Fuzzy Logic based user friendly Pico-Hydro Power generation for decentralized rural electrification

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***Abstract*— Pico-Hydro Power Plant (PHPP) is becoming one of the most important renewable energy sources in the world for remote or rural locations day by day. It does not encounter the problem of population displacement and is not as expensive as solar or wind energy. However, PHPP units are usually isolated from the grid network; thus, they require user friendly self control to maintain a constant frequency, the scheduled power and the voltage for any working conditions and trouble shooting. In this study, a new user friendly controller based on artificial intelligence (A.I.) or fuzzy logic has been designed for PHPP. The controller is able to maintain a constant the frequency, the scheduled power and the voltage in spite of varying user loads. Further, the controller manages the available water (in order to save it) depending on the users demand by using only the needed quantity of water for electricity generation. Results obtained by simulation show the rapidity and the robustness of the fuzzy logic controller. The used model for simulation was constructed based on the mathematical equations that summarize the behaviour of the PHPP. To the best of the authors knowledge this novel fuzzy logic controller approach of optimized generation in PHPP is absent in renewable energy literatures due to its assessment complexity.**

***Keywords*— Pico-hydro power, hydro power, fuzzy logic, AGC**

I. INTRODUCTION

Providing access to clean sustainable energy services in remote or rural areas is a big challenge. A decentralized generation system is very flexible, as it can be based on renewable or non-renewable energy sources. A comprehensive societal development cannot be achieved when rural and peri-urban communities have limited access to modern and clean energy options in remote areas. As energy is an engine to economic development and poverty elevation, access to energy services supports localized economic development, enabling local income generation through non-farm employment, in addition to better health and education **[1, 2]**. Thus rural development should have an overall priority in meeting the access challenge through decentralized energy systems in isolated situation using conventional and renewable sources.

PHPP technology is a relatively cheap and environment friendly mechanism of generating renewable energy in smaller capacities to electrify a few households, a village or a wayside business establishment and also have the opportunity to power mechanical drives for milling and turning operations **[3, 4]**. It is becoming a mature technology which can now be considered an alternative in technically feasible areas as compared to grid extension, diesel generators, and solar photovoltaic (PV) systems with reference to the cost saving as successfully operating in Village Gunpati, Ri-bhoi Dist. Meghalaya (Design Power: 4.5 KW) and Village Elephant det., W Kameng Dist. Arunachal Pradesh (Design Power: 1.5 KW) of N.E. India. There is a need to support the popularization of Pico hydro opportunities at various end use levels, be it sole for business development activities or for social development. A cash flow analysis indicated that the village PHPP will be financially sustainable as the annual revenue generation would be about 10-11% of the capital cost, which could be utilized for covering the cost operation and maintenance cost of the plant over the life span and also could be used to repay the capital cost after subsidy. As the technology become widely available in NE India, off-grid rural electrification projects can be accelerated to improve the living standard of remote village communities in the region or other parts of the country. Off-grid rural electrification projects can be grouped in following categories:

Small Hydro (500 KW to 1 MW of generating capacity)
Mini Hydro (100 KW to 500KW of generating capacity)
Micro Hydro (5 KW to 100 KW of generating capacity)
Pico Hydro (less than 5 KW of generating capacity)

II. MATERIALS & METHODS

In PHPP generation, a constant frequency value is desired against the varying load value. But the main problem on hydro power generation is to keep the frequency value constant because these plants get affected quickly by a small change in the regime of stream or river (flow or head). System frequency varies depending on the difference between demand and generated power. Many control techniques have been used for this operation. The complex "Proportional-Integral-Differential" (PID) controller is one of the popular controllers applied to governor systems in hydro power generation earlier. In future it can be replaced by compatible rule or logic based fuzzy logic controllers (FLC) **[8, 9]** which are more user-friendly and efficient.

Membership functions for FLC are created for error, change-in-error and change-in-output to control fuzzy logic of some variable process. Mamdani defined odd nos. (3,5,7 etc) of membership functions for each variable. They were triangular in shape (most popular and widely used), symmetrical, evenly spaced and overlapping **[15, 16]**. Some experimentation was done with different numbers and shapes of membership functions, but the increase in complexity was not adequately rewarded by a performance improvement. The FLC rule base is intuitively constructed by firing optimum no. of rules for realistic output.

