Design and Analysis of IMC based Load Frequency Controller for NMP - Hydro Turbine Power System

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Abstract:
Electricity is essential for human life. Literature review shows that power grid failure may cause blackout; many people get affected due to these blackouts. For power generation, different turbines are used viz. steam turbine, gas turbine, hydro turbine, etc. Load Frequency Control (LFC) or automatic generation control is a very crucial parameter in power system control that needs to be tackled. It is observed that traditional controllers like PID controllers and soft computing-based controllers are designed to address the problem faced by most of the power systems. Literature indicated that there is scope to design an efficient and advanced controller for such a critical power system. This paper is a sincere attempt to design and analysis of IMC based controller for a non-minimum phase behaviour type hydro turbine power system. The performance of the designed IMC controller for load change scenarios is presented. Simulation results show the efficacy of the IMC controller and are one of the good options for a non-minimum phase (NMP) hydro turbine power system(HTPS).

Keyword: Load Frequency Control (LFC), NMP, IMC, Hydro Turbine Power System

I. Introduction

Electricity plays a vital role in our day-to-day life. Our day starts with electricity and ends with electricity i.e., starting from electric vehicles or kitchen appliances like mixer, grinder, electrical hotplate cooktop, fridge, etc. to cell phones, television, personal computers, etc., and many more. We can’t imagine life without electrical power. Also, electrical energy/power is the energy that gets easily converted into other forms of energy like heat energy, light energy, etc. Electrical energy is nothing but electrical power is very easy to control. For example, we can control the speed of the fan, or we can easily change the room temperature by adjusting the air conditioner’s set point; that means heat energy manipulation is done when input is merely electrical energy. While talking about industries all the equipment required directly or indirectly the electrical energy. The important aspect of this energy is it can be easily transmitted from generation point to its consumption over long distances with the help of overhead transmission lines. Thus, electricity is a very essential thing in the current digital world. Human life will stand still if electricity fails.

Researchers have designed many controllers to overcome the problem of an imbalance in the power system. Optimization of fuzzy self-tuning PID controller design based on Tribe-DE optimization algorithm is done and rule weight adjustment method for load frequency control of interconnected multi-area power systems which has the advantages of good transient behaviour, less sensitivity to parameter variations and load disturbances as well as the obtained results confirmed the integrity of this approach [1]. The robust PID controller for load frequency control of a non-minimum phase hydropower plant is reported which guaranteed robust stability and a good disturbance rejection ratio [2]. S. K. Pandey et al have done a considerable literature review of load frequency control (LFC) in power systems in 2013. The author tried to cover various configurations of power system models and control techniques & strategies that alarms LFC issues have been spoken in conventional as well as a distribution generation-based power system.

The traditional power systems which have essential parts consist of generation of electricity and transmissions of the same to a different area. The non-conventional energy source plays a vital role due to the diminution of fossil fuel and threats to environmental pollution in the 21st century. The LFC problem is significant concern in the traditional and D.G. distribution power generation viz. thermal, hydro, and nuclear. LFC issues for the D.G. system is considered and emphasis is given to it [3]. A robust distributed model predictive control (RDMPC) based on linear matrix inequalities is designed and successfully attained robust performance [4]. A review of the PID controller is done by addressing future requirements in LFC control [5]. The author reviewed the different models of a transfer function of various arrangements of power systems and PID controller designing and tuning. Categorization of these controllers is addressed like soft computing techniques, IMC-PID controller, robust control techniques, and fractional order PID controller. The challenges in LFC in power systems are also investigated like to cultivating a high robust PID controller which can maintain variations in frequency strictly in identified bounds [5]. The second major problem of the delay in transmission of the control signal is also addressed with more robust controller. The IMC-PID controller for reduced order model is designed which achieved robustness against load distribution and good dynamic response with the higher order system [6]. Literature shows that different optimization techniques are used in a controller design some of them are particle swarm optimization (PSO) [2], bat inspired algorithm based dual mode PI controller [7], Artificial Cuckoo Search Algorithm [8], and Grey wolf optimization [1], etc. Also, artificial intelligence, machine learning, deep learning, emotional learning, etc. soft computing techniques are developed in the recent past.

