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# Fuzzy Logic Based Proportional Integral Control of Frequency for Small Hydropower Plant

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**Abstract** Small hydropower is one of the most cost effective and reliable energy technologies to be considered for providing clean electricity. Any mismatch between generation and demand causes the system frequency to deviate from its nominal value. Thus high frequency deviation may lead to system collapse. This necessitates a very fast and accurate controller to maintain the system frequency. The frequencies of the existing small hydropower plants are controlled by mechanical governors. However, these governors are costive, complex and not fast in response. In this paper simple, less cost and fast response fuzzy logic based proportional integral (PI) controller of frequency for small hydropower plant is modeled, designed and simulated by Matlab/Simulink. The frequency controller controls the flow rate of water by acting on stepper motor and keeps the frequency of the small hydropower system nearly constant. Finally the simulation results of conventional PI controller is compared with fuzzy PI controller and proved that Fuzzy PI controller yields better control performance.

**Keywords** Fuzzy logic controller, Hydraulic turbine model, PM Stepper motor, PI Controller

## 1 Introduction

Nowadays renewable energy is becoming more and more popular as it is a sustainable and environment friendly source of energy. Hydropower plants are clean sources of energy that convert potential energy of water into electricity and they are much more reliable and efficient source of energy than the fossil fuel power plant. Energy is a fundamental thing for society and economic growth of any country. SHPP (Small Hydropower plant) are used to electrify residential homes, cottages, ranches, lodges, parks, factory, industries and small communities [1]. An increased access to electricity enhances opportunities form industrial development and improves health and education. A SHPP consists of diversion dam, conveyance of water system, forebay, penstock, wicket gate, powerhouse, tailrace structure of the body and electrical and mechanical equipments [2].

Generation capacity of small hydropower plants ranges from 1MW to 50MW [3]. One of the challenges in developing small hydropower plants is the control system. In a power system, usually, voltage and frequency are controlled separately. Voltage is maintained by control of reactive power of the synchronous generator. Most commercial synchronous generators have built-in automatic voltage regulators. The frequency of a small hydropower system exclusively depends on real power balance. Thus, the objective of this paper is to model, design and simulate a less expensive, less complex and fast response frequency control system for small hydropower plants.

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In a power system operation, load frequency control is important for supplying efficient electrical power of a good quality. Frequency of a power system depends on power system active power balance and should remain nearly constant in different operating conditions. Frequency is a common parameter throughout the system and a change in active power generation or demand at one bus affects the whole system frequency [4]. Many control techniques have been used for this operation [5, 6]. But, these conventional governors are not suited for frequency control of small hydropower systems, because of their cost, slow in response and complexity.

## 2 Frequency controllers Scheme

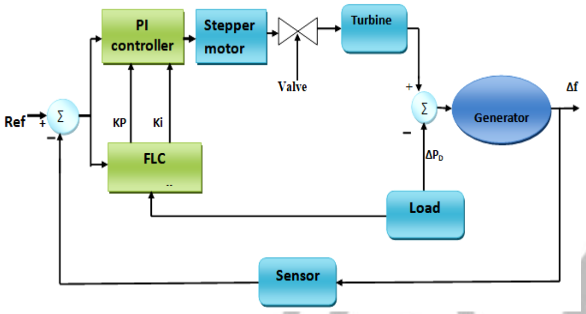

**Fig.1** Frequency control scheme of small hydropower plant

## 3 Dynamic Model of Small Hydropower Plant

Mathematical modeling is the process of representing the dynamic behavior of a physical system by set of mathematical equations. The most commonly used mathematical models in designing a control system are differential equation model, state space model and transfer function model. In this paper, to model the small hydropower system component transfer function model is used.

### 3.1 Hydraulic Turbine Modeling

Hydraulic turbines convert potential energy of flowing water into mechanical energy in the form of rotating shaft. There are two types of turbine models from these linear turbine model is used in this paper which is expressed as [7].

$$\frac{\Delta \overline{p_m}}{\Delta \overline{G}} = \frac{1-0.5T_w s}{0.5T_w s+1} \tag{1}$$

Where, $T_w$ water starting time and given by

$$T_w = \frac{LU_o}{a_g H_o}$$

### 3.2 Synchronous Generator and load Modeling

Generator is an electrical component which converts mechanical energy of the prime mover to electrical energy and it has different ratings. The model of the synchronous generator is derived from the swing equation [8].

$$\Delta \overline{\omega_r}(s) = \frac{\Delta \overline{p_m}(s) - \Delta \overline{p_e}(s)}{2Hs} \tag{2}$$

The overall frequency-dependent characteristics of a composite load can be expressed as [9].

