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Load Frequency Control of Small Hydropower Plants Using One-Input Fuzzy PI Controller with Linear and Non-Linear Plant Model

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Abstract

This study presents an intelligent approach for load frequency control (LFC) of small hydropower plants (SHPs). The approach which is based on fuzzy logic (FL), takes into account the non-linearity of SHPs—something which is not possible using traditional controllers. Most intelligent methods use two-input fuzzy controllers, but because such controllers are expensive, there is economic interest in the relatively cheaper single-input controllers. A non-linear control model based on one-input fuzzy logic PI (FLPI) controller was developed and applied to control the non-linear SHP. Using MATLAB/Simulink SimScape, the SHP was simulated with linear and non-linear plant models. The performance of the FLPI controller was investigated and compared with that of the conventional PI/PID controller. Results show that the settling time for the FLPI controller is about 8 times shorter; while the overshoot is about 15 times smaller compared to the conventional PI/PID controller. Therefore, the FLPI controller performs better than the conventional PI/PID controller not only in meeting the LFC control objective but also in ensuring increased dynamic stability of SHPs.

Keywords

Small Hydropower Plant, Linear and Non-Linear Model, Load Frequency Control, Non-Linear Control, Fuzzy Logic Controller, Renewable Energy

1. Introduction

Global awareness of the environmental problems associated with fossil fuel-based energy generation and the necessity to ensure sustainable development have led to increased interest in harnessing and exploiting various renewable

energy sources, including biomass, solar, wind, and hydropower. Hydropower is the major source of renewable energy but large-scale hydropower generation is constrained because of high financial investments, high gestation periods, and issues with rehabilitation of displaced populations [1].

Small-scale hydropower, comprising pico, micro, mini, and small hydropower plants have relatively fewer constraints and thus are the preferred renewable energy source, especially for low-income countries. But the inability to meet technical requirements such as constant voltage and frequency may limit exploitation of even the smallest of hydropower capacities (pico hydro). This study focuses on small hydropower plants, the highest capacity energy source within the category of small-scale hydropower. According to the European Small Hydropower Association (ESHA), the European Commission (EC), and the International Union of Producers and Distributors of Electricity (UNIPEDE), small hydropower plants (SHPs) refer to hydropower plants with installed capacities ranging from 1 MW to 10 MW [2] [3]. Such capacities are very suitable for the electrification of rural localities in developing-country environments which are isolated, far from the grid, and lack skilled labor to operate and maintain the hydropower equipment [4] [5].

In recent years, we are experiencing increased demand for electrical energy in all sectors of human activity. One way to satisfy this demand is through decentralized electricity production; which can be readily achieved through the deployment and use of SHPs. Currently about 66% of the global SHP potential of 229,142 MW is not yet developed [6]; and given the worldwide increase in power demand, there is dire need for the injection of renewable energy sources in to the power grid. SHPs with the appropriate controllers are a suitable source for such injection by being incorporated into micro grids that can ultimately be integrated to the national grid. The pursuit of renewable energy resources as a means of combating greenhouse gas has also heightened interest in the exploitation of SHP. Furthermore, SHPs have been recognized as the most valuable low cost energy production system [7] and many countries view SHPs as a technology that can enhance energy security, accessibility, reliability, and affordability and therefore support sustainable development and growth [8].

Despite the increased interest in SHPs, widespread exploitation of SHPs is limited due to many factors, including technical operation requirements and non-technical barriers such as restraining legal and regulatory frameworks [6]. For isolated rural communities to be completely and comfortably dependent on SHPs as energy sources, SHPs must be able to provide uninterrupted power daily at the required voltage and frequency. In order to maintain the voltage and frequency within the stipulated limits, controls are required on the SHP. Voltage is maintained constant by controlling the excitation of the generator; while frequency is maintained constant by eliminating mismatch between generation and load demand.

This study focuses on load frequency control. Load frequency is an important quality performance index for SHPs; its effective control ensures the achieve-

ment of rated power and voltage for specified load demand, *i.e.*, maintaining the speed value constant with variation in load demand. Research indicates that variation in frequency leads to stability problems [9], and so, load frequency control (LFC) of SHPs is not only essential for performance but is mandatory for the efficient supply of electrical power of good quality [1] [2].

In essence, the LFC objective of SHPs is to ensure that the actual frequency of the SHP is the same as the desired frequency. In other words, any change in frequency (delta omega) at any specific time must be equal to zero for the desired performance. This requires matching generation with load at all times to ensure constant frequency for various daily load variations [4]. LFC in SHP is achieved through the primary control system, whose role is to maintain the angular speed constant with respect to its nominal value [10] and by doing so, real power is balanced in the energy system [11].

Frequency control techniques applied to SHPs can be classified as traditional and intelligent. The traditional techniques which include the use of conventional PI/PID controllers and various electronic devices are the oldest techniques in the history of control and have found the widest application in the industry. But these techniques, especially the conventional PI/PID controllers are not only time-consuming when it comes to fine-tuning them, but are also linear, and not suitable for non-linear systems such as SHPs. Consequently, intelligent control techniques have emerged as an alternative to conventional PI/PID controllers. Intelligent controllers developed on the basis of fuzzy logic have been widely used in the control of stand-alone and micro-grid connected hydropower plants [9] [12] [13].