The power systems are the interdependent control areas through tie lines. The generators in a control area always vary their speed together (speed up or slow down) for maintenance of frequency and the relative power angles to the pre-defined values in both static and dynamic conditions. Day by day consumption of electricity is increasing drastically. Technical investigations are done by many researchers in this area, and as per their findings, when power systems are interconnected [6], any minor change in load can cause “a major change”, i.e., variation of power in tie line [9][10]. In this case, the very first objective of managing the Load frequency is to balance an important frequency as well as the power output within the interconnected area in megawatt [11]. Also, it’s a challenging task to control a non-minimum phase (NMP) hydro turbine power system [12] due to its pernicious time domain behaviour [13].

Literature reports the design of conventional controllers for the power system. Variants of PID controllers and their performance analysis are presented [14][15]. The performance of the existing controller is not satisfactory for load conditions. It is observed that there is scope to design a robust controller for the hydro turbine power systems. Even a hydro turbine is a non-minimum phase system [16]. This paper presents the design and analysis of IMC based controller for a non-minimum phase behaviour type hydro turbine power system. The performance of the designed IMC controller for load change scenarios is presented. Simulation results show the efficacy of the IMC controller and are rather a good choice for a non-minimum phase (NMP) hydro turbine power system.

The paper is organized as, section 2 covers the mathematical modelling of hydro turbine power system starting from basic water velocity through penstock and mechanical turbine power to linearized model of hydro turbine power system. In section 3, the design and development of IMC controller with different filter designs is carried out. Also glimpse of different existing controller designs for HTPS are cited. Section 4 is dedicated to simulation of closed loop system with step response analysis with graphical representation of output variation with variation in IMC controller parameters. The conclusion of the work and future work is discussed in section 5.

II. Modelling of Hydro Turbine Power System

The Hydro Turbine Power system which is nonlinear [17] can be mathematically modelled by simply using water velocity v_w coming down via the penstock and mechanical power of turbine MP_T. The mathematical expressions are given in Eq. (1) & Eq. (2):

$$v_w = \alpha P\sqrt{h}, \qquad Eq.(1)$$

$$MP_T = \beta h v_w, \qquad Eq.(2)$$

where,

P is the Gate position,

h is the hydraulic head at the gate,

α & β are proportionality constants.

After linearization, the transfer function [18] can be written as shown in Eq. (3): -

$$\frac{\Delta MP_T}{\Delta P} = \frac{1 - sT_w}{1 + 0.5sT_w}, \qquad Eq.(3)$$

where $, T_w$ is the time required for a hydraulic head h_0 to rush water from penstock to halt with zero velocity.

The generalized block diagram of the Non minimum Phase Hydro Turbine Power system [20] with droop characteristics is shown in Fig. 1. Block diagram consists of a governor, hydro turbine, generator and load connected in series. The change in load frequency ΔP_L is a disturbance to the plant which is generally considered 20%.

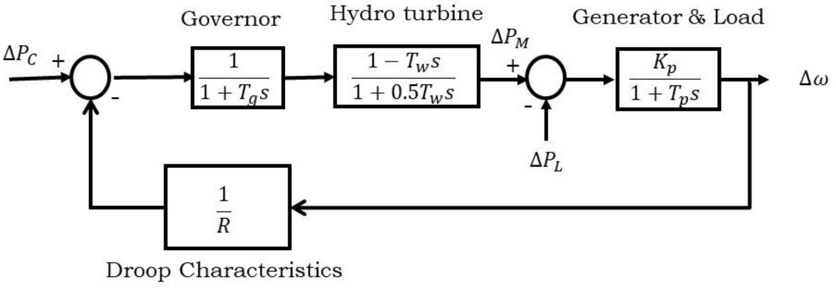

Fig. 1: Non minimum Phase Hydro Turbine Power system with droop characteristics.

The transfer function of the above block diagram can be simplified using a simple block reduction method (neglecting droop characteristics) as shown in Eq. (4).

$$\frac{\Delta\omega}{\Delta P_C} = \left(\frac{1}{1+T_g s}\right)\left(\frac{1-T_w s}{1+0.5T_w s}\right)\left(\frac{K_p}{1+T_p s}\right). \qquad Eq.(4)$$

For plant mathematical modelling with droop characteristics,

$K_p = 1, T_p = 6, T_w = 4, T_g = 0.2, R = 0.05$ are as used by Soumyadeep (2018).

