Rotor Speed Control of Micro Hydro Synchronous Generator Using Fuzzy PID Controller

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Abstract - Hydro energy is one of the common renewable energy utilized for power generation system in Malaysia. The hydro energy rotates a turbine in which the turbine is used to drive the generator. In this study, stand alone micro hydro power generation system is chosen to bring in electrical energy to rural area since it is costly to transmit energy to rural area. The generated electrical energy by stand alone micro hydro generator is distributed to the users by transmitting the electrical energy to the load. However, the load is not consistent as there is different power demand at different time interval. The responded rotor speed will be determined and corrective action will be applied to generate power to match the load. Proportional-integral-derivative (PID) controller will be implemented into stand alone micro hydro power generation system to control the gate of the water flow. PID controller is subsequently replaced by Fuzzy PID for auto tuning purpose.

1.0 INTRODUCTION

Energy is essential to maintain quality of life of human beings. Electrical energy is usually generated by generators which are driven by turbines. In general, the driven turbines are operated by using conventional sources such as diesel and natural gas. However, the depletion of the conventional sources has raised the world’s concern. In addition, conventional sources for power generation produce a lot of wastes and pollutants that contribute to acid rain, smog and climate change. As a result, renewable sources for power generation have been explored. Renewable energies such as hydro, solar, wind, geothermal and so on are clean, abundant and flexible to match the load growth [1]. Renewable energy system also does not require environmental cleanup or waste disposal system.

Malaysia has the tenth highest rainfall over its land area in the world. The annual rainfall in Malaysia is 289 cubic centimetres of water volume per square centimetre of land area [2]. This statistic shows that hydro energy has a great potential to be developed in Malaysia. The water is reserved in the dam at higher ground. The potential energy of the running water is used to rotate the mechanical turbine. The mechanical turbine however will drive the generator and consequently, the electricity will be generated [3].

To upgrade the quality of life of the rural area, energy needs to be supplied to the rural area. However, the utility company refuses to do so because of high installation cost. In addition, people from the rural area consume only small amount of energy, which the utility company will not earn any profit from transmitting power to rural areas. In addition, the utility company needs to spend for maintenance of long distance power supply. Thus, stand alone power generation system is needed to supply energy to rural areas.

The generated power by micro hydro power generation system is distributed to the users. Load power however changes with time as there is different load demand. It will affect the rotor speed of the generator. Corrective action needs to be taken to maintain the rotor speed at normal speed to retain the quality of electricity. Good quality of electricity should have constant voltage and frequency.

PID controller is applied to the system to control the gate of the running water and thus control the rotor speed of the turbine. The PID controller is eventually replaced by Fuzzy PID controller since Fuzzy PID controller is able to tune the parameter of the PID automatically at different conditions. Fuzzy PID controller is expected to perform better than PID controller even there is disturbance in the system.

2.0 METHODOLOGY

2.1 Micro Hydro Synchronous Generator

A micro hydro power generation system consists of a hydro turbine and synchronous generator. The block diagram of micro hydro power generation system is shown in Figure 1.

![Figure 1: Block Diagram of Micro Hydro Power Generation System](image)

The stability of the generated power is taken into consideration since the load power is changing with time. As the load power is changing, the rotor speed of the synchronous generator will be changed. The rotor motion is determined by Newton’s second law [4], given that
\[ J_\alpha(t) = T_m(t) - T_e(t) = T_a(t) \]  

where \[ J \] = total moment of inertia of the rotating masses, kgm\(^2\)  
\[ \alpha_\alpha \] = rotor angular acceleration, rad/s\(^2\)  
\[ T_m \] = mechanical torque supplied by prime mover minus mechanical losses, Nm  
\[ T_e \] = electrical torque that accounts for the total three phase electrical power output of the generator plus electrical losses, Nm  
\[ T_a \] = net accelerating torque, Nm  

The mechanical losses and electrical losses are neglected. \( T_m \) and \( T_e \) are positive for generator operation. In steady state operation, \( T_m \) and \( T_e \) are equal and therefore, the net accelerating torque is zero. However, if the load power decreases, \( T_e \) will be reduced. \( T_m \) will be greater than \( T_e \). The net accelerating torque will be positive resulting in positive rotor angular acceleration. The rotor speed of synchronous generator will be increased. This situation could cause the electrical frequency of generated power being varied and affects the quality of generated power. Thus, a PID controller is introduced to control water flow based on the feedback output rotor speed and output active power of the synchronous generator.

