Development Trends and Future Prospects of Hydro-Turbine Control Systems

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***Abstract*—Hydropower system is considered to be a matured technology if it consists of fixed speed synchronous generators, simple rectifier (AC-DC) based excitation, well established hydraulic structures, mechanical components and their control systems. This system is confined to single input (speed/frequency) and single output (gate opening) control, which is enough for a generator operating independently at constant head and driven by a Francis type turbine having fixed blade angle. But the hydropower system is complex now in view of variable speed induction generators, multi-megawatt voltage source power electronic converters and coordinated control system for hydraulic governor for compensating wide variation in water head, and low frequency power oscillations. Therefore, there is a critical necessity for advanced modeling and control techniques for optimum utilization of hydropower plants. This paper gives an overview of various models and different types of controllers (linear and non – linear) designed for hydraulic turbine control system. Further, future scope and design challenges associated with the hydropower control system are illustrated.**

Keywords— Control system, hydro-turbine, hydropower, modelling, stability, variable speed hydro.

I. INTRODUCTION

Since 1900's, synchronous machine based fixed speed hydropower plant (HP) has been installed in the European, American and Asian continents, and now more than 140 GW fixed speed PSPP operating in the world [1]. Nowadays, adjustable speed HP is an emerging technology in a pumped storage system where it has several benefits, specifically: (i) increased efficiency in generation/pumping mode with respect to the varying water level in the dam, (ii) taking minimum time during mode transition from pumping to generation and vice versa, (iii) high dynamic stability during grid voltage and speed perturbations, (iv) high ramp rate compared to fixed speed HP (iv) acting as flywheel energy storage, etc [2]. The first adjustable speed HP was commissioned in the early 1990's [3] and till now 18 nos of such power plants are installed/under construction all over the world with a total capacity of 9425 MW.

In fixed speed HP, Hydraulic Turbine Control system (HTCS) is responsible for delivering active power at desired grid frequency, whereas in variable HP, both generator control and HTCS are responsible [4]. Water wheel was invented in 13B.C. Subsequently, fly ball (centrifugal governor) was invented in 1860. In 1930, mechanical governor was invented and significant modifications were done until 1964 to regulate the turbine speed [5]. These mechanical governors were of fixed structure type with proportional, integral (PI) or proportional, integral and derivative (PID) actions. When electronics come in existence, fly ball phased out. Electronic system is used for speed or frequency calculation. The conventional electro-hydraulic governors are operated with PID controllers. With the evolution of control theory, many controllers were developed: sliding mode controller, fuzzy logic based controller, hybrid neuro fuzzy, neural network based controller, and Hamiltonian energy theory [6].

In literature, two types of models are found: linear models, and nonlinear models. Linear models are used, when there is a case of small signal variation, whereas nonlinear models for large signal variation [7].

A. *Contribution*

HTCS is a non-minimum phase, and non-linear system due the presence of number of non-linear components. These are inertia of the turbine, water elasticity affect, water hummer in penstock, and unpredictable load [8] - [9]. It is found in various literatures that turbine speed is affected by the change in the position of gates, nozzles, valves, and runner blade angles. So non-linear models are required in changing environment, in various situations as islanding, restoration of the system and load rejection etc. These models have great importance, especially in case of a long penstock where compressibility effect of water is considered [10]. HTCS has been reviewed in this paper as depicted in Fig. 1 with unit control board from various aspects and focused on some important points as: (i) turbine- penstock modeling in case of long penstock, (ii) Parameter optimization of PID variant in case of long penstock, and (iii) nonlinear modeling with external disturbances and system uncertainty. In addition, future scopes of HTCS are also identified and discussed briefly.

B. *Organization of the paper*

The rest of the paper is organized as follows. Section II shows a brief review of HTCS. Section III discusses the different types of models of the hydraulic turbine. Section IV briefly reviews of linear and non-linear controllers designed for HTCS. Finally, in section V future vision and challenges are provided and in section VI conclusion is described.

II. HYDRAULIC TURBINE CONTROL SYSTEM

HTCS with different components is as depicted in Fig.1. Governor consists of electrohydraulic servo system and controller which govern the unit speed or frequency [11].