There for final transfer function can be written as shown in Eq. (5).

$$G_p(s) = \frac{\Delta\omega}{\Delta P_C} = \frac{(1-4s)}{(2.4s^3 + 13.6s^2 + 8.2s + 21)}. \quad Eq.(5)$$

III. Proposed of IMC based controller

Internal Model Controller (IMC), is a model-based control strategy. Good setpoint or input tracking i.e. no overshoot after reaching to setpoint and disturbance rejection can be achieved using IMC. It also removes the steady state error efficiently [32]. IMC tuning rules are less sensitive to positive errors. The available model of plant and controller design depends on a tuning parameter of the IMC filter.

a. Existing controller for HTPS

The Hydro Turbine Power system is non-minimum type of system as its zero lies in the right half of the S-plane; in addition to that it is a non-linear system [12]. So, controlling such a system which exhibits parametric changes when load disturbance happens is a very tedious task [16], which requires proper tunning of the controller. Traditional PID controller [19] with QFT method [18] and various robust controllers like sliding mode controller [24][26], H-infinity controller, fuzzy logic controllers [1][15] are used till date to control NMP hydro turbine power system.

b. The Procedure of designing IMC based controller:

The basic structure of IMC based controller closed loop system is shown in Fig. 2 [19]. $\tilde{G}(s)$ is the plant model designed to track the original plant.

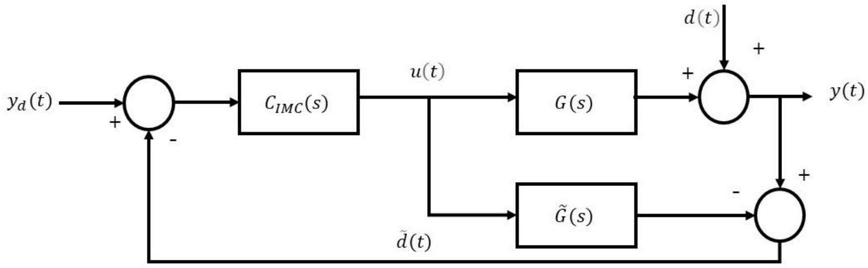

Fig. 2. IMC Structure.

IMC controller is mathematically calculated by deriving negative part of plant model and choosing appropriate low pass filter as shown in Eq. (6). The complete plant model is divided into two parts as shown in Eq. (7) viz. negative and positive part of plant model. The positive part of model consists of all delays in system and any positive zero whereas the negative part consists of negative zeros and remaining components of plant. If the plant model is perfect then good setpoint tracking can be achieved which is not possible in practical case. The filter is derived from two variables which ensure the properness and speed of the IMC controller.

IMC controller is given as,

$$C_{IMC}(s) = \frac{1}{\tilde{G}_{-}(s)} LPF(s), \qquad \text{Eq. (6)}$$

where, after separating the plant model as,

$$\tilde{G}(s) = \tilde{G}_{+}(s)\tilde{G}_{-}(s), \qquad Eq. (7)$$

where,

the factor $\widetilde{G}_{+}(s)$ contains all time delays and positive zeros and,

the factor $\widetilde{G}_{-}(s)$ has no delays and all of its zeros are negative.

And $LPF(s) = \frac{1}{(1+T_f s)^n}$ is low pass filter selected such a way that IMC controller is proper,

where, n is selected to achieve properness of IMC controller,

T_f is speed response adjustable parameter.

For the given system $n = 3$ selected to ensure properness of IMC controller and three different values of T_f are taken into consideration as $0.5, 1.0$ and 2.0 as suggested by Yousef, H.A. (2017).

For the hydro turbine power system given in Eq. (5) we have designed an IMC controller. Following IMC controllers are obtained for different filter parameters in terms of speed.

$$Tf\_1 = 0.5 \Rightarrow C\_IMC\_1 = \frac{2.4s^3 + 13.6s^2 + 8.2s + 21}{0.125s^3 + 0.75s^2 + 1.5s + 1}, \qquad Eq. (8)$$

$$Tf\_2 = 1.0 \Rightarrow C\_IMC\_2 = \frac{2.4s^3 + 13.6s^2 + 8.2s + 21}{s^3 + 3s^2 + 3s + 1}, \qquad Eq. (9)$$

$$Tf\_3 = 2.0 \Rightarrow C\_IMC\_3 = \frac{2.4s^3 + 13.6s^2 + 8.2s + 21}{8s^3 + 12s^2 + 6s + 1}. \qquad Eq. (10)$$

The closed loop controller (Eq. 8) (Eq. 9) (Eq. 10) simulation results for hydro turbine system (Eq. (5)) are presented.

