_t + T_p T_r T_t + T_g T_p T_r + T_g T_r T_t)$,

$e = R(T_g T_p + T_g T_t + T_g T_r + +T_p T_t + T_p T_r + T_t T_r)$,

$f = R(T_g + T_p + T_r + T_t) + K_p c T_r$, $g = R + K_p$

Hydro turbine: The transfer function of a hydro turbine is a third order model which can be presented as follows:

$$G_3(s) = \frac{as + b}{cs^3 + ds^2 + es + f} \quad (10)$$

where a, b, c, d, e and f depend on the parameters of the turbine.

Without droop characteristics: The transfer function for the power system without droop characteristics is given by (10) with the following values of a, b, c, d, e and f.

$a = -K_p T_w$, $b = K_p$, $c = 0.5 T_g T_p T_w$,

$d = T_g T_p + 0.5 T_p T_w + 0.5 T_g T_w$, $e = T_p + T_g + 0.5 T_w$, $f = 1$

With droop characteristics: The transfer function for the power system with droop characteristics is of the form given by (10) with the following values of a, b, c, d, e and f.

$a = -RK_p T_w$, $b = RK_p$, $c = 0.5 T_g T_p T_w R$,

$d = R(T_g T_p + T_p T_w + 0.5 T_g T_w)$,

$e = R(T_p + T_g + 0.5 T_w) - K_p T_w$, $f = K_p + R$

6. BRIEF REVIEW OF PID BASED CONTROL TECHNIQUES

LFC is basically a disturbance rejection problem wherein the primal objective is the minimisation of frequency deviations and unwanted tie line interchange. Various control schemes for the design of PID controller are given in literature. Here, we have broadly classified them into IMC based control techniques, fractional order (FO) based control techniques, soft computing approaches and robust control schemes.

6.1 IMC based control

Internal model control (IMC) is a well laid out mechanism for controller design based on Q parameterization concept and has been developed for integer order (IO) as well as fractional order (FO), SISO and MIMO continuous time and discrete time systems. It provides a good trade-off between a robust controller and an optimal controller. A detailed literature review of IMC scheme is presented by Saxena and Hote (2012). It is primarily used in process control industries owing to steady state error minimisation and good disturbance rejection properties. In Liu (2009), a TDF-IMC design is studied for a single machine infinite bus system with non reheat, reheat and hydro turbine. A unified PID tuning method based on a two degree of freedom (TDF) IMC approach and PID approximation procedure is proposed by Tan (2010) for a single area power system comprising of a non-reheated, reheated and hydro turbine. A reduced order model obtained via Logarithmic approximations is utilized for the design of 2 DOF IMC-PID controller for a single and two area reheat hydrothermal power system in Singh et al. (2017) and is observed to exhibit an excellent dynamic response and robustness to load disturbance. In Tan et al. (2010), a decentralised LFC is tuned for multi area power system with communication delays via TDF-IMC tuning technique. The studies discussed above are solely based on the design of integer and fractional order PID for LFC problem. Apart from these, various other IMC based control designs for LFC problem are given in Saxena and Hote (2013) and Avvari et al. (2017).

6.2 Fractional order based control schemes

A fractional order (PID) can be thought of as a natural extension of a traditional PID controller and can be mathematically formulated as follows:

$$C(s) = K_p + \frac{K_i}{s^\lambda} + K_d s^\mu \quad (11)$$

These days, FO systems have garnered immense interests since a real world system can be better characterized by a FO differential equation. A FOPID increases the degree of freedom by 2 over an integer order PID controller. Existing studies have confirmed that a best FOPID controller will always surpass the performance of a best integer order PID (IOPID) controller(Chen et al. (2009)). Owing to its advantages, FOPID has been extensively used in LFC design. Sondhi and Hote (2014) designed a FOPID controller via stability boundary locus (SBL) for three types of turbine, i.e., non-reheated, reheated and hydro turbines. An exhaustive comparative analysis validated the robustness and load disturbance rejection capability of the proposed controller. In Ahuja et al. (2014), the parameters of a FOPID controller are tuned via PSO meta-heurisic search technique, whereas in Topno and Chanana (2016), Differential evolution (DE) has been utilized for obtaining the controller parameters for a two area hydrothermal power system. A FOPID controller is designed for an interval model of the single area LFC via Kharitonov's theorem in Sondhi and Hote (2016) and is found to be robust to a larger range of system parameter variations as compared to the existing controllers. It also gives a choice of range of parametric variations desired by the control practitioner. In Alomoush (2010), the authors have investigated LFC and automatic generation control (AGC) for interconnected and isolated power system via FO controllers which results in an improvement in the stability and time response. Conflicting design objectives are contemplated by Pan and Das (2015) for a multi objective based LFC to tune the gains of FOPID controller in an interconnected power system. Chathoth et al. (2015) have implemented FOPID as a supplementary controller for the enhanced performance of an interconnected multi area deregulated power system and it is found to best amongst integer order hybrid fuzzy PI controller, GA tuned PI controller and GA tuned PID controller. A hybrid linear FO fuzzy PID (FOFPID) controller is applied to Egyptian power system in Ghany et al. (2016) and the results are compared with integer order PID tuned via bacterial foraging algorithm (BFA) and a FOPID tuned via genetic algorithm. The FOFPID is found to exhibit better performance in comparison to the existing techniques in the literature. The FO controllers have thus been combined with existing tuning techniques and have introduced an exciting field for further research in the field of LFC.

