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Evolutionary Computation Techniques for the Design of Essential Process Controllers in Hydropower Plants

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Abstract: Power plants' controllers are essential in meeting dynamic load needs. Designing a controller for a power plant is usually a difficult and time-consuming job because of the plants' highly complex nonlinear behaviour under various operating circumstances. An application of evolutionary computing methods to the construction of optimum controllers for thermal and hydroelectric power plants is examined in the entire study, with the goal of improving plant performance in the long run. The present work also explores the possibility of design and implementation of \ PID controller for HTGS.

1. Introduction

Due to the accelerated growth in power demand, the power sectors have received special attention in recent times, which should meet the continuously increasing power demand with available limited resources, while ensuring safe, stable, economic, and efficient operation of power plants. To meet the ever-increasing power demand of the electric grid, thermal and hydroelectric power plants play a leading role in conventional power industries. Controllers play a critical role in power plants in meeting dynamic load demands without jeopardising the safety of the plants' personnel and equipment. Furthermore, controllers are highly dependable elements in power plants for maintaining process parameters at desired levels in order to achieve efficient operation in accordance with design specifications. Power plant controller design is considered a difficult task because real-time plants exhibit highly interactive nonlinear behaviour under a wide range of operating conditions, more stringent operating constraints of actuators, and the plant's large inertia phenomenon. Controllers serve as critical components in power plants, allowing them to meet dynamic load demands as dictated by the power grid while also ensuring the safety of the plant's personnel and equipment. Furthermore, controllers serve as accountable elements in power plants, regulating the various process parameters to desired levels in order to achieve desired operating efficiency.

Assuring safe, stable, economic, and efficient operation of hydroelectric power plants[1][2][3] [4] is the primary function for which the hydraulic turbine governing system (HTGS) is responsible. For example, the hydraulic turbine-generator set (HTGS) must be regulated for power and frequency to meet the dynamic demand of electric grid [5][6]. To account for the highly interacting nature of nonlinear components such as the governor and penstock and the hydraulic turbine and generator, the HTGS is regarded a complex nonlinear system. It has become increasingly important to improve HTGS performance under dynamic operating conditions due to recent developments in the field of control and automation. Conventional PID controllers are widely used in HTGS today because of their structural simplicity, reliability, and cost effectiveness. The performance of PID controllers is heavily influenced by the tuning parameters connected with them. Various methods of tuning PID controllers have been proposed in the literature in order to improve the performance of the plants. There is a chance to build a new controller with better views because of recent developments in the area of fractional calculus. While traditional integer terms are still used in fractional calculus, they can be replaced with fractional powers to ensure that models of natural processes are more realistic. There are two additional degrees of freedom provided by the addition of and to the controller design, allowing for greater flexibility. There are more complex mathematical calculations involved in the design of fractional order PID (FOPID) controllers. Various methods for optimum tuning of FOPID controllers have been described in the literature[7][8].

Many different control applications are now relying heavily on fuzzy logic controllers to manage complicated, nonlinear, and time-varying processes. Adding FLC to PID closed loop may improve the controller's overall performance, according to some reports. According to published literature, there are a variety of ways to implement FLC for nonlinear processes. While the choice of fuzzy parameters, such as inputs, membership functions (MFs), a suitable rule base, as well as fuzzification and defuzzification techniques have been studied, no exact mathematical formulation has been published. The input-output scaling factors (SFs) of FLC are reported to have a greater influence on control performance than the choice of MFs. For FLC to perform optimally, the fixed input-output SFs may not be enough to achieve the desired control performance. In order to achieve the best performance, the present study uses fixed MFs and a fixed rule base for FLC and attempts to find optimal input-output SFs along with fractional order derivative and integral terms.[9][10]

Finding the optimal tuning parameters for a fuzzy FOPID controller is a difficult task because it involves more complex and numerous parameters and exhibits nonlinear characteristics. During the optimization process, most of the approaches in the literature focus on single-objective optimization, such as fast tracking or less settling time, and minimum over- shoot. While focusing on achieving one goal, it is forced to sacrifice another. If you're trying to improve dynamic response of your control system, however, you'll want to reduce the settling time and keep the oscillations to a minimum. Due to this, multiobjective optimization is a must in order to find noninferior solutions to the conflicting objectives. According to the designers' limitations and operating constraints, they can choose one of the non-inferior solutions.