### 2.2 PID Controller

The electrical load power and the mechanical turbine rotor speed have been compared as the model is simulated in per unit (pu) form. Figure 2 shows the structure of error acquisition system to obtain the error signal which is the input of PID controller.

![Figure 2: Structure of Error Acquisition System](image)

The difference of rotor speed can be obtained by comparing the reference rotor speed and actual synchronous generator rotor speed. The comparison of reference mechanical power and synchronous generator output active power provides difference of power. The error from the difference of rotor speed and the difference of power contributes to rotor angular acceleration. In stable situations, the error should be zero. However, the changing of load demand causes the output active power to be changed and the system become unstable. Thus, the divergence of rotor speed and power is fed into PID controller to take corrective action maintaining the stabilization of the power generation system.

The error signal is fed into a PID controller. The structure of PID controller is shown in Figure 3.

![Figure 3: PID Controller](image)

The PID controller takes corrective action to ensure the error signal is always zero. The corrective action can be done by controlling the gate of water flow, which the speed of running water determines the rotor speed of hydro turbine and eventually determines rotor speed of synchronous generator.

**PID parameters need to be set correctly for the well functioning system.** The equation of PID controller can be shown as below.

\[ u = K_p e + K_i \int_0^t e \, dt + K_d \frac{du}{dt} \]  

where,  
\[ K_p \] = proportional gain  
\[ K_i \] = integral parameter  
\[ K_d \] = derivative parameter  
\[ e \] = input error signal  
\[ u \] = output controlled signal

The parameters \( K_p \), \( K_i \) and \( K_d \) are set using Ziegler-Nichols tuning method [5]. Ziegler-Nichols tuning method provides some rules and formulas to obtain the parameters value. By only using proportional controller, the gain is increased from zero until ultimate gain at which the output first exhibits sustain oscillation. The parameter value of the proportional controller is the ultimate parameter and the corresponding period is ultimate time. Generally, proportional controller reacts fast with the error signal and reduces the rising time of corrective action. However, the system experiences overshoot and steady-state error. Derivative controller corrects the overshooting and the integral controller corrects steady-state error.

### 2.3 Fuzzy PID Controller

The Fuzzy PID controller has a better performance compared to PID controller. Fuzzy PID controller is an effective tool to deal with disturbances and uncertainties in term of vagueness, ignorance and imprecision [6]. The combination of the fuzzy technology and conventional PID forms the Fuzzy PID controller [7]. The Structure of Fuzzy PID controller is shown in Figure 4.

Fuzzy responses to the error signal and change of error signal and decide the best magnitude for proportional gain, integral parameter and derivative parameter based on the membership function and rule based set. The change of error signal is the difference of existing error and past error through a delay. The Fuzzy PID controller has been developed to have an individual fuzzy for each of P controller, I controller and D controller. The fuzzy
controller works individually to determine each of the proportional gain, integral parameter and derivative parameter.

![Fuzzy PID Controller Diagram]

Figure 4: Fuzzy PID Controller

Since P controller and I controller require more weightage on the error signal, more membership functions are built in input error in fuzzy inference system (FIS). Meanwhile, Fuzzy D controller has been designed to have more membership function in input change of error because D controller needs more weightage on change of error. More membership functions are built in corresponding input error and change of error in Fuzzy P, Fuzzy I and Fuzzy D to ensure the FIS acts sensitively to determine the suitable parameter.

Figure 5 shows membership functions set to input error, input change of error and output gain of Fuzzy P.

![Membership Functions of Fuzzy P]

Figure 5: Membership Functions of Fuzzy P

Figure 5 shows that membership functions of output gain is set more deviate to the right hand side. This is because high proportional gain need to be chosen to correct high error. The implemented Fuzzy P aims to be more sensitive on selecting high gain.