Electrical frequency of generator voltage is sensed and compared with the reference ferquency and processed by the control board. Servo motor is operated to adjust the guide vanes and/or main inlet valve based on the signal received from the control baord. Generator voltage control is done of excitation

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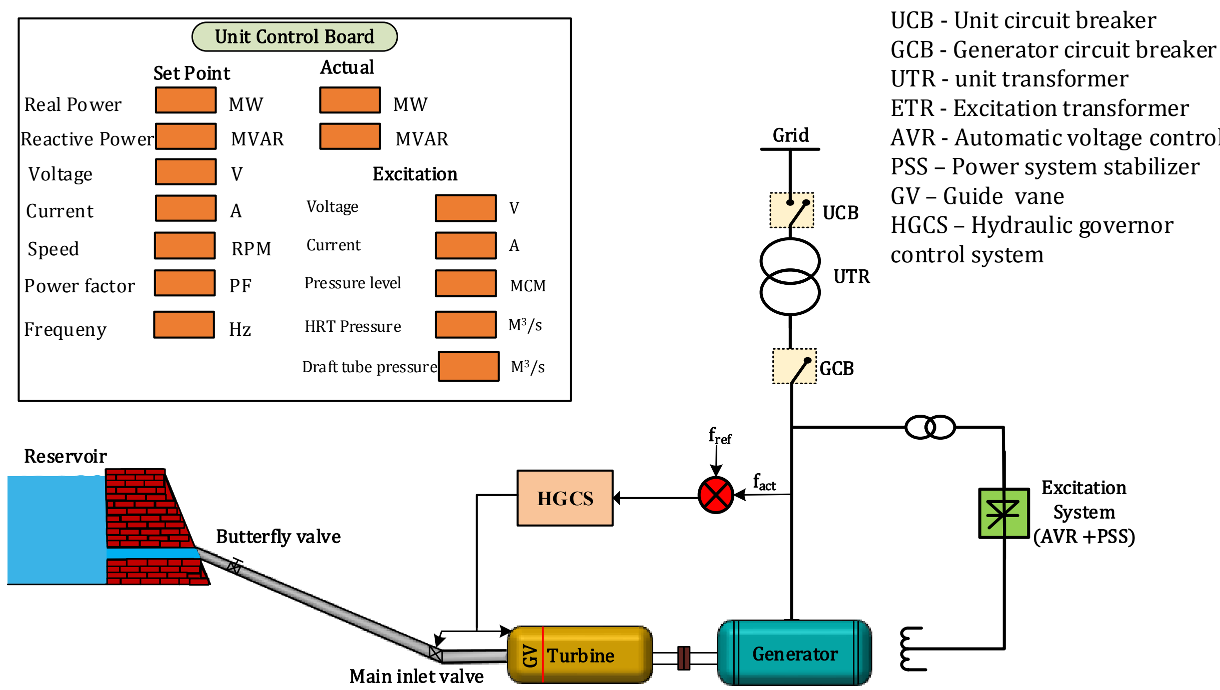

Fig. 1. Hydrological and electrical diagram of fixed speed hydrogenating unit

circuit with automatic voltage regulator (AVR). Power System Stablizer is used for damping out low frequecy oscillations by altering the reference (input) to AVR. PID contoller plays an imporatnt role in hydralic governor control system. Setpoints on various performance related parameters including active/ reactive power shall be done at unit control baord.

III. Models

Modeling is an important part of any system under analysis [12]. System design and stability analysis are usually done with the help of models [13]. IEEE working group has been published number of models of HP [14]-[16]. Models are further classified as linear and nonlinear as represented in Fig. 2 and are discussed in the subsequent sections.

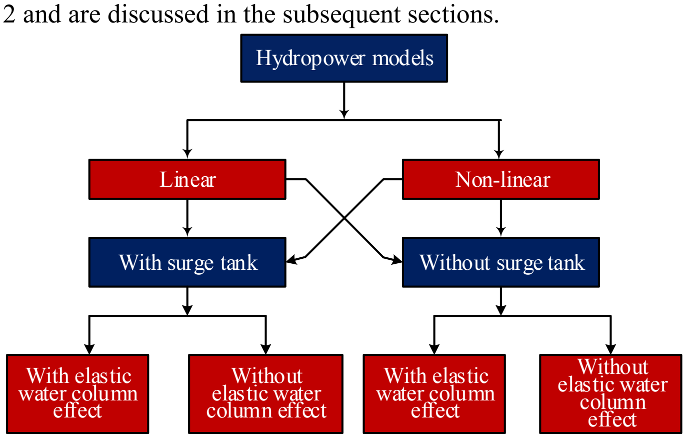

Fig. 2. Types of hydropower plants models.