2. DESCRIPTION OF PLANTS WITH MATHEMATICAL MODELS

HYDRAULIC TURBINE GOVERNING SYSTEM (HTGS)

The hydroelectric power plant is made up of a mountain reservoir, a penstock, a wicket gate, and a hydro turbine connected to a generator. There are diagrams of the hydroelectric power plant's overall structure with its main components in Figures 1 and 2. Using a hydraulic servo system based on the turbine speed controller, wicket gates regulate the amount of water flowing into the turbine.

It reacts when there is a discrepancy between the torque produced by the hydro turbine and the power requirement of the linked electric generator. Hydro turbine mechanical output torque (mt), rate of flow (q), output of conduit (h), and generator speed (x) are used to regulate the frequency of the HTGS (Fang et al. 2011). Most HTGS systems are modelled using linearized models in the literature. For controller design and implementation, the current study examines nonlinear HTGS models that are feasible (Chen et al. 2015).

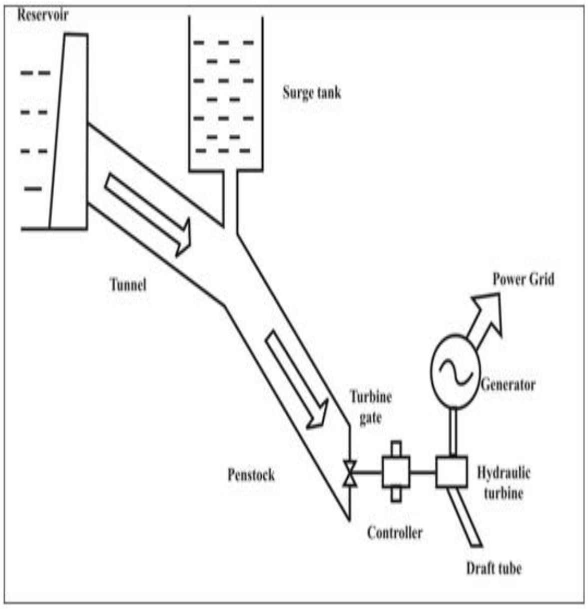

Figure 1General Structure of Hydro Electric Power Plant with its Major Components

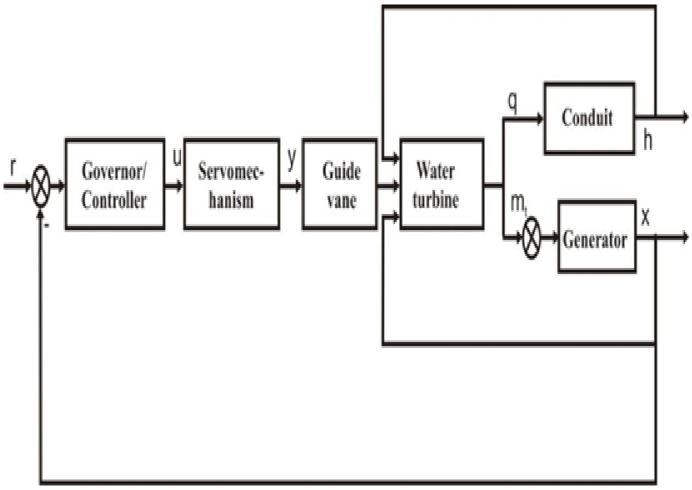

Figure 2 Functional Block Diagram of Hydro Electric Power Plant

Model of Turbine Governing System

Turbine regulating systems utilize traditional PID controllers the most at the moment, according to a study. Its structure is as follows:

$$G_{PID}(s) = k_p + \frac{k_i}{s} + k_d S \ldots.(1)$$

The output of the controller is shown.