$$\Delta \overline{p_e}(s) = \Delta \overline{p_D}(s) = \Delta \overline{p_l}(s) + D\Delta \overline{\omega_r}(s) \tag{3}$$

Where, $\Delta \overline{p_e}(s)$ is electrical power output, $\Delta \overline{p_D}(s)$ is power demanded; $\Delta \overline{p_l}(s)$ is non frequency sensitive consumer load changes; $D\Delta \overline{\omega_r}(s)$ is frequency sensitive load changes. Now, by substituting Equation (3) into Equation (2), we get load model which is given by

$$\Delta \overline{\omega_r}(s) = \frac{\Delta \overline{p_m}(s) - \Delta \overline{p_l}(s)}{2Hs + D} \tag{4}$$

### 3.3 Stepper Motor modeling

Stepper motor is used for controlling the spear valve of a small hydropower system. The mathematical model of the PM stepping motor is developed from two main equations [10].

- Rotor dynamic equation (the motion of PM stepper motor)
- Voltage equation for stator winding

For load torque disturbances about the operating point at the end of the step and the initial load torque equal to 0, the transfer function is a second-order system [10].

$$\Delta\theta(s) = -\frac{\Delta T_L(s) N_{RT}}{Js^2 + Ds + \sqrt{2} K_T I N_{RT}} \tag{5}$$

Where, J is the moment of rotor inertia (Kg.m$^2$), D is viscous damping coefficient, $K_T$ is constant, I is the currents in windings and $N_{RT}$ is a number of rotor teet h and all parameters are given in Appendix.

## 4 Design of the control system of SHPP

### 4.1 PI controller Design

The process of selecting the controller parameters to meet a given performance specification is known as controller tuning. Ziegler-Nichols(ZN) tuning rule was the first such effort to provide a practical approach to tune a PI controller. Ziegler-Nichols tuning method is used in this paper and I set the values of the parameters Kp and $T_i$ according to the formula shown in the Table1.below. Then, the PI controller parameters are determined from critical gain (Kcr) and critical period (Pcr) of the system transfer function and the initial gains $k_{po}$ and $k_{io}$ are found to be $k_{po}$=0.266 and $k_{io}$=0.823.

**Table 1**Tuning of PI controller Parameter according to ZN Tuning (second method) [12]

| Controller | $K_p$ | $T_i$ |
|---|---|---|
| P | 0.5 $k_{cr}$ | --- |
| PI | 0.45$k_{cr}$ | $\frac{1}{1.2}$ |

### 4.2 Design of Fuzzy Logic Controller

Fuzzy logic is an artificial intelligent control that deals with reasoning algorithms used to strive human thinking and decision making in machines. The following steps are applied to design the fuzzy logic controller.

- Fuzzification
- Rule base
- Inference Engine
- Defuzzification should be designed appropriately.

As shown in Fig. 1, two coefficients $K_p$ and $K_i$ of a PI controller are tuned by using the fuzzy logic controller. Input variables of the fuzzy inference system are error and load information and output variables of the fuzzy inference system are $K_p$ and $K_i$ parameters.

The membership functions for the input and output variables are shown in Fig.2, Fig.3, Fig.4 and Fig.5. The linguistic variables are NL, NM, NS, NVS, ZR, PVS, PS, PM and PL, where ZR is zero; PS is positive small; PM is positive medium; NL is Negative large; PL is positive large; PVS is positive Very small; NM is Negative medium; NS is Negative small and NVS is Negative Very small. The range of input variable for frequency error is taken to be [-0.05 0.05]. Hence the standard frequency deviation in any electric power system should not be greater than 5% of the nominal frequency [11].Kp and Ki parameters were taken as [-0.975, 0.975]. In this paper, the rules are presented to the controller in a format similar to the one below

**Rule 1**: IF X is $A_1$ and Y is $B_1$, THEN $K_P$ is $C_1$ and $K_i$ is D1.

**Rule 2**: IF X is $A_2$ and Y is $B_2$, THEN $K_P$ is $C_2$ and $K_i$ is D2.

**Rule K**: IF X is $A_K$ and Y is $B_K$, THEN $K_P$ is $C_K$ and $K_i$ is $D_K$.

Rule tables are also developed for $K_p$ and $K_i$ as shown in (table 2 and table 3). The fuzzy logic control rules are determined from practical experience and simulations in order to obtain maximum performance for the controller. Fuzzy logic controller is designed as Mamdani type and max-min inference process is used. The centroid method is chosen as defuzzification method.