Most intelligent techniques use two- or multiple-input fuzzy controllers. However, because such controllers are expensive, there is an economic interest in single-input controllers which are relatively cheaper. With the foregoing considerations, the main objective of this study is to develop a non-linear control model based on a one-input fuzzy logic PI (FLPI) controller and subsequently apply it to control the non-linear real-world model of the turbine governor system of SHPs. Attention is focused on the non-linear models of hydraulic turbines proposed by the IEEE Working Group on Prime Mover and Energy Supply Models for System Dynamic Performance Studies [14] [15] to develop a hydro turbine governor control system based on a one-input, one-output fuzzy controller associated with a PI controller. The rest of this paper is presented as follows: In Section 2, we present the dynamics and models of the relevant components of the SHP. Section 3 is dedicated to the fuzzy logic control system for the SHP. Section 4, presents the simulation results and discussions; and Section 5 concludes with discussions on the results and direction for further research.

2. Dynamics and Modelling of Small Hydropower Plant (SHP)

2.1. Physical Plant Model

The schematic diagram of a physical SHP presented in **Figure 1** [16] depicts the

permanent magnet synchronous generator (PMSG), turbine, penstock, and water reservoir/river flow arrangement, with hydraulic head, h and flow rate q.

Water from the reservoir at a higher height is conveyed by the penstock to the turbine system at the lower end of the river over the head, h. The penstock is equipped with a gate system that controls the water inlet into the turbine system. The turbine system converts the potential and kinetic energy in the water that falls over the head, h, into hydroelectricity. For modeling purposes, we consider the hydraulic turbine model to embody the dynamics of the penstock, tunnel, servomotor and turbine, alongside with the head losses as depicted in **Figure 1** [16]. The schematic representation of the LFC is presented in **Figure 2** [17] with T_m, the Mechanical Torque exerted on the rotating machine by the turbine, the Electrical Torque exerted on the machine by the generator T_e, the Mechanical Power input P_m, the Electrical Power output P_e, and the Load P_l.

Of relevance to this study are models of the servomotor, turbine, penstock, and generator; which are examined in the next subsections.

Servomotor Model: The servomotor manages the gate position and in the process ensures the control of water flow into the turbine to generate power in the SHP. The conventional model of servomotor can be represented as in Equation (1) [18]:

$$T_y \frac{dy}{dt} = u(t) - y(t) \tag{1}$$

where;

T_Y is the time constant of the servomotor.

y is the gate position, and u is the input control.
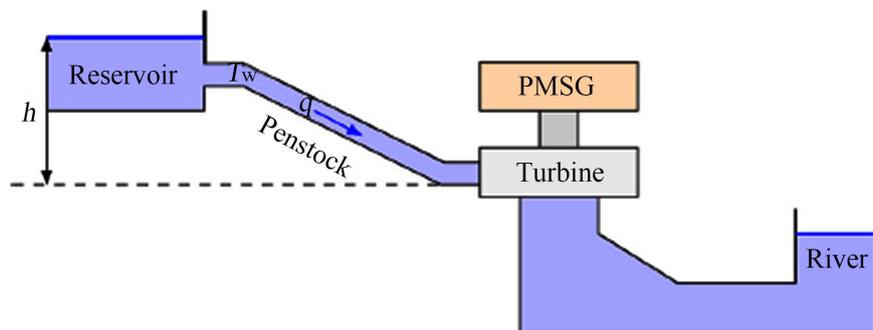
Figure 1. Schematic diagram of a SHP [16].
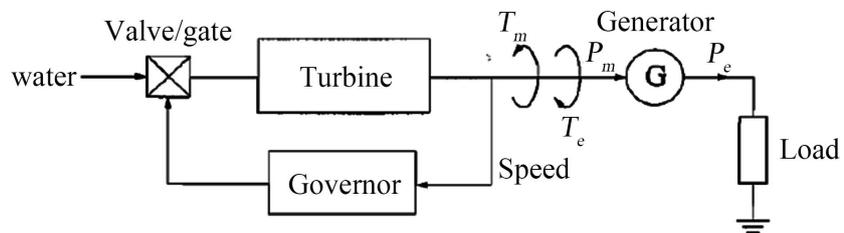
Figure 2. Schematic representation of LFC system [17].

In previous research, the input control has generally been achieved by using conventional PID controllers [19]. For the simulation in MATLAB/Simulink, the gate servomotor is modelled as a second order system with gain, Ka and time constant Ta as shown in **Figure 3** [14] [15]:

Turbine and Penstock Model: The approximate transfer function of the turbine and penstock component for the analyses is given by Equation (2) [20] [21]:

$$G_t(s) = \frac{-T_w s + 1}{0.5 T_w s + 1} \tag{2}$$

where;

T_w is the water starting time constant in the penstock.

s is the Laplace transform complex variable operator.

Generator-Load Model: The combined transfer function for the generator load model is shown in **Figure 4** [22] [23].

This model gives the relation between the change in frequency (Δf) as a result of the change in generation (ΔPG) when the load changes by a small amount (ΔPD) [23].