The rule editor is essential to instruct the FIS to determine P gain, I parameter and D parameter. Figure 5 shows some rules for Fuzzy P, Fuzzy I and Fuzzy D. The input error of Fuzzy P has been divided into 5 fuzzy regions whereas the input change of error has been divided into 3 fuzzy regions. Thus, Fuzzy P has 15 rules to be created. Fuzzy I however have 7 fuzzy regions of input error and 3 fuzzy regions of input change of error. Therefore, there are 21 rules to be formed. Fuzzy D have 3 fuzzy regions of input error and 5 fuzzy regions of input change of error. Hence, Fuzzy D has 15 rules to be considered.

The abbreviation of nh, nm, nl, ze, pl, pm, ph, ne and po are defined as negative high, negative medium, negative low, zero, positive low, positive medium, positive high, negative and positive. Positive and negative value of error and change of error have been taken into consideration and divided into high, medium and low depending on the concerned district. The ascending order of output control action of Fuzzy P, Fuzzy I and Fuzzy D however are L4, L3, L2, L1, H1, H2, H3 and H4 with L4 is the lowest gain and H4 is the highest gain.

Referring to Figure 6(a) first rule, if the error is negatively high and the change of error is negative, it is predicted that the error is becoming larger. Thus, Fuzzy P is expected to select the highest gain. Hence, the output Fuzzy P has been set to the highest in the rule editor.

Figure 6(b) is the rule editor for Fuzzy I. Fuzzy I will only correct the error when the change of error is approaching zero. Positive and negative change of error should have the minimum of integral parameter. Therefore, 8th and 9th rule in Figure 6(b) which consists of negative change of error is set to have the lowest integral parameter. Consider the 2nd rule, if the error is positively high and the change of error is zero, it means that there is a high positive value of steady state error. High I parameter need to be selected by Fuzzy I and therefore, the output Fuzzy I has been set to the highest in the rule editor.

1. If (Error is nh) and (ChangeOfError is ne) then (outputFP is H4) (1)

(a)

2. If (Error is ph) and (ChangeOfError is ze) then (outputFP is H2) (1)

8. If (Error is nh) and (ChangeOfError is ne) then (outputFP is L2) (1)

9. If (Error is ph) and (ChangeOfError is ne) then (outputFP is L2) (1)

(c)

Figure 6: Partially Rule Editor of (a) Fuzzy P, (b) Fuzzy I and (c) Fuzzy D
Fuzzy D has more membership functions in change of error since change of error is the main concern for Fuzzy D. Consider the 8th rule in Figure 6(c), if the error is zero and the change of error is zero, there is no change of error. Thus, the output Fuzzy D is set to the lowest.

The defuzzification method applied in FIS is centroid which the calculated output control gain is the centre of area under curve [8]. The overlapping of membership function in output proportional gain of Fuzzy promises a smooth output gain despite the nonlinear input error and change of error. Rule viewer of Fuzzy illustrates the way of determining output gain via defuzzification method. Figure 7 shows the rule viewer of Fuzzy P.

![Figure 7: Rule Viewer of Fuzzy P](image)

The rule viewer displays the fuzzy inference process of input error, input change of error and output gain. Each row of plot represents one rule. Since 15 rules have been set in Fuzzy P, there are 15 rows shown in rule viewer as Figure 6. By adjusting the index line, the output gain can be checked. If the error is -0.312, and the change of error is -0.136, there will be overlapping of error and change of error in 1st rule, 2nd rule, 4th rule and 5th rule. Through centroid defuzzification method, the centre of total area under curve is calculated. The output Fuzzy P gain is 0.77 in the particular case mentioned.

3.0 SIMULATION RESULTS & DISCUSSIONS

The changes of load demand cause the unbalance between electrical power and mechanical power. It will lead to acceleration or deceleration of the rotor speed. Fuzzy PID has been introduced to the system to maintain the electrical power same as the mechanical power. The system model is simulated in pu form.

