SAFE AND EFFICIENT CONTROL OF HYDRO POWER PLANT BY FUZZY LOGIC

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Abstract

Many factors related to river run-off are vague, subjective and difficult to quantify. The fuzzy logic method is very useful for such problem solving approach such as small hydro power generation. The rule base and membership functions have a great influence on the performance and efficacy of the plant and also to optimize the small hydro power generation in the high altitude region particularly in India. The fuzzy linguistic variable performance can be easily characterized by common terms. The paper initially presents a new Fuzzy Logic Controller (FLC) method for safe reservoir control of dams through spillway gates. Finally it presents FLC method for turbine valve to control the water flow through turbine for hydro power generation. Thus it shows overall effective control and operation of the mechanical equipments in a hydro electric power generation project with FLC and its usefulness. The hardware of control system for fuzzifiers and defuzzifiers can be designed according to the need of system. All above proposed simplified models uses "Tabu Search Algorithm", "Fuzzy Delphi Method" and "Mamdani Inference Method" to evaluate using manual "C.O.G. Defuzzification" and MATLAB FIS editor validation.

Index Terms: *Hydro Power, Fuzzy Logic, Spillway Gate Control, Turbine Valve Control etc.*

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1. INTRODUCTION

From a small hydro electric power generation project, consumers require power at rated frequency and voltage. To maintain these parameters within the prescribed limits, various controls are required. Voltage is maintained by control of excitation of the generator and frequency is maintained by eliminating mismatch between generation and load demand as a result of the river flow and head through turbine. Power can be controlled by controlling flow through turbine and dams are maintained safely through controlling spillway gates [1]. The total installed power generating capacity in India during March 2012 was reported as 2, 02,979.03 MW out of which only 19.24% i.e. 39,060.40 MW is through hydro power. The cost of clean-green-friendly hydroelectricity is relatively low i.e. Rs1.5/kW to Rs2.5/kW [5, 10], compared to others and thus making it a competitive source of renewable energy.

In water or hydro power generation [6, 10] "Water-the white coal" is used non-destructively by the force of gravity, which is a totally carbon-free and inexhaustible resource to generate power. Naturally flowing rivers and streams, flow towards lesser elevation and thus provide suitable site for hydropower generation. The falling water of waterfalls can be used directly to drive turbines due to its sharp elevation in hilly area. If the natural fall is not steep, a head is created artificially by damming the river or stream, making a reservoir, and diverting its water to a nearby location with a penstock where the water is made to fall under gravity, driving a turbine for power generation.

Hydro power became increasingly popular as an advantageous [6, 9] clean – green – friendly renewable energy resource. Unlike thermal power plants there is no pollution of gaseous or fly-ash emissions in-case of hydropower. Again in nuclear power plants, [11, 13] there are radioactive wastes. The water used in hydro power generation remains fully intact and utilizable or reusable afterwards. Setting up of reservoirs by damming rivers had also appeared to be a safe and wise strategy because it promised to enable utilizing the river-flow to a maximum extent by flood control, ensure year round availability of water for irrigation-cultivation, navigation, entertainment, fish culture etc.

2. MATERIALS & METHODS

The main components of a small hydro-electric power plant are the river, reservoir, dam with spillway gates, penstock, flow control-turbine valves, hydro turbine, generator and draft tube. Dam with spillway gates and reservoir [3] is also necessary for the flood control, irrigation system, tourism and public water supply other than power generation. In order to release or block water though penstock, a flow control-turbine valve is used for power generation in hydro turbine. Water on releasing from the reservoir gets to the blades or vanes of the hydro turbine all the way through the penstock. Turbine produces electrical energy through generator coupled with it by water power near upstream side and then the water is released to downstream side where the drainage system is brought into action according to the requirements. Similarly in order to release or block water of reservoir operating system in dams, a sluice or spillway gate is used to control overflow. Here the study approach is involved in setting up fuzzy rule base for both spillway gate and turbine valve control and then simulating their operation in a synchronized way.

Safe Spillway Gate Control: The application of FLC system for dam or reservoir safety [12] consisting of two input variables: “Dam Lake Level” and “Water Inflow Rate”. “Openness of the spillway gate” is the only output variable and is controlled by the FLC rule base. The main aim of this control problem is to discharge excess water (danger level or above) in shortest possible time for the overall safety [3] of the system and thus bringing it back to safe or desired level (below danger level) through FLC.