2.2. Simulation of Plant Model

Given the physical plant models presented above, the simulation model of the SHP was developed by using the blocks available in MATLAB/Simulink SimScape. The block diagram for the simulation is depicted in **Figure 5**.

3. Fuzzy Control System

3.1. Brief Overview

Fuzzy control is based on mathematical foundations of fuzzy set theory, first introduced by Zadeh in 1965 [24]. In fuzzy control, fuzzy rules are used to represent knowledge or experience in a mathematical format such that the process and system dynamic characteristics can be described by fuzzy sets and fuzzy relational functions. Ultimately, control decisions are generated based on the fuzzy sets and functions.
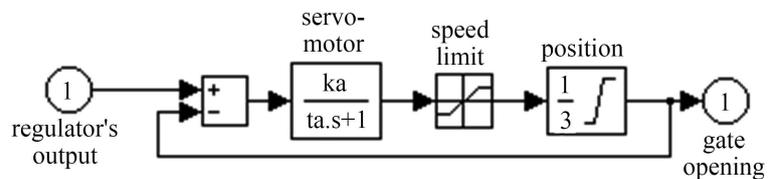
Figure 3. Servomotor model [15].
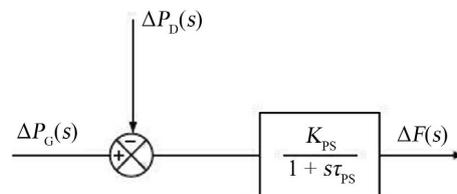
Figure 4. Generator-Load model [22] [23].
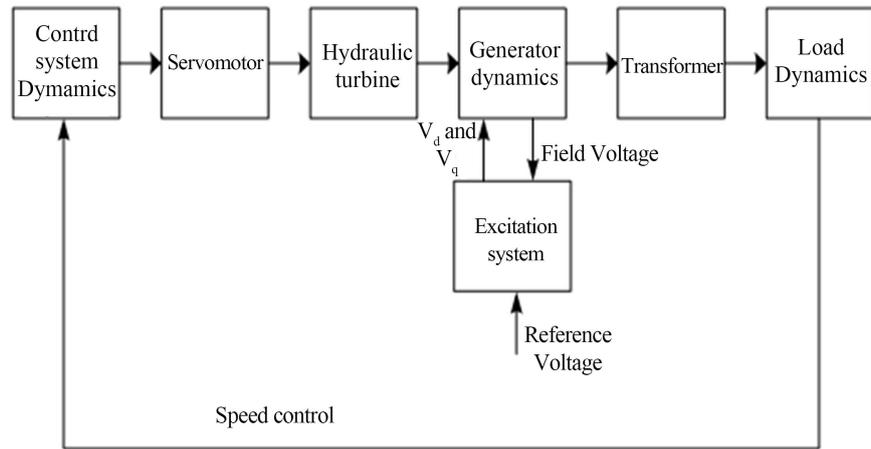
Figure 5. Block diagram of SHP.

The fuzzy logic controller (FLC) owes its popularity to its ability to operationize linguistic control; wherein an exact mathematical model for the system to be controlled is not required as opposed to other control strategies that require crisp numerical values. Fuzzy logic control basically tries to replicate the human thought process in its control algorithm, using linguistic variables; which in effect are variables whose values are words rather than numbers.

Fuzzy control system design essentially entails three major steps: First, choosing the fuzzy controller inputs and outputs. Choosing the input entails identifying what to control, while choosing the output entails specifying what we should observe as a result of controlling the input(s). Second, choosing the pre-processing that is needed on the controller inputs and possibly post-processing that is required on the outputs. In other words, the second step entails doing what is required to get the inputs and outputs in the appropriate format, respectively for the fuzzy controller and real-world operations (conditioning the input(s) and output(s) of the fuzzy controller). Third, designing the components of the fuzzy controller as depicted in the block diagram of **Figure 6** [25].

The fuzzy controller is composed of the following elements [25] [26]:

1) A knowledge base, which includes a data base and rule-base. The data base contains data about the plant while the rule-base contains a fuzzy logic quantification of the expert's linguistic description of how to achieve required control.

2) A fuzzy inference engine, which emulates the expert's decision making process in interpreting and applying knowledge about how best to control the plant. In its operation, the inference engine determines the extent to which a rule is relevant to current control requirements and draws conclusions on the current inputs and the rules, resulting in the firing of rules and establishment of the state of the outputs.

3) A membership function which specifies the degree to which a given input corresponds to a given set or is related to a control concept linguistically.
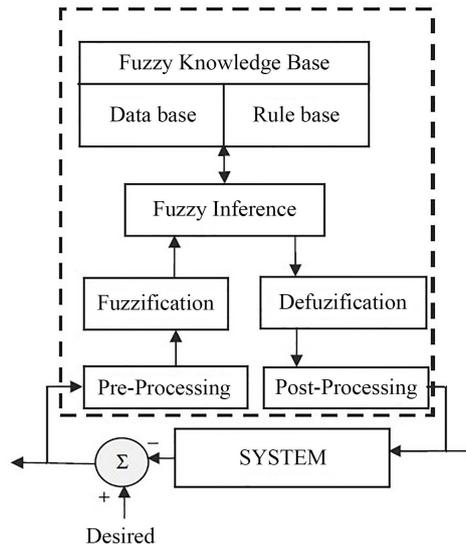
Figure 6. Structure of the fuzzy controller [25].