The predictive accuracy of the fuzzy model is very reasonable. It is well understood that the data scarcity problem in small hydro power plant in hilly area for the estimation of its input versus required output can be easily solved using fuzzy logic **[11, 13]**. From the very approximate data, the model is capable of generating reasonably accurate output. The fuzzification interface simply modifies the inputs so that they can be interpreted and compared to the rules in the rule-base. The "rule-base" holds the knowledge, in the form of a set of rules, of how best to control the system. The inference mechanism evaluates which control rules are relevant at the current time and then decides what the input to the plant should be. The defuzzification interface converts the conclusions reached by the inference mechanism into the inputs to the plant **[12, 14]**.

III. NOMENCLATURE

P_t : turbine power [W],
Q_t : water flow [m^3/s],
g : gravity acceleration [m/s^2],
ρ = 1000kg/m^3: water's density,
H_e : effective high [m],
V_t : drive speed of the turbine,
v_1 : water's speed in the contact of the jet with the buckets,
v_2 : the water's speed at the exit of the buckets,
m : report of v_1 and v_2,
β : angle between $\vec{v}_1$ and $\vec{v}_2$,
R_t : ray of the turbine (m),
q_t : turbine flow (pu),
v_1 : jet speed (pu),
n_t : turbine speed (pu),
Q_{tn} : nominal flow of the turbine (m^3/s),
V_{1n} : nominal speed of the jet (m/s),
Ω_{tn} : nominal speed of the turbine (rad/s).
P_{tn} : nominal turbine power (W)
c_t : the turbine torque (pu),
H_t is the effective fall (m),
H_{tn}: nominal fall (m),
h_t: effective fall in (pu),
C_t: the mechanical torque (N.m),
Ω_t: angular velocity of the generator (rad/s),
C_e: the resistant torque (N.m),
S_n : nominal power (VA)
J_Δ: combines moment of inertia of the generator and turbine.
F_r: frequency of the generated e.m.f (Hz).
f_r: frequency of the generated e.m.f (pu).
P_e: load consumption.
P_d: electrical power dissipated on the ballast load.

IV. THEORY AND CALCULATIONS

The proposed mathematical model is for PHPP using Pelton type hydro turbine. The Pelton turbine is used for the high head falls having small flows. It consists of a set of specially shaped buckets mounted on the periphery of a circular disc. It is turned by jets of water discharged from one to six nozzles that strike the buckets. By a mobile needle (spear) inside the nozzle the water flow can be adjusted.

Mathematical nonlinear PHPP model: The main components of a PHPP may be classified into two groups. First, the hydraulic system components that includes the turbine, the associated conduits – like penstocks, tunnel and surge tank. Secondly, the electric system components formed by the synchronous generator and its control system.

Hydraulic part: The PHPP model with Pelton turbine is based on equations for steady state operation, relating the output power to water flow and head:

$$P_t = \rho g Q_t H_e$$

OR

$$P_t = \rho . Q_t . V_t (V_1 - V_t)(1 + m \cos \beta)$$

Power equation using per units:

$$p_t = \rho.(1 + m\cos\beta).\frac{q_t.Q_{tn}.R_t.n_t.\Omega_{tn}}{P_{tn}}.(v_1.V_{1n} - R_t.\Omega_{tn}.n_t)$$

OR

$$p_t = \frac{q_t.\sqrt{h_t}}{1-k_t}n_t - \frac{q_t.k_t}{1-k_t}n_t^2$$

Electrical part: The differential equation at linkage of the mechanical torque and the resistant torque above the shaft in turbine-generator assembly is given by:

$$J_\Delta.\frac{d\Omega_t}{dt} = C_t - C_e$$

OR

$$\frac{P_t - P_e}{\Omega_t} = J_\Delta.\frac{d\Omega_t}{dt}$$

Torque equation using per units:

$$\frac{dn_t^2}{dt} = 2.T_a(p_t - p_e)$$

$$T_a = \frac{S_n}{J_\Delta.\Omega_{tn}^2}$$

A Matlab-simulink model was obtained and its behaviour was validated by analysing a PHPP model performances. In the proposed scheme, a single valve or gate is used to regulate the flow of water (at a constant head). The valve or gate provides flow control to generate power in consonance with the load demand. The gate is a spear-valve based for 'continuous' flow control. A servomotor is used to operate the spear valve. This gate is positioned below the penstock and at turbine entry, regulates the flow of water into the turbine. A control model based on user friendly fuzzy logic controller of a PHPP has been proposed to overcome the disadvantages of the traditional PI controller (rise time, overshoot, settling time, etc). Its effectiveness and practicability are tested and verified in Matlab-simulink.

V. CONTROL METHOD - SIMULATION

PHPP is one of the small scale renewable energy technologies to be developed immediately. It has the potential to produce an important share of power, with a low price, more than solar or wind power. PHPP are usually built in rural or remote communities, as they use the river's flow in the mountains. In addition, they are often isolated from grid networks. Therefore, their technical characteristics require control to maintain an uninterrupted power at rated frequency and voltage, for directly powering loads. Mainly, voltage is maintained by controlling the excitation of the generator (if it's accessible) and frequency is maintained by eliminating the mismatch between generation and load demand **[5, 6]**. In case of a permanent magnet generator, no way to directly control voltage, and control of frequency is sufficient. So, PHPP control consists in maintaining fixed the frequency of the voltage waveform. Governor governs the turbine speed by adjusting the electrical load on the alternator, thus by balancing the total electrical load torque with the hydraulic input torque from the turbine. Therefore, they maintain a constant electrical load on the generator in spite of changing user loads **[7, 10]**. The turbine gate opening is kept constant in order to use a constant and the maximum year round water flow and hence guarantee the maximal mechanical power at the generator shaft. This also permits to use of a turbine with automated flow regulating devices. Fig.-1 shows the block diagram of a fuzzy controller for PHPP model.

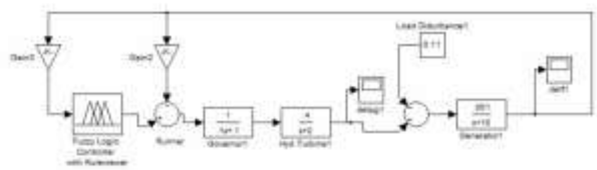

Fig.-1 PHPP Matlab-Simulation model

Here one input (flow control) and one output (valve or gate opening for power generation) is considered for the sake of simplicity in demonstrating the PHPP model with the fuzzy controller as shown.

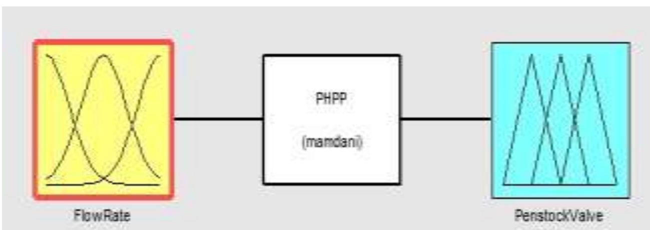

Fig.-2 Matlab-FIS model

The input is the error between reference value (constant frequency) that is desired output value and generator output value.

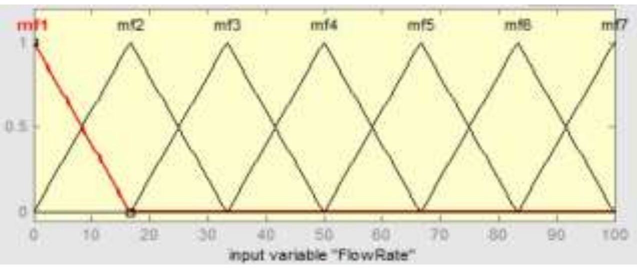

Fig.-3 Matlab-FIS Input Membership Functions

The fuzzification stage is determined by the choice of the range, shape and number of the membership functions. Seven triangular membership functions are chosen for both input and output variable.