IV. Simulation Result and Analysis

The Simulink block diagram of the IMC controller with 20% load disturbance is shown in Fig. 3.

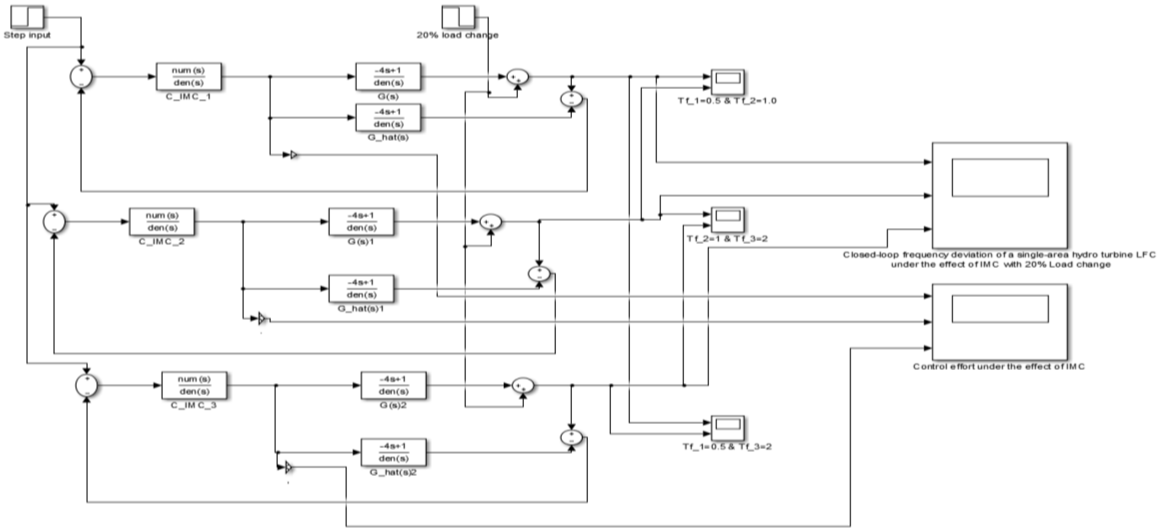

Fig. 3. The Simulink block diagram of the IMC controller

Table 1. shows comparative study of time domain parameters. The comparison of time domain parameters achieved for different filter selection for IMC based controller.

Table-1: Time domain parameters of the different filter selection for IMC based controller

	Tf_1=0.5	**Tf_2=1.0**	**Tf_3=2.0**
Rise Time(s):	1.0484	4.1177	7.6779
Settling Time(s):	164.0515	120.4973	18.3129
Overshoot:	30.6642	11.9723	2.1347
Undershoot:	187.546	82.4724	32.1515
Peak:	1.8797	1.1223	1.0237

The comparison between different values of speed response adjustable value chosen are shown in Fig. 4, Fig. 5 & Fig. 6 where in Fig. 4 when speed response values are increased from 0.5 to 1.0 the undershoot which occurs due to non-minimum phase behaviour of hydro turbine model as discussed by Soumyadeep (2018) is reduced by 56% as well as overshoot reduced by 60.95% also the settling time is reduced 26.54%.

In second case where speed response values are increased from 1.0 to 2.0 as shown in Fig. 5 the undershoot is reduced by 61% as well as overshoot is reduced by 82% also the settling time is reduced by 84.8%. In the third case where speed response values are increased from 0.5 to 2.0 as shown in Fig. 6 the undershoot is reduced by 82.85% as well as overshoot is reduced by 93% also the settling time is reduced by 88.8%.