4) A fuzzification interface or module, which transforms the crisp controller inputs into fuzzy sets that the inference engine uses to activate and execute rules. In effect, the fuzzification process ensures the mapping of the crisp value of inputs to linguistic variables using membership functions.

5) A defuzzification interface, which transforms fuzzy outputs (conclusions) from the fuzzy inference engine into crisp outputs, that serve as the actual inputs for the process under control.

3.2. Design of the Fuzzy PI Controller

According to the standard IEC: 60034, the normal frequency variation in a power network should be within 2% of the reference frequency. For a power system with standard frequency of 50 Hz, this means a controller should not allow frequency variations below −1 Hz and above +1 Hz. Consequently, the required operational frequency ranges from +49 Hz to +51 Hz. Frequencies out of this range are judged to be disturbance by the control technique in place; which ultimately triggers the electrical protections of the SHP in reaction to such disturbances.

The modeling of the FLC was done in MATLAB Simulink; and the Mamdani-type fuzzy controller selected in view of its simplicity. Fuzzy rules were formulated using Mamdani-type fuzzy rules which comprised "IF-THEN" conditional statements [13]. For economic reasons, the controller was designed with only one input (the frequency error $e(t)$) as reflected in Equation (3). The system produces one output, which serves as servomotor input signal $u(t)$, Equation (4)).

$$dw = e(t) = f_{ref} - f(t) \tag{3}$$

$$u(t) = K_p e(t) + \frac{1}{\tau} \int_0^t e(t) \, dt \tag{4}$$

where;

$e = dw$: speed deviation (pu).

f_{ref}: reference frequency (1 pu).

$f(t)$: instantaneous frequency.

K_p and τ are the proportional and time constants.

$e(t)$ is the instantaneous error.

The pre-processing and post-processing elements were chosen after performing several tests to select the appropriate combination corresponding to the system. Seven linguistic variables were selected for the input and output of the fuzzy logic controller with corresponding values as depicted in Table 1.

Figure 7 and Figure 8 depict the input and output membership functions respectively.

The fuzzy rules applied to the FLC are presented in Table 2. As an example, one rule would read as follows: "IF *dw* is NS THEN *u* is NS" and is represented as the bold entry in the Fuzzy Rule Table of the system (Table 2). This can be interpreted physically as follows: If the frequency increases by a small amount *i.e.* more than 1 pu (due to a little decrease in load demand), then the output signal should close the valve by a small amount. The system nonlinearity can be viewed by the control surface shown in Figure 9.
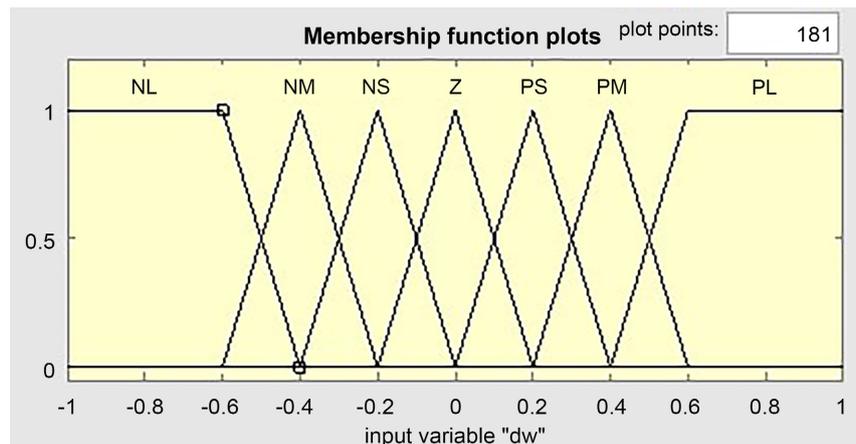
Figure 7. Membership function of fuzzy logic control input.
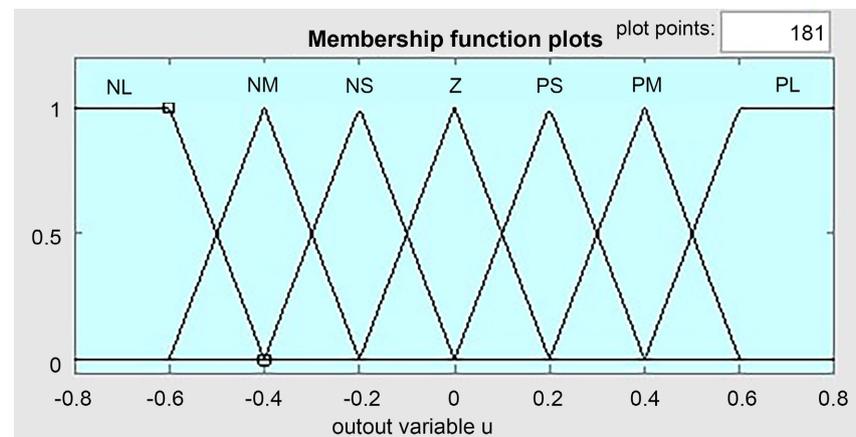
Figure 8. Membership function for fuzzy logic control output.