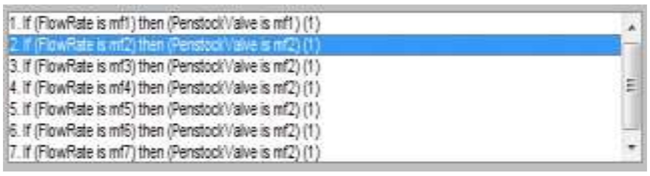

Fig.-4 Matlab-FIS Rule Editor

The fuzzy controller is used the max-min inference method that called as the Mamdani type inference. Mamdani's individual rule based fuzzy logic inference is utilized in this system. It computes the overall decision outcome based on the individual contribution of each rule in the realistic rule base.

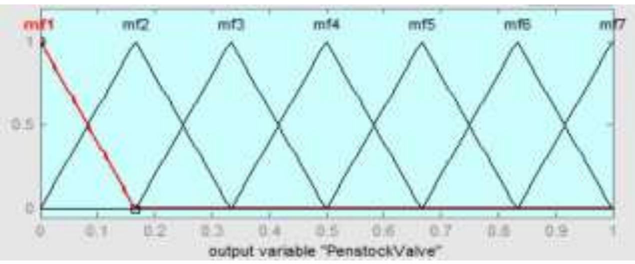

Fig.-5 Matlab-FIS Output Membership Functions

Centroid Defuzzification method is chosen. We have seven linguistic levels of input error and seven linguistic levels of control signal. So this rule base is composed of seven rules.

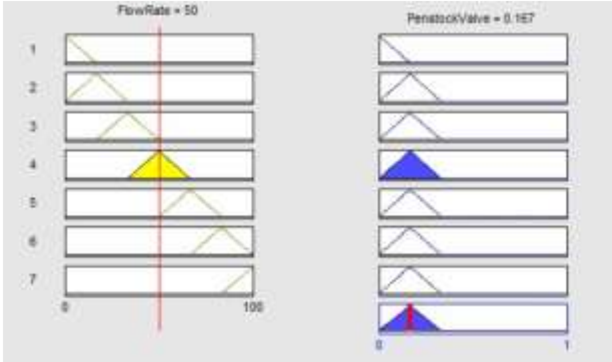

Fig.-6 Matlab-FIS Graphical Rule Viewer

Defuzzification is carried out to find a compromise value from all clipped fuzzy sets that represent the overall fuzzy output variable. It converts each fuzzy output variable resulted in inference process into the crisp value.

VI. RESULTS AND DSICUSSION

The model is considering of regulator servomotor, turbine and generator. The servomotor is used as governor and it is regulated depending on the signal come from fuzzy controller. The model was designed using Matlab-Simulink. After the fuzzy based hydraulic controller was designed based on realistic outputs, the simulation results were obtained. Results are observed on two scopes which show parameters such as generator terminal voltage and frequency.

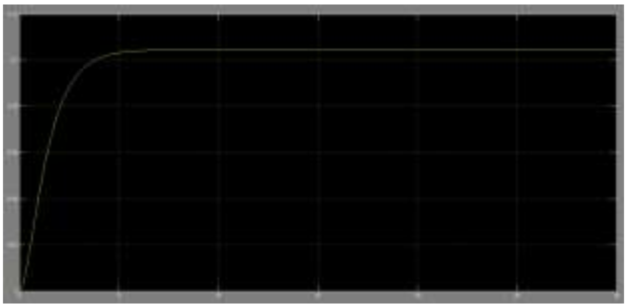

Fig.-6 Matlab-Simulink: ΔP_g vs Time response (pu)

The significance of fuzzy logic in PHPP control system is to implement an automated system that maintains the frequency constant in spite of changing user load (11%) at any operating point. The Simulation results prove that fuzzy based turbine governor has good performances.

Fig.-7 Matlab-Simulink: Δf vs Time response (pu)

Moreover, good transient and steady state responses for different operating points of the processes can be achieved. As synchronous generators are nonlinear systems fuzzy controller will suitable for it for constant frequency. The simulation results show that the system adjustment time and overshoot decrease significantly, and control performance is also much improved after the fuzzy logic controller is applied in place of conventional PID controller.