Figure 8 shows the system model of Fuzzy PID micro hydro power generation system which has been developed in MATLAB SIMULINK. The synchronous generator is connected to the load, where the load power is designed to be varied to test the model. The rotor speed and the output active power of synchronous generator have been fed back to Fuzzy PID controller. The Fuzzy PID will decide the proportional gain, integral parameter and derivative parameter to control the gate of the running water and subsequently, control the rotor speed of hydro turbine. Thus, the rotor speed of the synchronous generator which is driven by hydro turbine can be controlled to maintain at 1 pu.

Figure 9 shows the designed signal of desired load power at different time interval. The load power which is representing the user load demand will affect the synchronous generator rotor speed. The problem however can be solved by controlling the mechanical rotor speed of hydro turbine to match to the synchronous generator rotor speed.
Figure 10 shows the simulated result of micro hydro power generation system. It can be observed that the output active power generated by synchronous generator is similar to the desired load power. The simulated result shows that there is some overshooting when the changes of demanded load power taking place. This is due to the changing of demanded load power altering the rotor speed of synchronous generator and subsequently changing the generated output active power. It is however can be corrected by Fuzzy PID controller. Fuzzy PID controller will take corrective action to maintain the rotor speed at 1 pu. In fact, the rotor speed varies between 0.95-1.05 pu during the corrective action for sometimes. The system needs time to settle down at exact 1 pu.

Figure 11 shows signal of input error, input change of error, Fuzzy P gain, Fuzzy I parameter and Fuzzy D parameter.
The input error signal is obtained by comparing the difference of rotor speed and difference of power (Refer Figure 2). It can be observed that the proportional gain, integral parameter and derivative parameter changes with time, depending to the condition of error and change of error signal. Based on the setting of membership function, and the rule set, the Fuzzy PID is able to function correctly to select the most suitable gain for error correcting action.

Initially, the error signal is very large. The Fuzzy P gain is expected to select large gain to correct the error. The error will be reduced and the proportional gain should be reduced with the decreases of the error. Results show that Fuzzy P gain is selected as 0.85 initially as the large error, followed by proportional gain of 0.60 to correct the intermediate error and lastly proportional gain of 0.25 to correct the small error at the first 100s time interval. Overall, it was found out that the Fuzzy P selects large proportional gain when the error is large and small proportional gain when the error is small. Thus, Fuzzy P met the objective of selecting suitable proportional gain to correct the error.

Derivative control reduces the overshooting and improves the transient response of the system [9]. Thus, Fuzzy D should select large derivative parameter if the system experiences large overshooting. The error signal in the system should be controlled to maintain at zero. Since initially the error is large, overshooting has taken place as shown in Figure 11. Fuzzy D is able select large derivative parameter trying to reduce the large overshooting of the system. As the decreasing of the overshooting, Fuzzy D is able to tune the suitable derivative parameter to correct the overshooting. Generally, Fuzzy D is functioning well, responding to the error and change of error signal and deciding on suitable derivative parameter for the system.

Integral control has a function of correcting the steady state error. Result from Figure 11 shows that the Fuzzy I is changing the integral parameter. The system has less steady state error.

It can be observed from Figure 10 that although the generated output active power is matched with the demanded load power, the rotor speed of synchronous generator hardly settling down at exact 1.0 pu. Integral control has the effect of eliminating steady state error, but it could also cause the transient response become worse [9]. The membership function and rule base of Fuzzy PID need to be revised for better performance.

4.0 CONCLUSION

Micro hydro stand alone power generation system is used to supply power to the rural area which is far away from the city. The generated power is supplied to the users, but the consumable power is not constant. In this study, the micro hydro power generation system has been modelled in MATLAB SIMULINK. The load which is representing user’s power demand is connected to the synchronous generator. The model has been investigated with different demanded load power. Fuzzy PID controller has been implemented to the system to correct the error. It can be concluded that Fuzzy PID responses well in order to generate same amount of demanded power while maintaining the rotor speed at the rated 1.0 pu.

The performance of micro hydro power generation system could be improved. In future, fine tuning of membership function of Fuzzy PID will be carried out. Through the tuning, it is expected Fuzzy PID can be used to assist the power generation system achieve fast response, less overshooting, less oscillation and at the same time eliminate steady state error. In addition, delay will be taken into consideration since practically the response of the gate of water flow acquire some time.

5.0 REFERENCES