$$u(s) = G_{PID}(s).\big(r(s) - x(s)\big) \ldots..(2)$$

The proportional, integral, and derivative gains of the PID controller are represented by the tuning parameters k_p, k_i, *and* k_d. u(s) is the controller output, r(s) is the speed reference, and x(s) is the generator's actual speed. The lower and higher limits for the controller have been added to minimize the mechanical wear and tear of the turbine guiding vane during frequent changes. The enforced restriction is regarded as a saturation element, as seen below:

$$u = N(q) = \frac{u_h}{2q_a}(|q + q_a| - |q - q_a| \dots .(3)$$

Where u_h is upper limit of controller output and qa is is the maximum input linked with u_h.

Model of Servo Mechanism

The actuator of a hydro turbine is the electro-hydro servomechanism. It consists of a main servo motor and an auxiliary servo motor. The servo mechanism model is presented as a first order system.

$$G_c(s) = \frac{1}{c_t s + 1} \dots .(3)$$

$y(s) = G_c(s).u(s)$.....(4)

where, Ct is major servo time constant and $y(s)$ is the Laplace transform representation of servo output y.

Model of Hydro Turbine and Penstock System

The combination of the hydro turbine and the penstock system is regarded as an integrated system in HTGS. Because of the nonlinear connection between flow rate and pressure, it is always difficult to describe the movement of fluid laws in a penstock. After accounting for plant parameter changes and the effect of elasticity in the penstock, the transfer function of inelastic water hammer may be characterized as

$G_h(s) = \frac{h(s)}{q(s)} = -T_w(s)$....(5)

where h(s) and q(s) are the Laplace transforms of net water head h and rate of flow q, respectively. Tw is the hydro reaction time constant. The actuator of a hydro turbine is the electro-hydro servomechanism. It consists of a main servo motor and an auxiliary servo motor. The servo mechanism model is presented as a first order system. The nonlinear behavior of the Francis-turbine is shown as, (Chen et al. 2015).

$mt = f1(x, y, h)$........(6)

$q = f2\ (x, y, h)$.......(7)

even if, the nonlinear functions $f1(.\ )$ and $f2(.\ )$ are unknown, the model of hydro turbine is approximated as a linear model around steady state conditions as,

$$m_t = e_x x + e_y y + e_h \dots \dots \dots .(8)$$

$$q = e_{qx} x + e_{qy} y + e_{qh} h$$

Where , $e_h = \frac{\partial m_t}{\partial h}, e_x = \frac{\partial m_t}{\partial x}, e_y = \frac{\partial m_t}{\partial y}$

$e_{qh} = \frac{\partial q}{\partial h}, e_{qx} = \frac{\partial q}{\partial h}, e_{qy} = \frac{\partial q}{\partial y}$

On the basis of the moment and flow characteristics curves provided by turbine manufacturers, the six transfer coefficients mentioned above may be estimated. There will be some effect on torque and flow rate from turbine speed, because generator units in grid are part of power distribution systems. According to the following equations, a turbine and penstock system's dynamics are:

$$G_t(s) = e_y \frac{1 - e_m T_w s}{1 + e_{qh} T_w s}$$

M(s)= $G_t(s).y(s)$

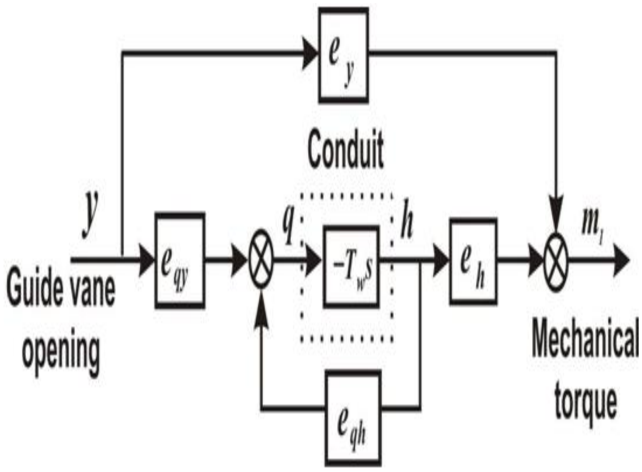

Figure 3 Block Diagram of Hydro Turbine Transfer Function (s)