6.3 Soft computing

Soft computing techniques belong to the Computational Intelligence (CI) family, which comprises of a vast number of innovative heuristic search techniques inspired from broadly four branches like mathematics, biology, physics and chemistry. A total of 134 such techniques are enlisted in Bo Xing (2014). Some of the widely known and popularly used are Genetic algorithm (GA), Particle swarm optimization (PSO), Big Bang Big crunch algorithm (BBBC), Firefly algorithm (FFA), Base optimization algorithm, etc. They exploit a combination of randomness, tolerance to imprecision and inductive reasoning to circumvent the problems observed in the traditional optimization algorithms. Owing to their numerous advantages, researchers have also applied them in the tuning of parameters of PID in LFC problem. In Kumar et al. (2017), BBBC algorithm has been utilized to tune the parameters of a fractional order PID controller owing to its more flexible nature as compared to a traditional PID controller, whereas in Yesil (2014), same algorithm is used to tune the scaling factor and footprint of uncertainty (FOU) for the membership functions of an interval type-2 fuzzy PID controller. Dhillon et al. (2015) have employed a combination of fuzzy based inferences and PSO algorithm to efficiently tune a PID controller for a five area LFC model, and Jagatheesan et al. (2017) have used FFA to optimize the parameters of a PID controller and compared the results with GA and PSO. In Ahuja et al. (2014), PSO algorithm is used to obtain a robust FOPID controller for a single area non reheated type power system. In Zamani et al. (2016), the authors have incorporated the advantages of Gases Brownian Motion Optimization (GBMO) and fractional order to design a FOPID controller by taking consideration of the saturation limits of the governor, while in Sahu et al. (2013), differential evolution (DE) is employed to design a 2- degree of freedom PID controller for a realistic power system which incorporates the effects of physical constraints such as time delay, generation rate constraint (GRC) and governor dead band (GDB). Further, the superiority of the proposed approach is demonstrated by comparison of the results with Craziness based PSO (CPSO) for an interconnected two area thermal system and the authors have used an modified objective function which is derived by using weighted integral time absolute Error (ITAE), damping ratio of dominant eigenvalues, settling times of frequency and peak overshoots. A two degree of freedom based proportional integral double derivative (PIDD) controller is presented by Debbarma et al. (2015) for a three unequal area thermal system and is found to be robust for wide change in the position of step load perturbation (SLP). A new optimization technique called as quasi-oppositional grey wolf optimization algorithm (QOGWO) is used for the first time to solve a LFC problem in Guha et al. (2016) and the results are compared with other intelligent methods like fuzzy logic, artificial neural network (ANN) and adaptive neuro-fuzzy interface system (ANFIS). Further, sensitivity analysis is performed to investigate the robustness in an uncertain environment. Apart from the aforementioned techniques, several other soft computing based techniques are elucidated for LFC problem in Yesil et al. (2014), Abdelaziz and Ali (2016), Abdelaziz and Ali (2015) and El-Hameed and El-Fergany (2016).

6.4 Robust control schemes

Robustness can be simply defined as the ability of the system to withstand changes in parameters, uncertain environment, measurement noise, load disturbances, etc. It is the capacity of system to perform optimally, provide that the uncertain parameters are found within a typically compact set. Thus, trade-off between robustness and performance is one of the key issues of controller design. Various robust techniques include linear quadratic Gaussian (LQG) control, quantitative feedback theory (QFT), H-infinity, Lyapunov based control, etc. In Tanaka et al. (2016), a control method is proposed based on H-infinity control theory for a power system with distributed generation (DG) and validated via power transmission simulator. The proposed technique results in the suppression of maximum frequency-deviation parameter and there is a marked reduction in overall frequency deviation also. Davidson and Ushakumari (2016a) suggest a decentralized PID control via H-infinity approach based loop shaping method for a two area deregulated power system. The proposed approach is advantageous as compared to the conventional H-infinity controller as it simplifies the trial and error procedure to obtain various weighting functions. In Hanwate et al. (2018), an adaptive scheme for LFC is reported for different cases of single and multi-area power systems to achieve an improved performance. A new robust PID design based on QFT and convex-concave optimization is developed in Mercader et al. (2017). The design problem is articulated as a convex-concave optimization problem and it extends the MIGO method to include process uncertainty characterized by a set of plants. In Satpati et al. (2008), PSO algorithm is employed in a reduced order robust controller design for a non-minimum phase hydro power plant to ease the computational effort and automate the loop shaping stage of QFT design. Various other approaches based on QFT are elucidated in Khodabakhshian et al. (2006), Khodabakhshian and Golbon (2005) and Davidson and Ushakumari (2016b). Yazdizadeh et al. (2012) presented a decentralized robust optimal MISO PID controller based on characteristic eigen values and Lyapunov method. Further, the proposed scheme is validated on a practical control area comprising of Karoon3 and Dez hydro power plants in Khozestan which is a province is southwestern part of Iran. Apart from these, a few other robust control techniques are elucidated in Horie et al. (2017) and Khooban et al. (2016).

7. CONCLUSION AND FUTURE CHALLENGES

A brief literature review of the recent PID tuning techniques for load frequency control is done in this paper. The authors have attempted to include most of the advances in the PID design, but the presence of omissions is inevitable, considering a extremely large number of papers that are published in this area each year. The primary challenge in LFC is to develop a highly robust PID controller that maintains frequency deviation strictly in specified limits even in the presence of nonlinearities like Governor deadband (GDB) and Generation Rate constraint (GRC), physical constraints and uncertain environment and validate it on an appropriate hardware setup. Further, there is a need of proper investigation on the effect of communication delay for transmitting the control signal from control center to remote terminal unit and ways and means to minimise it. Thus, there is an ample scope of research that the future publications can focus on to further robustify the power system.

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