Efficient Turbine Valve Control: Similarly, here the application of FLC system consist of two input variables: River “Water level” and “Flow rate” and one output variable: “Turbine valve openness”; The main aim of this control problem is to regulate the flow of water being fed to the turbine in accordance with the load perturbations and thereby maintaining the constant output frequency [2] of the system at the desired level through FLC.

Optimal Turbine-Governor–Generator Control: In all small hydro power 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 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 controller applied to governor systems in hydro power generation and can be replaced by simple rule or logic based FLC. PID feedback control has elegant design based on the deviation, or error, between a target value (set point) and the value of a process variable. An output, or manipulated, variable that affects the controlled variable is made to change. Its signal is calculated from the magnitude of the error (proportional mode) the persistence of the error (integral mode) and the rate-of-change of the error (derivative mode). In the early to mid 1970's, Mamdani investigated the fuzzy logic control as an alternative to the PID controller. He designed a controller that followed rules rather than a complex numerical formula. His rules were analogous to PI control. As a result, rules generated an output by evaluating error and change in error. For a reverse acting control loop, a large positive error calls for a large negative output change, while a small positive error calls for a small negative output change. Similarly, large change in error calls for large change in direction of the output, while a small change in error calls for a small change in direction. When there is no error or change in error, there is no change in output. This is an excellent application of fuzzy logic control because it's easily generalized to almost any process. The rules can be represented in a truth table. The symmetry of the outputs for these rules can be noted easily. The next issue is to define what constitutes a large error and large output. Membership functions 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. 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 using “Delphi Method”. Initially, variables, membership functions and rule base were defined randomly. Then, “Tabu Search Algorithm” (TSA) is used to choose the most appropriate parameter values characterizing the fuzzy membership functions. 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. From the very approximate data, the model is capable of generating reasonably accurate output.

3. FUZZY LOGIC PRELIMINARIES

Fuzzy Logic: The main advantage of the fuzzy control method is to control the processes that are too complex to be mathematically modelled. The membership functions must be optimally determined to design an efficient FLC for a problem. Many factors related to Run-off River or hydro power are subjective and difficult to quantify in this type of process such as Water Level or Depth is at “Below Danger Level-Danger Level-Above Danger Level”. Similarly the water flow rate is “Slow-Normal-Fast” etc. Still fuzzy logic enables the evaluator or the decision maker to incorporate this information in the environment performance evaluation system which is imprecise, vague and subjective. Therefore, the FLC method is a very suitable method for small hydro electric power generation problem. The rule base and membership functions have a great influence on the performance of FLC. The fuzzy linguistic variable performance can be easily characterized by common terms as: "Good – Moderate – Bad; Strong – Average – Weak; High-Medium-Low" etc. Each term is called a linguistic modifier. Hence a fuzzy set is formed when a linguistic variable is combined with a linguistic modifier. Fuzzy arithmetic can be solved either manually or in MATLAB Software.

Application of Fuzzy Logic [14, 15] in hydro power comprised in three stages:
1. Fuzzification (Assigning input and output variables; Converts the Classical or Crisp Values to Fuzzy Sets)
2. Fuzzy Logic Rules and Fuzzy Inference Methods (Mamdani Inference Method)
3. Defuzzification (Converts the Fuzzy Set to Classical or Crisp Values)

Fuzzification: Usually, a fuzzification of mathematical concepts is based on the generalization of these concepts from characteristic functions to membership functions. Let us assume M and N be two fuzzy subsets of X. Intersection (M∩N) and union (MUN) are defined as follows: (M∩N)(x)= min(M(x),N(x)), (MUN)(x)= max(M(x),N(x)). A simple fuzzification is usually based on min and max operations [4].

Fuzzy Rules and Fuzzy Inference Methods: Mamdani inference method, as defined for solving either manually or in MATLAB Software, expects the output membership functions to be fuzzy sets. After the aggregation process, there is a fuzzy set for each output variable that needs defuzzification. It enhances the efficiency of the defuzzification process because it greatly simplifies the computation required. There are several ways to define the result of a rule, but one of the most common and simplest is the "max-min" inference method, in which the output membership function is given as the truth value generated by the premise.