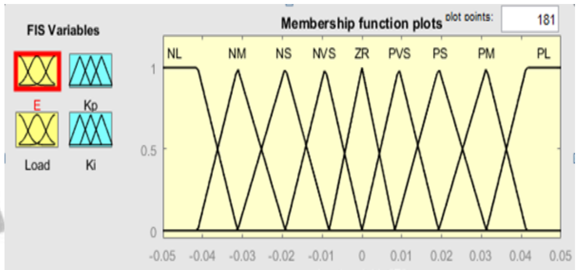

**Fig.2** Input membership function for frequency error

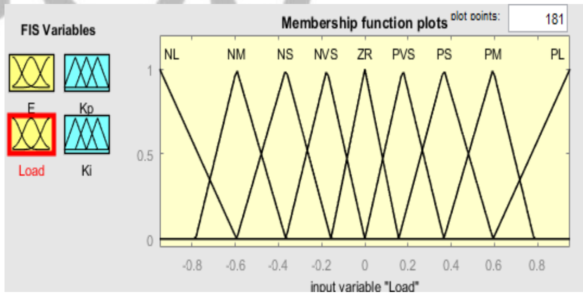

**Fig.3** Input membership function for load

**Table 2** Rule table for output Kp

| **Error** | **Load** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **NL** | **NM** | **NS** | **NVS** | **ZR** | **PVS** | **PS** | **PM** | **PL** |
| **NL** | **PL** | **PL** | **PM** | **PM** | **PL** | **PS** | **PS** | **ZR** | **ZR** |
| **NM** | **PL** | **PL** | **PM** | **PM** | **PM** | **PS** | **PS** | **ZR** | **PVS** |
| **NS** | **PL** | **PM** | **PM** | **PS** | **PS** | **PS** | **ZR** | **PS** | **PS** |
| **NVS** | **PS** | **PS** | **PS** | **PS** | **ZR** | **PVS** | **PS** | **PS** | **PM** |
| **ZR** | **PL** | **PM** | **PS** | **PVS** | **ZR** | **NVS** | **NS** | **NM** | **NL** |
| **PVS** | **PS** | **PS** | **PVS** | **ZR** | **NVS** | **NS** | **NS** | **NM** | **NM** |
| **PS** | **PM** | **PS** | **ZR** | **NS** | **NS** | **NS** | **NM** | **NM** | **NL** |
| **PM** | **PVS** | **ZR** | **NS** | **NS** | **NM** | **NM** | **NM** | **NL** | **NL** |
| **PL** | **ZR** | **ZR** | **NS** | **NS** | **NL** | **NM** | **NM** | **NL** | **NL** |

**Table 3** Rule table for output Ki

| Error | Load | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | NL | NM | NS | NVS | ZR | PVS | PS | PM | PL |
| NL | NL | NL | NM | NM | NL | NS | NS | ZR | ZR |
| NM | NL | NL | NM | NM | NM | NS | NS | ZR | NVS |
| NS | NL | NM | NM | NS | NS | NS | ZR | NS | NS |
| NVS | NS | NS | NS | NS | ZR | NVS | NS | NS | NM |
| ZR | NL | NM | NS | NVS | ZR | PVS | PS | PM | PL |
| PVS | NS | NS | NVS | ZR | NVS | PS | PS | PM | PM |
| PS | NM | NS | ZR | PS | PS | PS | PM | PM | PL |
| PM | NVS | ZR | PS | PS | PM | PM | PM | PL | PL |
| PL | ZR | ZR | PS | PS | PL | PM | PM | PL | PL |

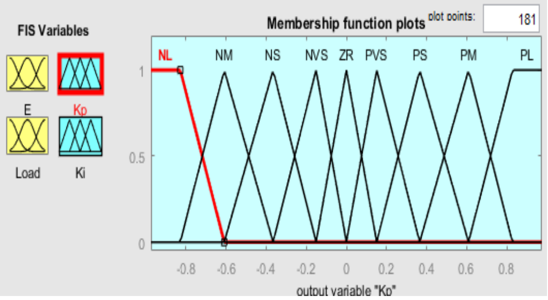

**Fig.4** Output membership function for KP and Ki

## 5. Simulation Result

The mathematical model of SHPP consist stepper motor, turbine and generator modeling. The stepper motor was used as a governor and it is regulated depending on the signals came from fuzzy PI controller. The model was designed using Matlab-Simulink. After the Matlab-Simulink model was designed the simulation results were obtained for different loads value and damping constant of the generator. Four different load values were used in this study; the values are 0.35, 0.55, 0.75 and 0.95 p.u and three different damping constant of generator 1.3, 1.5 and 1.7 were used. All of the figures show the obtained simulation results for a step load changes.