A. Linear Models

Linear models are basically developed for parameter identification of PID controller. Control parameters of PID controller are identified by improved gravitational search algorithm (IGSA) [17], modified gravitational search algorithm (MGSA) [18], mixed-strategy based gravitational search algorithm (MS-GSA) [19], and quantum particle swarm optimization (QPSO). IGSA has the advantages of both GSA and PSO [20]. It searches the global solution based on gravity rule and information of best particle. The identification is done by two objective functions i.e. traditional objective function (TOF) and improved objective function (IOF). Out of these two objective functions, IOF is found more effective in terms of average parameter error (APE). MGSA has the advantages of both GSA & differential evolution (DE). MS-GSA is obtained by using three improvement strategies i.e. elite agent’s guidance, adaptive gravitation constant function, Cauchy and Gaussian mutation operator. It searches the global solution based on gravity rule and information of best particle. Different parameters i.e. turbine speed, guide vane opening and turbine torque are analyzed. It is found that MS-GSA has very less parameter error (PE) and APE than GSA, IGSA, Gbest-Guided GSA (GGSA) and grey wolf optimizer (GWO) as depicted in Table I.

TABLE. I VALUE OF PE FOR DIFFERENT ALGORITHM

Param eters	Algorithm					
	GSA	IGSA	MGSA	GGSA	GWO	MS-GSA
K_p	0.0421	0.0845	0.0050	0.0236	0.2248	0.0090
K_i	0.0813	0.0187	0.0067	0.0077	0.0954	7.8e-4
K_d	0.3674	0.3102	0.0508	0.0574	0.7381	0.0551
T_y	0.1758	0.2280	0.0736	0.1095	0.6480	0.1133
T_w	0.2386	0.0022	0.0202	0.0368	0.4102	0.0028
T_a	0.0659	0.0461	0.0018	0.0024	0.0365	0.0012
e_g	0.0109	0.0081	0.0003	3.7e-4	0.0044	1.5e-4

B. Non-Linear Models

HTCS is modeled by non - linear differential equations with the consideration of elastic water hammer effect [21] - [22]. The hydraulic system has n-conduits downstream of the surge tank and m bifurcation penstocks at the end of each conduit. The differential equation model is compared with the transfer function model in terms of responses of the water head and output power. Two models of HTCS based on Neural network (NN) are developed i.e. non-linear auto-regressive with the exogenous signal (NNARX) and adaptive neuro-fuzzy interface system (ANFIS) which are used for identification of hydro turbine speed [23]- [24]. Input and output of the models are gate position and turbine speed, respectively. Levenberg-Marquardt method is used for training the NNARX. Back propagation and hybrid learning are used for training the ANFIS.

Zero-order Takagi-Sugeno (TS) fuzzy-based approach is used to determine the hydro turbine speed with different PID control variants [25]. Input and output to the model are control signal and the turbine speed respectively. The parameters of the fuzzy inference system are trained by gradient descent optimization technique, least square method and least square with adaptive directional forgetting (LSMADF) algorithm. The nonlinear mathematical model developed by using fractional order differential equation [26], six non-linear dynamic transfer coefficient of hydraulic turbine [27], including load rejection transient [28], and including effect of sloping ceiling tail race [29].

Different types of controllers (linear and non-linear) are discussed in the next section. Different parameters to be optimized under different mode of operations (start-up, operating and stopping mode) of HP are listed in appendix.

IV. CONTROLLERS

Controller's main function is to regulate turbo-generator speed, output frequency, and hence the active power in accordance with the changes in the demand. The advancement in the controllers according to the development in the control theory approaches are discussed in the following sub-sections:

A. Linear Controllers

The design of a controller is important for HTCS [30]. PID controller comes in the category of linear controller [31]. The standard equation of the PID controller is represented as (1)

$$u(t) = k_p \left(e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d \frac{d}{dt} e(t) \right) \quad (1)$$

Where k_p, is the proportional gain, T_i and T_d are integral time and derivative time of PID controller. Because of its simple structure PID is preferred in most of the industrial applications. It is reliable and simple in design. But parameter optimization /tuning is important. Different tuning method are categories as Classical tuning criterion, the modern approach of tuning of the PID and new approach of tuning of the PID.