Table 1. Linguistic variables and values for fuzzy logic controller.

Linguistic variable	Abbreviation	Value
"Negative Large in size"	NL	−0.6
"Negative Medium in size"	NM	−0.4
"Negative Small in size"	NS	−0.2
"Zero"	Z	0
"Positive Small in size"	PS	0.2
"Positive Medium in size"	PM	0.4
"Positive Large in size"	PL	0.6

Table 2. Fuzzy rule table of FLPI controller output.

dw	−0.6	−0.4	**−0.2**	0	0.2	0.4	0.6
u	−0.6	−0.4	**−0.2**	0	0.2	0.4	0.6
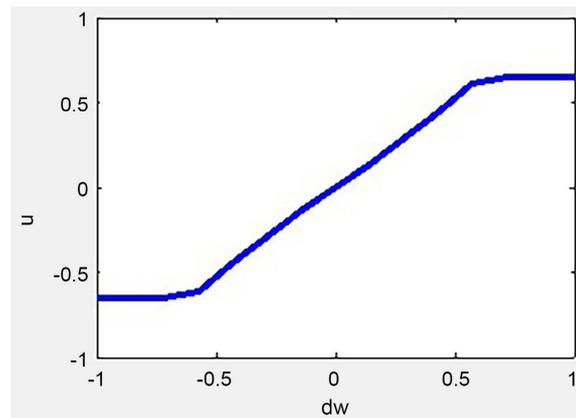
Figure 9. Control surface (nonlinearity) of fuzzy logic controller.

Several techniques have been used for defuzzification, including max-membership, centroid (centre of gravity), weighted-average, and mean-max technique [25] [26]. In this study, the Centre of Gravity (COG) method was used for its popularity. The final output COG (G), is then calculated as the average of the individual centroids of each rule, weighted by their heights as indicated in Equation (5) [26]:

$$COG = \frac{\sum_{i=1}^{R} x_i \int \mu_{(i)}}{\sum_{i=1}^{R} \int \mu_{(i)}} \tag{5}$$

where;

COG: defuzzification output.

$\mu_{(i)}$: membership function.

R: number of rules.

x_i: centre of membership function (where it reaches the peak in our case).

The final control system taking into account the designed fuzzy logic controller, the pre-processing and post-processing elements associated to a PI controller is shown in **Figure 10**.
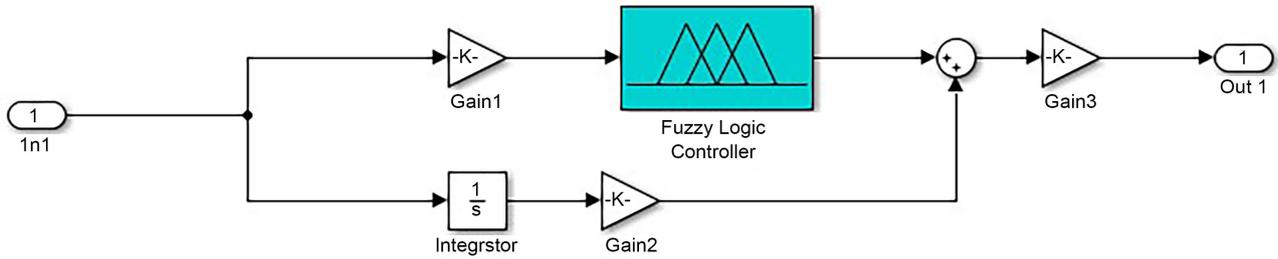
Figure 10. Fuzzy PI control system for the SHP.

4. Results and Discussions

In this study, load-frequency control using a linear and non-linear model of turbine and generator was proposed and simulated for an off-grid SHP. The linear and non-linear plants were designed and modeled using the MATLAB-SIMULINK software. A Fuzzy Logic Proportional Integral (FLPI) controller was applied to the SHP. The controller regulates the wicket gate position according to the load via the servomotor. The servomotor keeps the gate open or closed until the power production equals the power demand and the reference frequency is attained. The servomotor which is regulated by the controller is the governor of the system.

Two models were simulated and are characterized as follows:

Linear plant model (adequate for load variations below 10% of rated power) and

Non-linear plant model (adequate for load variations above 25% of rated power).

4.1. Linear Plant Simulation

The disturbance (demand change) was taken to be 3% of the rated power. We simulated two cases for the linear plant model: Linear plant with PID controller and Linear plant with FLPI controller. The block diagrams of the simulations are shown in Figure 11. The simulation results are shown in Figure 12, and the performance comparison is shown in Table 3.

4.2. Non-Linear Plant Simulation

Three cases were simulated for the non-linear plant model: case of no controller, case of a PI controller, and case of Fuzzy PI controller. With various considerations, we simulated SHP operations, briefly described below:

1) The simulation duration time of 250 seconds: An assumption was made that each load (except the plant load) has a reactive power of 130 kVar.