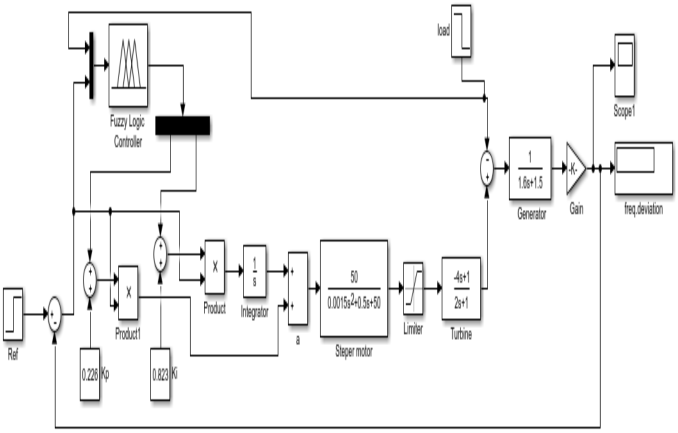

**Fig.5** Overall Simulation Simulink Model with Fuzzy PI controller

Fig.6 And Fig.7 Presents the frequency deviations of the small hydropower system with fuzzy PI controller for a 0.35, 0.55, and 0.75 p.u load rejection and addition.

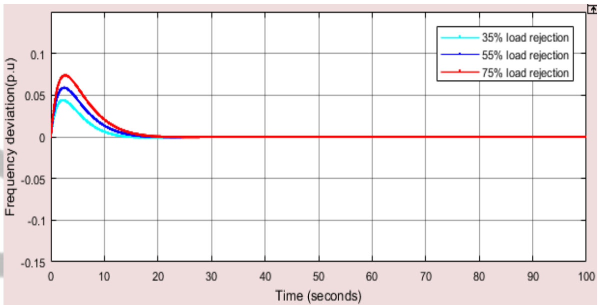

**Fig.6** Frequency deviation of the system with fuzzy PI controller for different load rejection

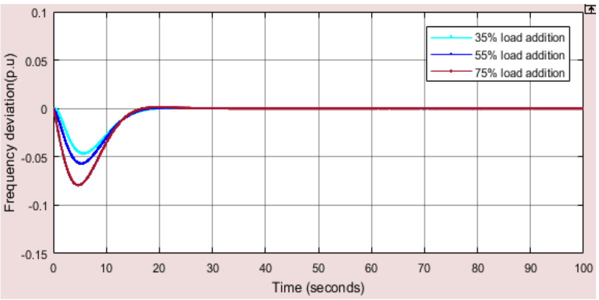

**Fig.7** Frequency deviation of the system with fuzzy PI controller for different load addition

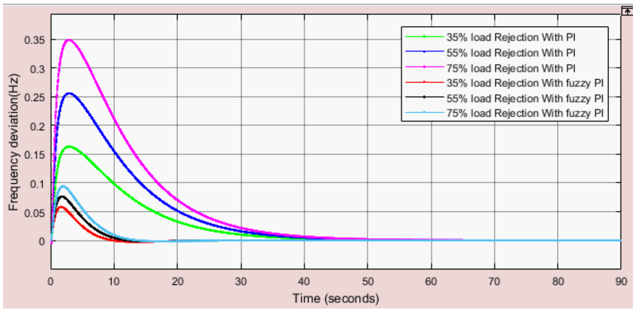

**Fig. 8** Frequency response of the system for 0.35, 0.55 & 0.75 P.U load rejection with PI and fuzzy PI controller

**Table 4** Transient and steady state performance of PI and Fuzzy PI controller for sudden 35%,55% and 75% load Rejection.

| Controller type | Overshoot (undershoot) | Settling time (seconds) | Steady state frequency Error in (p.u) |
|---|---|---|---|
| With PI (0.35 p.u) | 15.33% | 30 | 0 |
| With PI (0.55 p.u) | 24.81% | 33 | 0 |
| With PI (0.75 p.u) | 34.89% | 35 | 0 |
| With fuzzy PI (0.35 p.u) | 4.85% | 9 | 0 |
| With fuzzy PI (0.55 p.u) | 6.02% | 10 | 0 |
| With fuzzy PI (0.75 p.u) | 7.41% | 11 | 0 |