1) Classical Tuning Criterion

The stability boundaries of HTCS having PID governor are established using the root locus method in [32]. A model of an isolated HP with surge tank is developed for frequency control in [33]. Frequency stability has been analyzed under power control by varying different control parameters and compared with frequency control by applying Hurwitz criteria and numerical simulation. It is found that power control is effective than frequency control on stability.

A differential equation model is developed of HTCS to improve the performance of aged HP in [34]. To methods i.e., feed forward and Ziegler Nichols (Z-N) are applied for tuning of PID controller to reduce the effect of backlash. Finally, feed forward is found better than Z-N at both the interconnected and islanded operations. The flow charts of tuning methods using fuzzy and evolutionary algorithm are depicted in Fig. 3 and Fig. 4. It is found that the complexity increases from Ziegler Nichols towards SMC.

2) The Modern Approach of Tuning of the PID

An output feedback PID controller has been proposed for HTCS, [35] which guarantee the wide range stability and improve generator damping. The proposed scheme has been tested with WSCC-9 bus and Kunder-4-machine II bus system by using CYME package. It is found that modified PID controller improve the robustness of noise caused by differential feedback and gives better performance than the conventional PI controller in terms of low overshoot and fast response.

A fractional – order PID controller is designed using chaotic non- dominated sorting algorithm II (NSGAII) for HTCS. Two optimization functions are used for the tuning of controller parameters i.e. the integral of the squared error (ISE) and integral of the time multiplied by squared error (ITSE). Further, a comparative study has been done between optimum integer order PID controller and optimum FOPID controller under both unload and load running condition [36]. From the result, it is found that FOPID gives small overshoot and faster time response than PID.

In [37], power frequency control of HP with long penstock connected to an isolated system coexisting with a wind farm in small island is analyzed. A lumped parameter method is used to obtain a second-order reduced model of combine turbine – penstock system. Two criteria for tuning of PI governor, i.e. double real pole (DRP) and double complex pole (DCP) are used. DCP is found better than DRP in terms of less frequency overshoot. The dynamic response of governor with long penstock pumped storage hydropower

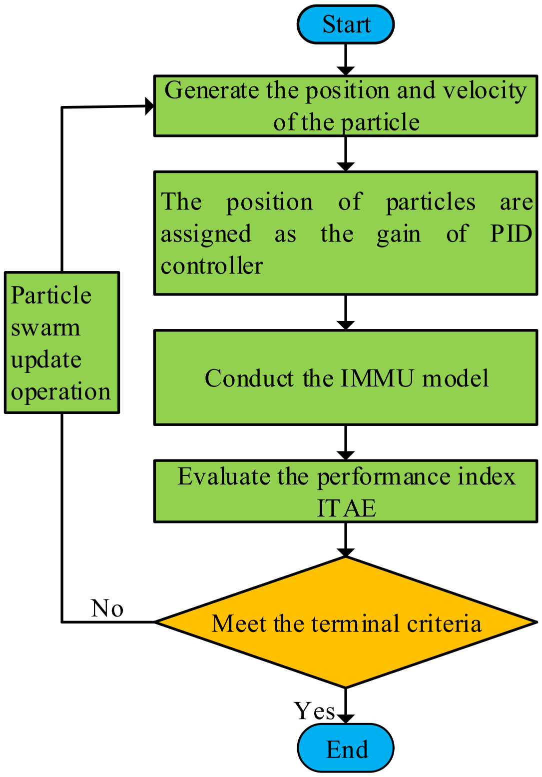

Fig. 3. Flow chart of PID tuned by PSO [52].