2) At the beginning of the simulation, there is a load demand of 700 kW and a plant load of 50 kW, hence there is a total load demand of 750 kW, that is 0.46875 pu. This will lead to a rise in frequency since the total demand is lower than the rated capacity of the alternator (1.45 MW). Hence the FLC interprets this to be a loss of 700 kW load.
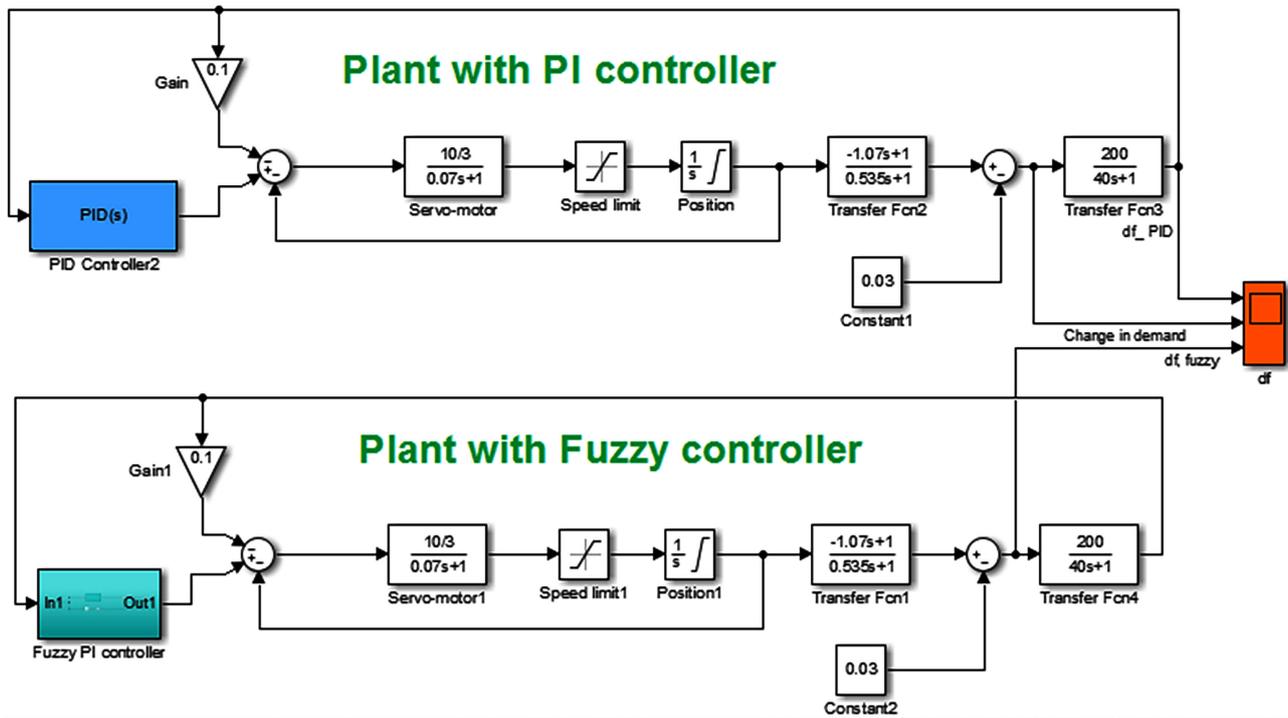
Figure 11. Linear plant model block simulation.
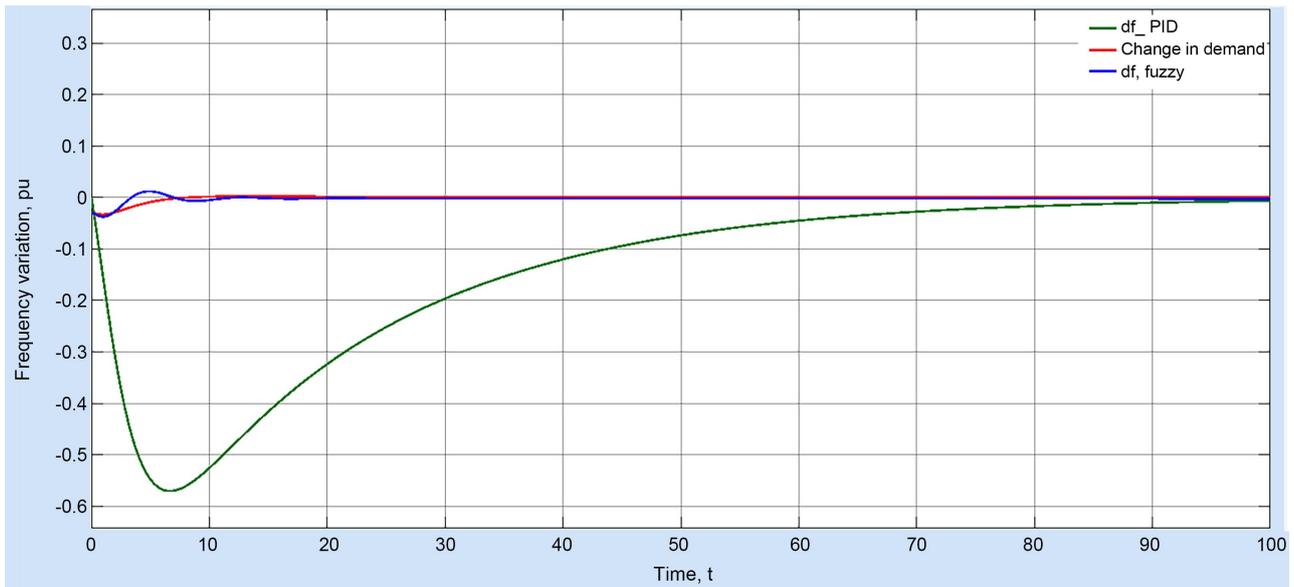
Figure 12. Linear plant model results.