Model of Generator System

The first order transfer function is used to describe the model of synchronous generator in hydro electric power plant,

$$G_g(s) = \frac{x(s)}{m_t(s) - m_g(s)} = \frac{1}{c_a s + a_n}$$

where mg(s) is the Laplace transform of the mechanical load torque mg, ca is the generator's time constant of inertia, and an is the generator's adjustable coefficient Figure 4 shows the HTGS block diagram for the transfer function. Figure 4 shows that HTGS is a complex system that combines saturation nonlinearity with linear transfer functions to produce a complex system. To build a controller and do simulations, we utilize a nonlinear model like that.

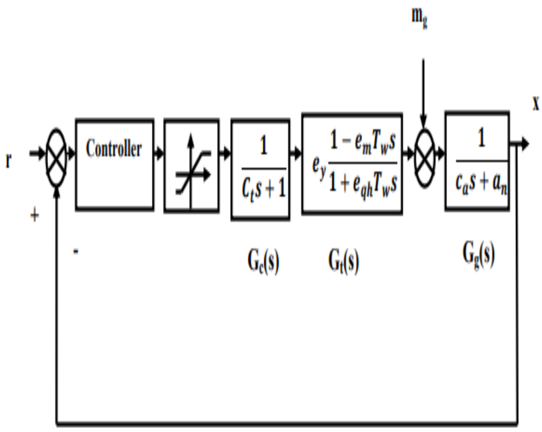

Figure 4 Block Diagram of Hydro Turbine Governing Systems Transfer Functions

Table 1 Model Parameters of HTGS

C_t	C_a	T_w	e_y	e_{qy}	e_h	e_{qh}	e_n
0.3	5.72	0.83	1.40	1.23	0.35	0.15	0.45

3. MULTI-OBJECTIVE EVOLUTIONARY COMPUTATION TECHNIQUES

As the name suggests, evolutionary computation techniques (ECT) are resilient search and optimization algorithms inspired by nature and created based on Darwin's theory of evolution and natural selection. Natural selection helps organisms survive in a changing environment such as climate conditions or food shortages and predator attacks. Natural selection and inheritance (crossover and mutation) play a role in the evolution of organisms over time. The finest living creatures will only be able to survive and pass on their genes to the next generation of living organisms. Living creatures that have evolved to the point where they have the best chance of surviving extreme environmental conditions will do so.

4. MULTI-OBJECTIVE GENETIC ALGORITHM (MOGA)

To tackle multi-objective issues, single-objective optimization methods are frequently used. It is possible that a multi-objective issue cannot be optimally solved using single-objective optimization methods because of the conflicts between the different goals. Single objective evolutionary computing methods utilize the "weighted average of goals" idea to solve multi-objective problems. Each objective's relative significance must be taken into account while determining the appropriate weight.

One of the most popular optimization methods is the Multi-Objective Genetic Algorithm (MOGA), which is an expanded version of single-objective optimization techniques that allows you to handle several objectives at once. The GA selection operator will be employed to determine the degree of pareto optimality, ensuring that each goal is treated individually. The forced integration of goals and priori knowledge is thus unnecessary. Because GAs are population-based, they provide a variety of options at once.

It was introduced and used by Fonseca & Fleming (1993) in MOGA, which is based on the pareto optimality idea. Fundamentally, there is a difference in the technique used to evaluate possible solutions between multi- and single-objective GA. An allocated vector will describe each solution's performance in relation to given criteria. Vectors in GA must first be converted into scalar values in order to make use of them. Ranking the solutions based on their fitness values and comparing them to one other may help accomplish this goal. Pareto dominance will be determined by comparing the individual solutions.