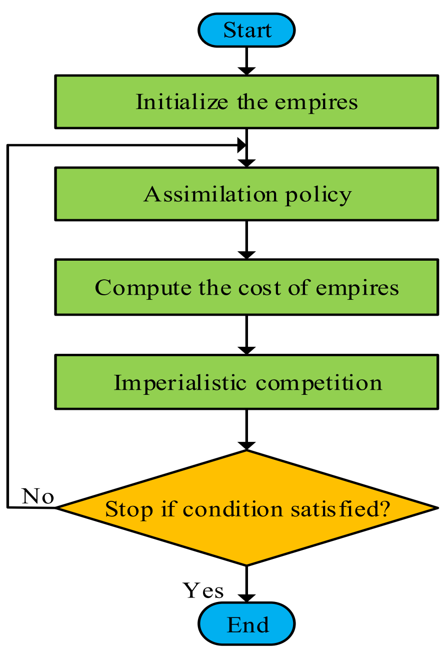

Fig. 4. Flow chart of FSMC tuned by hybrid imperialist competitive algorithm [53].

plant equipped with a single pump turbine and doubly – fed induction machine is analyzed [38]. A reduced order dynamic model of penstock is developed with elastic water column effect. Three different tuning methods, i.e. DCP, fixed damping ratio (FDR), and Pareto based are used for tuning of governor parameters. From results, FDR is found more effective in terms of damping of oscillations.

A multi-objective evolutionary algorithm, named adaptive grid particle swarm optimization (AGPSO) is used for tuning the PID gains of HTCS including the effect of the surge tank. It reduces settling time and overshoots level. Further, it is compared NSGAII and Strength Pareto Evolutionary Algorithm II (SPEAII) under both unload and load condition [39] and found effective.

3) New Approach of Tuning of the PID

A flow control based control of hydro turbine using a PI controller is designed in [40]. Flow is controlled by the gates and gate opening is controlled by the shear valve. Parameter optimization is done using the artificial neural network, especially for small HP. The tuning of PI controller is done by an artificial cuckoo search algorithm for load frequency control. A three –area system is investigated and results are compared with the genetic algorithm, particle swarm optimization and a conventional integral controller [41]. The Artificial cuckoo search algorithm has been proved superior in terms of lower settling time and compensating communication time delay.

B. Non-Linear Controllers

Mostly PID controllers are used but there is a drawback in these traditional PID controllers. It is not suitable for a dynamic system. Because its gain parameters remain unchanged throughout the system. This problem of PID controller is overcome by the non-linear controller [37]. The parameters of the non-linear controller changes as the operating condition of the system changes. The study is further divided into three main types of non-linear controllers in the following sub-sections.

1) Predictive Controllers

A NNARX model of HTCS is developed with elastic and inelastic water column effect in [43]. Mechanical power of the turbine is taken as the output and gate position as input. A predictive controller is applied to the model and controller parameters are determined using Levenberg-Marquardt and quasi-Newton algorithm. Finally, results show that frequent tuning of controller parameters is not required in predictive control approach in NNARX model. Deviated power tracking error is zero and overshoot in gate position is reduced. The model is valid for both changes in load and water disturbances.

A robust distributed model predictive controller (RDMPC) is designed for load frequency control (LFC) of the multi-area interconnected thermal-hydropower system in [44]. Optimization of controller parameters has been done by linear matrix inequalities (LMI) method. Two types of non-linearities i.e. the practical limits of the valve position of the governor and the generation rate constraints (GRC) are highlighted. From the results, it is found that RDMPC provides less overshoot and faster response than centralized MPC and conventional DMPC for frequency deviation.

2) Fuzzy Logic Based Controllers

A Two-stage controller based on neural network (NN) and fuzzy logic (FL) technique for LFC of a multi-area interconnected system is investigated in [45]. In the first stage, an NN-based NARMA-L2 model is used and in second stage

PD based FL architecture is used. The controller is applied to a six-control-area connected power system model to solve LFC problem in two cases, i.e. with and without using superconducting magnetic energy storage (SMES) devices. Out of the four controllers (PI, PI SMES, neural network fuzzy logic (NNFL) and NNFL SMES), NNFL SMES controller gives optimal control for frequency deviation and tie-line power flow with load changes.

An adaptive non-linear analytical fuzzy controller (FC) is designed for HTCS introducing non-linear analytical rules in the FC. Further, a comparative study has been carried out between FC and conventional PID controller under various load disturbances and head [46]. FC gives a better frequency response in terms of shorter settling time and decreased overshoot. A comparative study of fuzzy gain scheduling proportional, integral controller (FGPI) and the conventional PI controller is done for LFC. Both controllers are applied to a single area and two area hydro electrical power plants in Turkey. From the result, it is found that FGPI controller has better performance than the conventional PI controller in terms of reduced overshoot and fast response of output frequency (set value 50 Hz). A Takagi fuzzy controller is designed for HTCS, based on fractional-order Lyapunov stability theory in [47]. Meanwhile, the performance of the TS-fuzzy controller is compared with the existing robust FC. Finally, results show that TS- FC is better than an existing FC in terms of shorter settling time and fewer frequency oscillations.