Table 3. Performance comparison for linear plant model.

	Small Hydropower Plant	
Performance Parameter	**PI/PID controller**	**FLPI controller**
Settling time [s]	95	12.5
Maximum peak Overshoot [Hz]	−0.58	−0.04

3) Next, two separate loads of 400 kW and 200 kW are connected to the network via two circuit breakers which are in a closed state in the time intervals of [50, 160] seconds and [100, 160] seconds respectively. These increases in demand during the specified time interval will lead to a drop-in frequency.

4). At time $t = 160$ seconds, there is a sudden load loss of 400 kW and 200 kW (600 kW). This will lead to a rise in frequency.

Figure 13 presents the frequency curves for the three cases indicated in the legend, while the block diagrams of the simulations are shown in **Figure 14**.

The results for the plant simulation without the use of a controller show a non-regulation of the plant frequency back to the nominal frequency. This justifies the need of a controller since the rotor of the alternator will never turn at its normal speed after any sudden disturbance. For this not to happen, most SHPs function at full power potential and the active power control is done only at the level of the ELCs and ballast loads.

The impact of the FLPI controller can better be appreciated by comparing its performance to that of the conventional PI/PID controller in terms of two important power systems dynamics performance parameters: settling time and overshoot. Reduced settling time reduces generating costs while reduced overshoots help prevent corrosion of electrical machines, and so ensure overall lower cost in the exploitation of SHPs. From the simulation, it is observed that the FLPI controller has: 1) shorter settling time (about 8 times shorter than that of the conventional PI/PID controller), and 2) lower overshoot (about 15 times smaller than that of the conventional PI/PID controller). These observations indicate that FLPI controllers serve the purpose of LFC of SHPs better than conventional PI/PID controllers; while at the same time ensuring the dynamic stability (robustness) of the SHP.