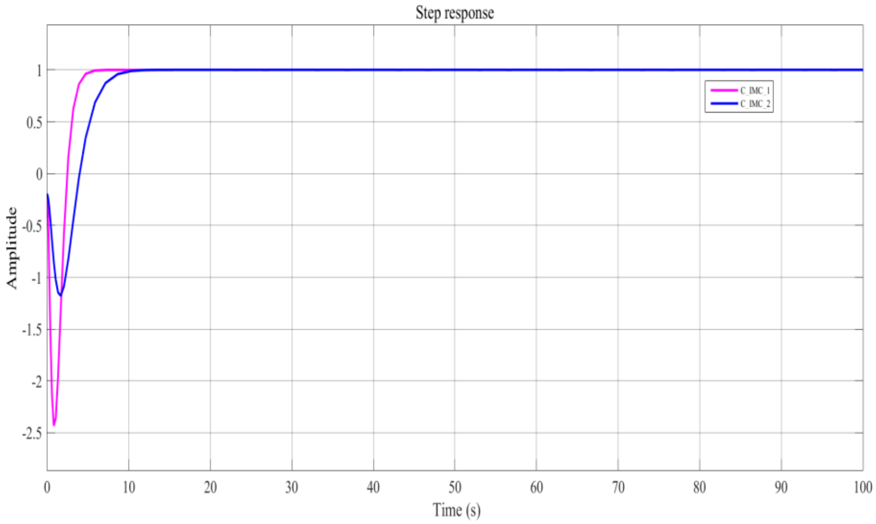

Fig. 4. Closed-loop frequency deviation of a single-area hydro turbine LFC under the effect of IMC for Tf_1=0.5 & Tf_2=1.0

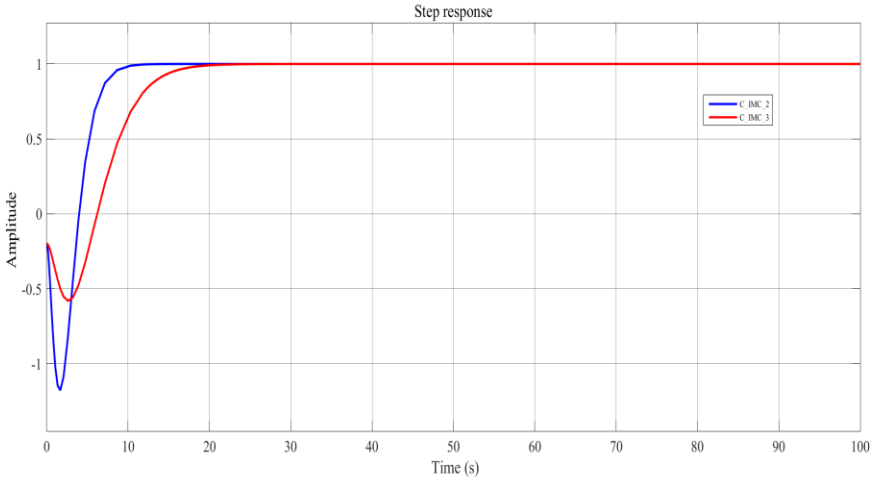

Fig. 5. Closed-loop frequency deviation of a single-area hydro turbine LFC under the effect of IMC for Tf_2=1.0 & Tf_3=2.0

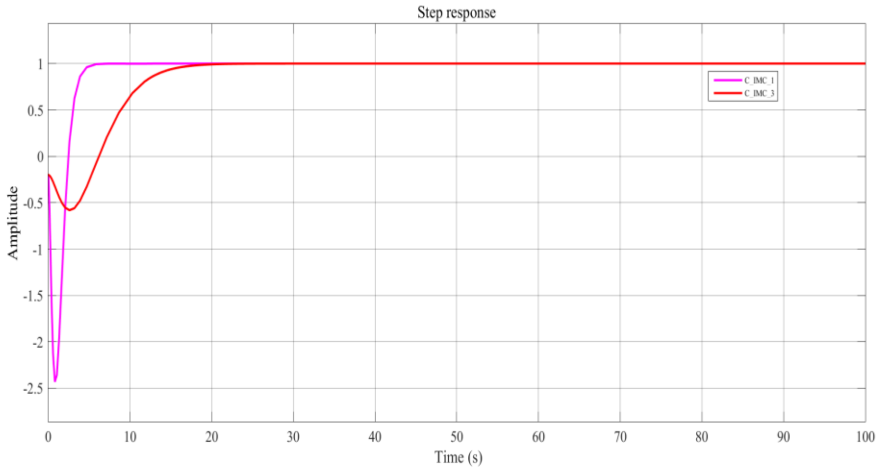

Fig. 6. Closed-loop frequency deviation of a single-area hydro turbine LFC under the effect of IMC for Tf_1=0.5 & Tf_3=2.0

Fig. 7 shows the comparative graph of plant performance when speed response adjustable parameter of IMC controller is increasing from 0.5 to 2.0 where performance of controller can be visibly also seen getting better. Fig. 8 shows the control effort under the effect of IMC controller which is reducing from C_IMC_1 to C_IMC_3.