The particular solution J with corresponding fitness function f_J can be said to be a dominated solution or better solution than solution K with fitness function f_K , if the former has provided performance of at least as well the as the later across all objective and provides superior performance in at least one objective. The pareto dominance and pareto optimality can be defined as below (Deb 2001).

Definition 1 (Pareto dominance): A vector fj = (fj1 , fj2 , … . . fjm) is said to dominate a vector fk = (fk1 , fk2 , … . . fkm) , if and only if fj is partially less than fk , i.e., ∀ i ∈ {1,2, … . m}, fji ≤ fki A Ei ∈

{1,2, … . m}; fji ≤ fki , where fji /fki is the ith criterion value of the performance vector fj/fk.

Definition 2 (Pareto optimality): A point $J \in \Omega$ is pareto optimal if for every

$J \in \Omega$ and $I = \{1,2, \ldots m\}$ either $\forall i \in I (fi(J) = fi(J'))$ or there is at least one i ∈ I such that fi (J) > fi (J').

Figure shows an example of the minimising of two objective problems. To find out which solutions are most popular, we'll survey every person in every generation. The first place will be given to the non-dominant answer. The solutions that are dominated by a single point will be given a rank of 2, and the ranking procedure will be repeated for the remaining solutions. Using this approach, solutions will emerge along the pareto optimum point surface.

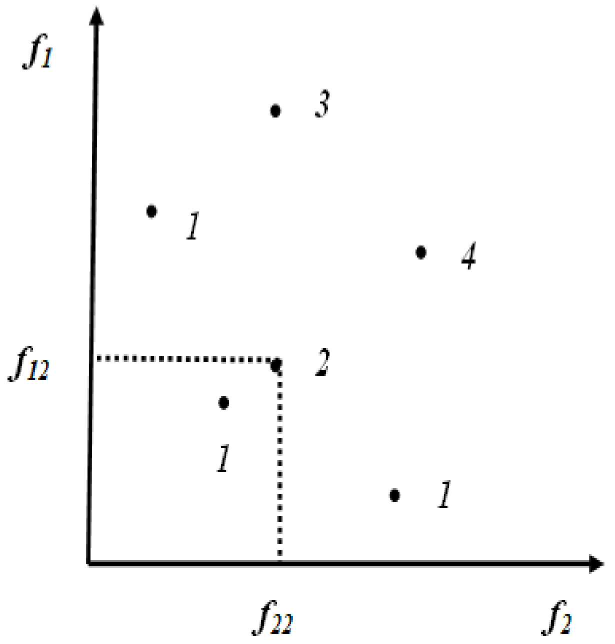

Figure 5 Pareto Ranking

5. Conclusion

Differential Evolution (DE) and Self-Adaptive Differential Evolution (SADE) have been described, as have single objective evolutionary computing methods such as Real-coded Genetic Algorithms (RGA), MPSO, and DE. A multi-objective optimization problem was used to reduce the control energy of the suggested controller, which dictates actuator size and cost. The current study looked at the potential of using multi-objective evolutionary computing methods for boiler-turbine system optimum nonlinear finite time convergent controller design in order to simultaneously minimise competing goals such as ISE and control energy.

After obtaining a suitable mathematical model, an effort may be made to build a nonlinear controller for the boiler-turbine system that also ensures better environmental quality, decreased throttling losses between actuators, and increased process efficiency. Complex boiler-turbine system problems may benefit from the use of the latest/hybrid optimization techniques. Fuzzy/neural networks may be used in conjunction with evolutionary computing methods, and the statistical performance can be verified. Multi-objective optimization issues may benefit from research that incorporates extra goals like ambient quality, process efficiency, and so on to increase the number of objectives to more than two.

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