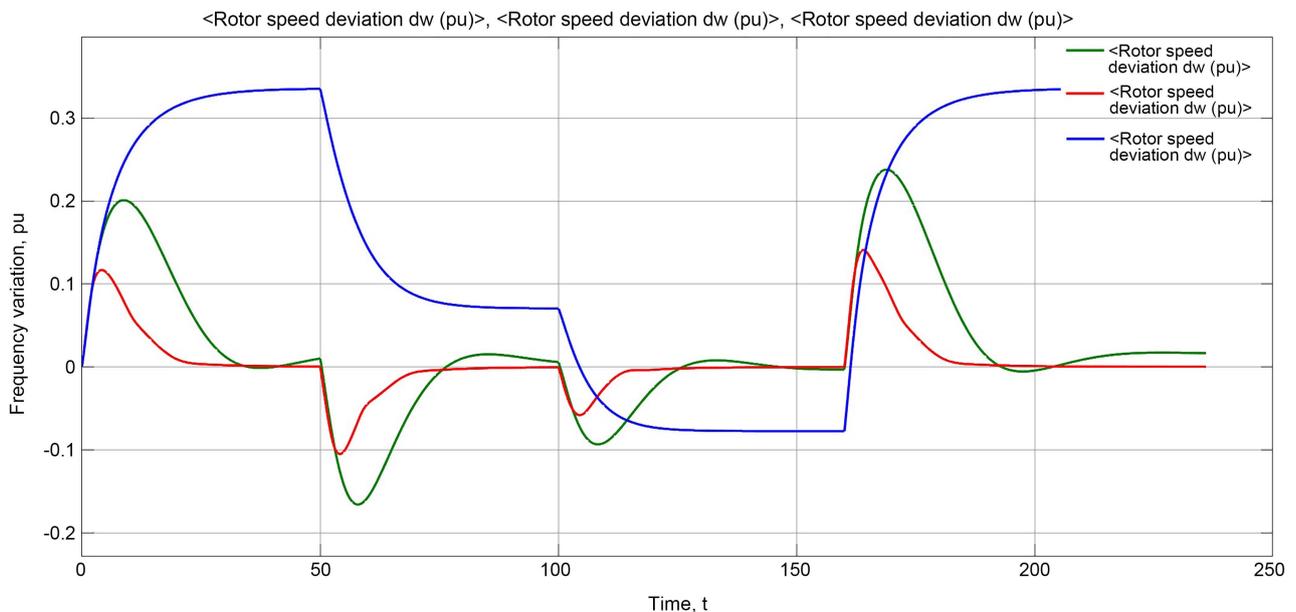
Figure 13. Variation of frequency due to load variation for three cases.
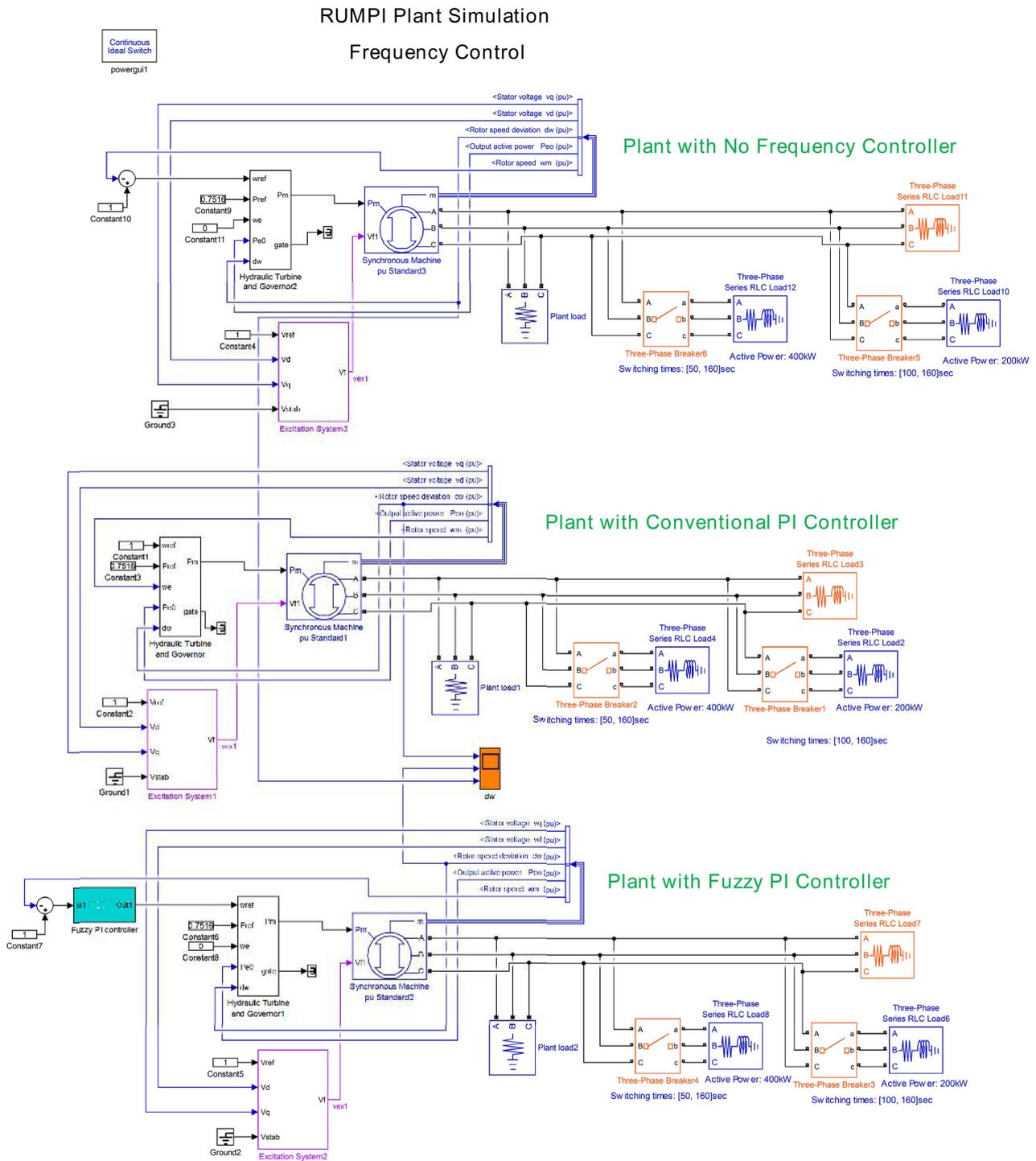
Figure 14. Non-Linear model block simulation.

5. Conclusions

Load frequency is an important quality performance index for small hydropower plants (SHPs). SHPs are non-linear and the widely used conventional PI/PID controllers are not suitable for load frequency control (LFC); and as such, there is a need for non-linear controllers. In this study, a non-linear control model

based on one-input fuzzy logic PI (FLPI) controller, which is cheaper than a two-input controller was developed and applied to control the non-linear SHP. The performance of the FLPI controller was investigated and compared with that of the conventional PI/PID controller. Simulation results show that the settling time for the FLPI controller is about 8 times shorter; while the overshoot is about 15 times smaller compared to the conventional PI/PID controller. Consequently, the FLPI controller has been shown to perform better than the conventional PI/PID controller not only in meeting the LFC control objective but also in ensuring increased dynamic stability of SHPs.

Directions of future research include development of more advanced cost-effective controllers for SHPs, identifying strategies to overcome barriers to widespread exploitation of SHPs, and integration of SHPs with other renewal energy sources such as solar photovoltaic in hybrid renewable energy systems. The combination of SHPs with other renewables is particularly important because it helps to off-set fluctuations in energy supply of isolated SHPs due to any seasonal variation of water flow.

Statement on Funding and Data Availability

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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