3) Sliding Mode Controllers (SMC)

An SMC is effective to study non-linear HTCS model with external disturbances and system uncertainty in [43]. There is a problem of chattering in SMC. It is removed by using a high slope saturation function. On comparing with PID SMC has less transition time and no overshoot. A reduced SMC [49] and fuzzy SMC [39] - [79] are designed for turbine's speed control of hydroelectric power plant including surge tank with the consideration of inner perturbations and noises. FSMC has the advantages of both SMC and FLC. Parameter optimization of the controller is done by GA [50] and PSO [51]. A fuzzy interface system is designed to reduce the chattering phenomenon and chaotic behaviors of FSMC. Stability of the system is analyzed using different techniques, i.e. bifurcation map, Lyapunov exponents, phase diagrams and power spectrum. It is found that FSMC is insensitive to external noise and system perturbations. Different performance parameters of FSMC such as IAE (integral of absolute error), ISE (integral of squared error) and ITAEare analyzed. It is found that FSMC has very small values of IAE, ISE, and ITAE under periodic orbit tracking. Overshoot is also reduced under fixed point stabilization and random noise disturbances in comparison with PID as shown in Table II.

TABLE.II COMPARISION OF PID, SMC AND FSMC

The performance under fixed point stabilization			
Controllers	**Rise time (sec)**	**Settling time (sec)**	**Overshoot (%)**
PID	1.1583	>6	33.1795
SMC	0.6327	0.7829	1.2591
FSMC	1.0230	1.2591	0.1506
The performance under periodic orbit tracking			
Controllers	**IAE**	**ITAE**	**ISE**
PID	1545.5	4223.6	1358.9
SMC	2.9622	8.8821	0.0065
FSMC	2.5604	7.6088	0.0048
The performance under random noise disturbances			
Controllers	**Rese time (sec)**	**Settle time (sec)**	**Overshoot (%)**
PID	1.1072	>6	40.650
SMC	0.6319	0.7832	0.1928
FSMC	1.0221	1.2576	0.1673

V. FUTURE PROSPECTS

Based on the discussion in all above sections and the experience gained from few of commissioned projects, this section provides some key points for future research work as given below:

A. Governor Control at Overloading of Hydrogenerator:

Large hydro generators, are usually overloaded at various situations such as period when excess water is available, with permissible silt content and when excess inflow is to be discharged to maintain reservoir level within limits. The period may have extended to many weeks under exigent conditions e.g. six weeks in case of Karcham Wangtoo Hydropower Station, India at 20% overload. Supervisory control system for governor has to be designed for better coordination with unit control board in view of allowable discharge limit (velocity) of head race tunnel.

B. Real-Time Simulation for Power Oscillation in Hydrogenerators:

Power System Stabilizer is used in synchronous hydro-generators for improving the energy transfer capacity of the power system by damping low frequency oscillations. Its main principle is damping the oscillation via modulation of the synchronous generators excitation system. It is observed from few commissioned projects that unacceptable power oscillations occur with the interference of compensated or uncompensated high voltage transmission lines which led to a path for real-time simulation to mitigate the same.

C. Starting of Pump Turbines:

In pumped storage plants smooth starting is performed to reduce start-up transients in the generating unit and grid [51]. This process may take five minutes which is led a path for energy conservation particularly on asynchronous generating units. Research shall be concentrated to design a suitable control system for energy efficient starting of pump turbine.

D. Supervisory Control during Mal-functioning of Breakers

During malfunctioning (mechanical failure) of unit circuit breaker (e.g. one or two contacts could not open at shut down process) there is a possibility to damage of damper windings if turbine rotation is stopped. Control mechanism is required to solve this problem as it is experienced in a commissioned project.

E. Governor Tuning in Case of Long Penstock:

In case of lengthy penstock in isolated system, governor tuning is not an easy task. Governor tuning become difficult, especially when the system is equipped with DFIG. Further, the tuning of governor parameters needs research with the advanced techniques in consideration of better coordination among generator and generator control system.