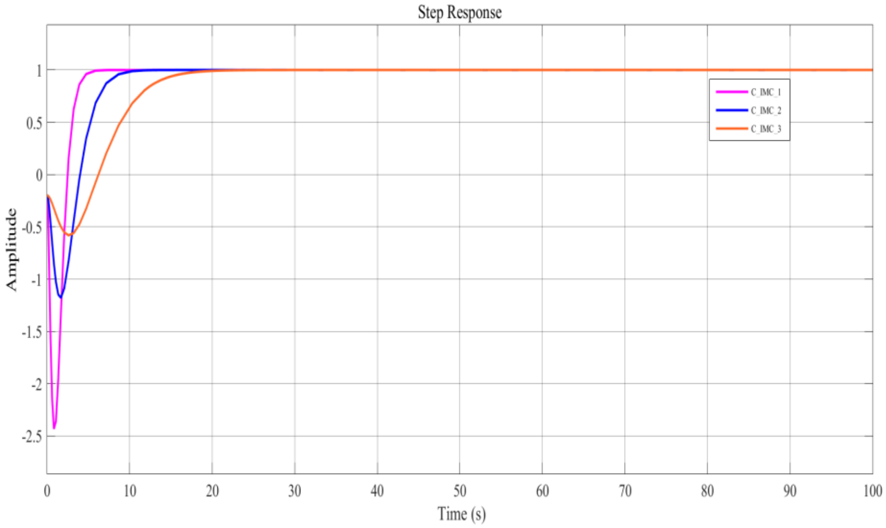

Fig. 7. Closed-loop frequency deviation of a single-area hydro turbine LFC under the effect of IMC for all Tf values

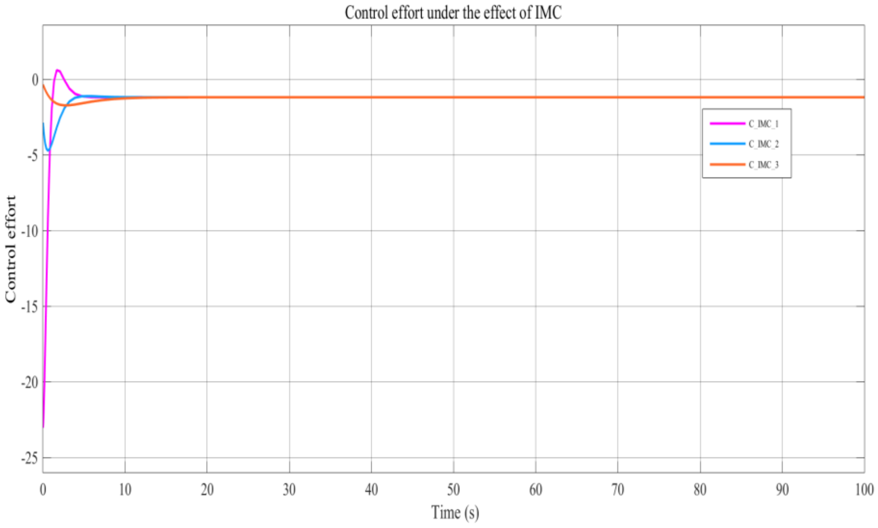

Fig. 8. Control effort under the effect of IMC

V. Conclusion

This paper is a sincere attempt of designing and implementation of IMC based controller for non-minimum phase hydro turbine power system. Finding controller tuning parameters is very difficult task because of zero from the right half of the S-plane as well as parameter variation due to sudden load (disturbance) change of NMP-nonlinear hydro turbine power system. Internal Model Controller uses this characteristic of the system and converts RHS zero to LHS pole. Comparative study of simulation results for different filter parameters i.e., 'n' for properness of IMC controller and 'T_f'- speed response adjustable parameter is presented and analysed. Control efforts required are also compared to prove the efficacy of IMC based controller. The overall observation is like it's a trade-off between performance parameters. From this analysis, it can be concluded that IMC based controller is one of the good options for a non-minimum phase (NMP) hydro turbine power system. The Load Frequency Control (LFC) in power system causes severe power outage. To subjugate this problem, there is a need of designing completely a new controller using soft computing like deep learning, artificial intelligence, particle swarm optimization (PSO) algorithms etc. or hybrid controller which will be an amalgamation of existing controller strategies, to enhance the performance.

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