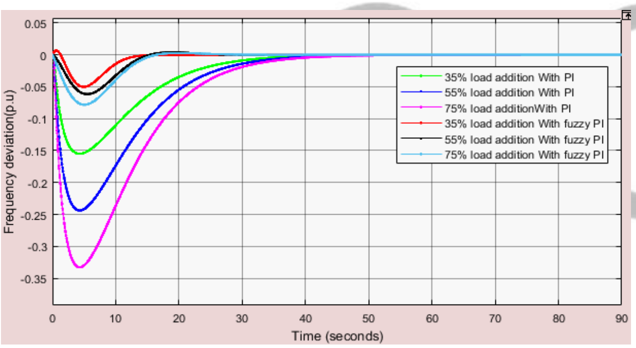

**Fig. 9** Frequency response of the system for 0.35, 0.55 & 0.75 P.U load addition with PI and fuzzy PI controller

**Table 5** Transient and steady state performance of PI and Fuzzy PI controller for sudden 35%,55% and 75% load addition.

| Controller type | Overshoot (undershoot) | Settling time (seconds) | Steady state frequency Error in (p.u) |
|---|---|---|---|
| With PI (0.35 p.u) | 15.48% | 32 | 0 |
| With PI (0.55 p.u) | 24.35% | 33 | 0 |
| With PI (0.75 p.u) | 33.23% | 35 | 0 |
| With fuzzy PI (0.35 p.u) | 4.95% | 11 | 0 |
| With fuzzy PI (0.55 p.u) | 5.89% | 13 | 0 |
| With fuzzy PI (0.75 p.u) | 7.72% | 14 | 0 |

Fig.10 shows that when we employee PI load controller for 0.3 p.u sudden load rejection it acts on gate position to close by 30%, after 33 seconds and when we employee fuzzy PI controller for 0.3 p.u sudden load rejection it acts on gate position to close by 30%, after 10 seconds. This result shows the capability of the fuzzy PI controller to supervise energy dissipated on ballast load.

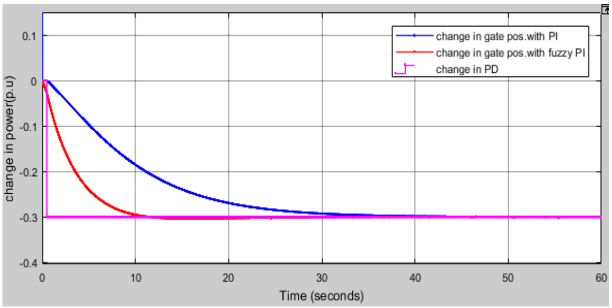

**Fig. 10** Change in gate position with fuzzy PI and PI controller for sudden 0.3 p.u load rejection

## 6. Conclusion

In this paper, a fuzzy logic based Proportional Integral controller for frequency control of a small hydropower plant is proposed to overcome the disadvantages of the conventional controller and evaluate the performance, such as the rise time, overshoot, settling time, etc. Its effectiveness and practicability are tested and verified with simulations results in Matlab-Simulink. The simulation results show that the system settling time and overshoot decrease significantly, and control performance is gotten much improved after the fuzzy self-tuning algorithm is applied in conventional PI controller. The proposed fuzzy logic based PI controller has more advantages, such as higher flexibility, control adaptability, better dynamic and static performance compared with conventional PI controller.

**Acknowledgment** I would like to acknowledge the Ethiopian electric power agency for their cooperation in giving the data and share of ideas.

## Appendix A

**TableA 1** Specifications of SFW3150-8/1730 synchronous generator

| **Parameter** | **Values** |
|---|---|
| **Type** | SFW3150-8/1730 |
| Current rating | 361 A |
| Power rating | 3150kW/3938kVA |
| Power factor | 0.8 |
| Voltage rating | 6.3kV |
| Rated speed | 750 rpm |
| Rated frequency | 50 Hz |
| Number of poles | 3 |

**TableA 2** Specifications of HLJ46-WJ-86 Hydraulic Turbine

| | |
|---|---|
| Type | 43HS2A200-654 |
| Penstock length | 95 m |
| Rated Head | 95 m |
| Initial speed of water(Uo) | 43.15 m/s |
| Acceleration due to gravity | 9.8 m/s2 |
| Rated speed | 750 rpm |
| Rated power | 3316 kW |
| Rated Discharge | 3.9 m3/s |

**TableA 3** Specifications of 43HS2A200-654 PM stepper motor

| **Parameter** | **Values** |
|---|---|
| **Type** | 43HS2A200-654 |
| phase Current | 6.5A |
| Phase resistance | 1 ohm |
| Phase inductance | 21mH |
| Lead wire | 4 |
| weight | 15kg |
| Holding torque | 30 Nm |
| Step angle | 1.8$^o$ |
| Moment of inertia | 0.0015kg.m$^2$ |
| Torque constant | 0.109 |
| Viscous Damping constant | 0.5Nm/rad/sec |
| Total number of rotor teeth | 50 |

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