VII. CONCLUSION

This work has proposed a novel technique of PHPP based electricity generation using flow control in a much user friendly manner to overcome the disadvantages of the traditional PID controller. Exhaustive simulations were performed on the proposed control scheme using the Matlab-Simulink to ascertain the efficacy of the proposed model. These simulations have demonstrated the suitability of the proposed model for the control of PHPP 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 proposed fuzzy logic controller has more advantages, such as higher flexibility, control adaptability, better dynamic and static performance compared with conventional PID controller as shown. User does not need domain knowledge on hydro power generation or operation as FLC system developer for the daily operations. Fewer inputs produce optimum or realistic and effective output through FLC within acceptable limits in a user friendly manner. This work can be extended to develop a method for relating fuzzy logic-linguistic variables with various efficient control of other energy generation in future as well as for automatic generation control (AGC) and its trouble shooting.

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The authors declare that there is no conflict of interests.

REFERENCES

[1] A.C. De-souza: Assessment and statistics of Brazilian hydroelectric power plants: dam areas versus installed and firm power, Renewable and sustainable energy reviews 12, pp. 1843–1863 (Elsevier), (2008)

[2] A. Flamos, et al: Hydro energy: techno-economic and social aspects within new climate regime, Int. J. Renewable Energy Technology, Vol.2, No.1, pp. 32-62, (2011)

[3] D.A. Chin, A. Mazumdar, P.K. Roy: Water-Resources Engineering (3rd Edition), Pearson Education Limited

[4] Gagan Singh, D.S. Chauhan: Simulation and Modeling of Hydro Power Plant to Study Time Response during Different Gate States, IJAEST, Vol.10, Iss.1,PP. 042 - 047,(2011)

[5] M. Hanmandlu and H. Goyal: Proposing a new advanced control technique for micro hydro power plants, Electrical power and Energy Systems-30, 2008, PP.272-282

[6] M. Hanmandlu, H. Goyal and D.P. Kothari: An Advanced Control Scheme for Micro Hydro Power Plants, International Conference on Power Eletronis, Drives and Energy Systems, PEDES 2006, PP.1-7

[7] Issam Salhi and Said Doubabi: Fuzzy controller for frequency regulation and water energy save on microhydro electrical power plants, IREC 2009, PP. 106-112

[8] L.A. Zadeh: The concept of a linguistic variable and its application to approximate reasoning, Information sciences, Vol.8, No.3, pp. 199-249, (1975)

[9] L.A. Zadeh: Multicriteria decision analysis or Fuzzy Logic= computing with words, IEEE Transactions on fuzzy systems Vol.4, No.2, pp.103-111, (1996)

[10] M.N. Rao: Implementation of a small hydro power project in India: issues and lessons, Int. J. Renewable Energy Technology, Vol.2, No.1, pp. 53-66, (2011)

[11] P. Adhikary, P.K. Roy and Asis Mazumdar: Safe and efficient control of hydro power plant by fuzzy logic, IJESAT, Vol.2, Issue-5, pp. 1270-1277 (2012)

[12] P. Adhikary, P.K. Roy and Asis Mazumdar: MCDA of manpower shift scheduling for cost effective hydro power generation, IJETED, Vol.7, Issue-2, pp. 116-127 (2012)

[13] P. Adhikary, P.K. Roy and Asis Mazumdar: Selection of Penstock material for SHP – A Fuzzy Logic Approach, IJAST^{TM}, Vol.6, Issue-2, pp. 521-528 (2012)

[14] P. Adhikary, P.K. Roy and Asis Mazumdar: Selection of hydro-turbine blade material – Application of Fuzzy Logic (MCDA), IJERA, Vol.3, Issue-1, pp. 426-430 (2013)

[15] P. Adhikary, P.K. Roy and Asis Mazumdar: Fuzzy logic based blade angle control of Kaplan turbine for a hydro power project, ICERTSD 2013 (BESUS), Paper No: ICERTSD-13-109.

[16] P. Adhikary, P.K. Roy and Asis Mazumdar: Hydraulic transient analysis of SHP: A MCDM application for optimum penstock design, IWMSID 2013 (IIT-Bhubaneswar), Paper No: IWMSID / WRE / 16.

BIOGRAPHIES

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