F. Cyber Security:

HP control systems (unit control board) shall be reinvestigated, to make it free from cyber-attack, in view in view of increased cyber-attacks on process controllers and measures suggested in recently released IEC Standard 62443 (2019): Security for Industrial Automation and Control Systems.

VI. Conclusions

Various aspects of models and controllers of HP have been reviewed. According to the requirement models are made and performance is tested and accordingly controllers are made. It is concluded that not much work has been done for nonlinear controller. Hence research is needed in the field of nonlinear controller of HP. It is concluded that research is needed for optimizing control function for generators operating on an infinite bus according to scheduled output but subjected to disturbances. Unit control board of generator shall also account the water head variation as an input and turbine blade angle as an output.

Appendix: Optimization Parameters in Various Modes

Parameters	Start-up	Operation	Stopping
y - guide vane opening	✓		
x - rotational speed	✓		
q - flow	✓		
h - water head	✓		
K_p- proportional gain		✓	✓
K_i - integral gain		✓	✓
K_d - differential gain		✓	✓
T_y - servomotor time constant		✓	✓
T_w - water time constant		✓	✓
T_a - generator inertia time constant		✓	✓
e_g-adjusting coefficient of generator		✓	✓
h_w - penstock characteristic coefficient			✓

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Response to the reviewers

Response to the suggestions and comments on Paper ID **90 – IAS meeting 2019** entitled "**Development Trends and Future Prospects of Hydro-Turbine Control Systems**" submitted to **IEEE-IAS Industrial Automation and Control.**

Authors thank the honorable reviewers and committee members for giving an opportunity to incorporate the suggestions given by reviewers, thereby improving the quality of the paper. We have carefully read the comments from the referees and incorporated the required modifications in the revised manuscript. We hope this revision will make our manuscript to meet the requirements of the IAS Annual meeting 2019. Suggestions and comments of the reviewers are depicted in **bold font style in red** and the reply is given in regular font style.

Reply to Honorable Reviewer 1:

1. **Good review paper. Please recheck correctness of references.**

   Author's reply: Thanks to the honourable reviewer for the appreciation. The correctness of the references has been checked.

Reply to Honorable Reviewer 2:

Comments: **This paper summarizes various aspects of modelling and control of hydraulic turbine.**

Author's reply: Thanks to the honourable reviewer for the appreciation.

1. **The motivation behind this work and contribution are not clear. The authors must include a paragraph about contribution of the work in the introduction section.**

   Author's reply: Thanks to the honourable reviewer for the valuable suggestion. Authors agree with honourable reviewer and a paragraph added in introduction section as below:

   HTCS is a non-minimum phase, and non-linear system due the presence of number of non-linear components. These are inertia of the turbine, water elasticity affect, water hummer in penstock, and unpredictable load [5] - [6]. It is found in various literatures that turbine speed is affected by the change in the position of gates, nozzles, valves, and runner blade angles. So non-linear models are required in changing environment, in various situations as islanding, restoration of the system and load rejection etc. These models have great importance, especially in case of a long penstock where compressibility effect of water is considered [4]. HTCS has been reviewed in this paper as depicted in Fig. 1 with unit control board from various aspects and focused on some important points as: (i) turbine- penstock modeling in case of long penstock, (ii) Parameter optimization of PID variant in case of long penstock, and (iii) nonlinear modeling with external disturbances and system uncertainty. In addition, future scopes of HTCS are also identified and discussed briefly.

2. **Authors must use figures and graphs to relate information. I found the paper to be very much theoretical.**

   Author's reply: Thanks to the honourable reviewer for the valuable suggestion. Authors agree with honourable reviewer and a Fig. 1 is added as below:

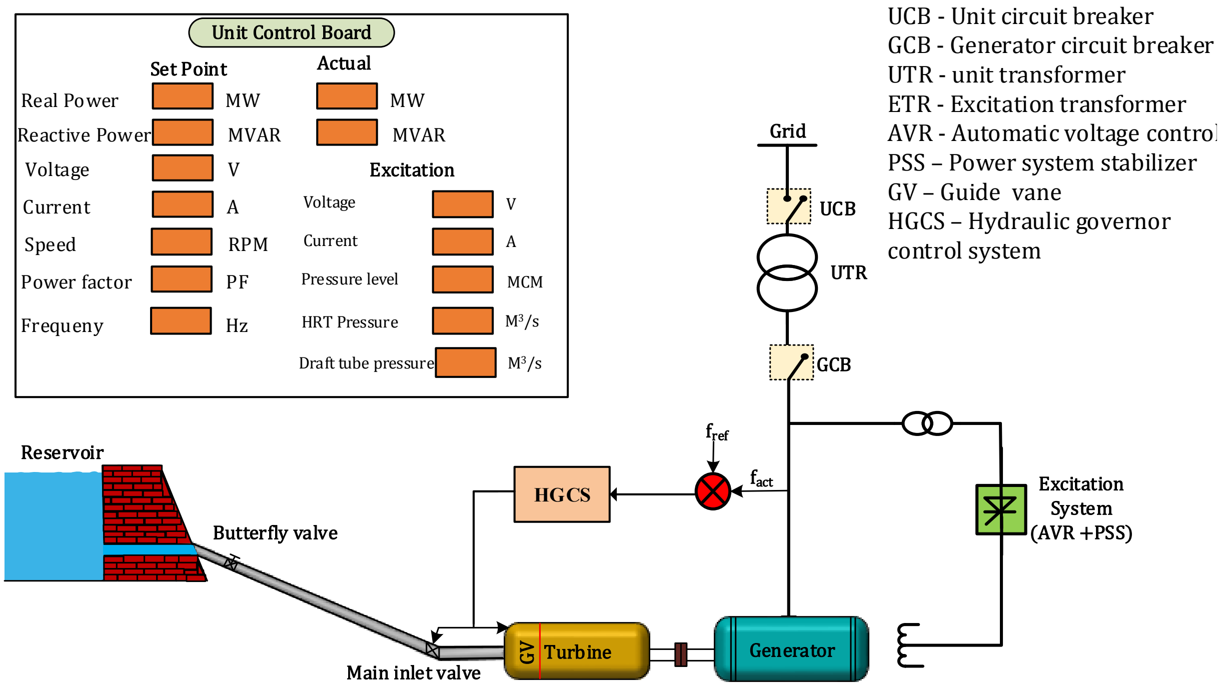

Fig. 1. Hydrological and electrical diagram of fixed speed hydrogenating unit

3. **Authors must compare the performance of various models and controllers and tabulate them for better quality.**

<u>Author's reply</u>: Thanks to the honourable reviewer for the valuable suggestion. Authors agree with honourable reviewer and two tables have been added as below:

TABLE. I VALUE OF PE FOR DIIFFERNT ALGORITHM

Parameters	Algorithm					
	GSA	IGSA	MGSA	GGSA	GWO	MS-GSA
K_p	0.0421	0.0845	0.0050	0.0236	0.2248	0.0090
K_i	0.0813	0.0187	0.0067	0.0077	0.0954	7.8e-4
K_d	0.3674	0.3102	0.0508	0.0574	0.7381	0.0551
T_y	0.1758	0.2280	0.0736	0.1095	0.6480	0.1133
T_w	0.2386	0.0022	0.0202	0.0368	0.4102	0.0028
T_a	0.0659	0.0461	0.0018	0.0024	0.0365	0.0012
e_g	0.0109	0.0081	0.0003	3.7e-4	0.0044	1.5e-4

TABLE. II COMPARISION OF PID, SMC AND FSMC

The performance under fixed point stabilization			
Controllers	**Rise time (sec)**	**Settling time (sec)**	**Overshoot (%)**
PID	1.1583	>6	33.1795
SMC	0.6327	0.7829	1.2591
FSMC	1.0230	1.2591	0.1506
The performance under periodic orbit tracking			
Controllers	**IAE**	**ITAE**	**ISE**
PID	1545.5	4223.6	1358.9
SMC	2.9622	8.8821	0.0065
FSMC	2.5604	7.6088	0.0048
The performance under random noise disturbances			
Controllers	**Rese time (sec)**	**Settle time (sec)**	**Overshoot (%)**
PID	1.1072	>6	40.650
SMC	0.6319	0.7832	0.1928
FSMC	1.0221	1.2576	0.1673

4. **Authors may include flow charts showing the tuning method of different controllers and compare the complexity of this process**

Author's reply: Thanks to the honourable reviewer for the valuable suggestion. To improve the quality of the paper and as per the suggestion of the reviewer two flow charts (fuzzy and evolutionary algorithm based tunings) are added.

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