Defuzzification: It is the process of producing a crisp or quantifiable result or output in fuzzy logic, from obtained fuzzy output sets and corresponding membership degrees. Most common and useful defuzzification technique is "Centre of Gravity Method". In "Centre of Gravity Method", the first step of defuzzification typically is to "cut off" parts of the triangular graphs to form trapezoids (or other shapes). Then, "The Centroid" of this shape, called the fuzzy centroid, is evaluated. The x coordinate of "The Centroid" is the defuzzified value. The "Centre of Gravity Method" is very popular and is used widely for calculation. To get the crisp value we use the following equitation for the defuzzification:

$$C.O.G. = \sum \mu i * \mu(i) / \sum \mu i$$

Tabu Search Algorithm: It is a meta-heuristic local search algorithm that can be used for solving combinatorial optimization problems (problems where an optimal ordering and selection of options is desired). Tabu search uses a local or neighbourhood search procedure to iteratively move from one potential solution to an improved solution in the neighbourhood of, until some stopping criterion has been satisfied (generally, an attempt limit or a score threshold). Local search procedures often become stuck in poor-scoring areas or areas where scores plateau. In order to avoid these pitfalls and explore regions of the search space that would be left unexplored by other local search procedures, "Tabu Search" carefully explores the neighbourhood of each solution as the search progresses. The solutions admitted to the new neighbourhood, are determined through the use of memory structures. These memory structures form what is known as the "Tabu List", a set of rules and banned solutions used to filter which solutions will be admitted to the neighbourhood to be explored by the search. In its simplest form, a "Tabu List" is a short-term set of the solutions that have been visited in the recent past. The memory structures used in "Tabu Search" can be divided into three categories:
a) Short-term: The list of solutions recently considered. If a potential solution appears on this list, it cannot be revisited until it reaches an expiration point.
b) Intermediate-term: A list of rules intended to bias the search towards promising areas of the search space.
c) Long-term: Rules that promote diversity in the search process (i.e. regarding resets when the search becomes stuck in a plateau or a suboptimal dead-end).

The Fuzzy-Delphi Method: It is a semi-structured communication method, developed as a systematic, [8] interactive forecasting method which relies on experts, engineers or managers. In the standard method, the experts answer the queries in two or more phase. After each phase, a facilitator provides an anonymous summary of the experts' detailed forecasts report. Thus, experts are encouraged to revise their earlier answers in light of the replies of other members of their panel. During this process the range of the answers will decrease and the group will converge towards the "correct" solution. Finally, the process is stopped after a pre-defined stop criterion. The mean or median scores of the final phase or rounds determine the final results. Delphi is based on the principle that forecasts (or decisions) from a structured group of individuals are more accurate than those from unstructured groups and has been mentioned as "collective intelligence". The technique can also be adapted for use in meeting individuals and is then termed as mini-Delphi. Delphi has been widely used for project or business forecasting and has certain advantages over another structured forecasting approach, prediction markets. First applications of the “Delphi Method” were in the field of science and technology forecasting. The main objective of “Delphi Method” was to combine expert opinions on likelihood and expected development time, of the particular technology, in a single indicator. It was also applied successfully and with high accuracy in project or business forecasting. Quantitative methods produced errors of 10–15%, and traditional unstructured forecast methods had errors of about 20% where “Delphi Method” had errors of 3-5%. Overall the track record of the “Delphi Method” is mixed. Later on, several extensions to the “Delphi Method” were developed to address this drawback that takes into consideration the possibility that the occurrence of one event may change probabilities of other events covered in the survey. Still the “Delphi Method” can be used most successfully in forecasting single scalar indicators. Despite these shortcomings, today the “Delphi Method” is a widely accepted forecasting tool and has been used successfully for thousands of studies and researches.

4. CASE STUDY

Safe and efficient fuzzy logic control of a hydro power project in the Himalayan region in India considered for the case study: In the first step of this method, the system variables, inputs, and outputs are determined according to expert’s views. The second step is to determine linguistic values of system variables (inputs and output). Then the fuzzy intervals of the input and output variables are characterized. According to the experts’ poll and based on obtained data [7] of the measurement, past experiences and calculation in the workplace, their membership function and other parameters are obtained. The linguistic variables, their linguistic values and related fuzzy intervals are then tabulated or defined. The most popular triangular membership functions for all inputs and outputs revealed.

4.1 Case-1:

Safe Spillway Gate Control: According to the experts’ poll and based on obtained data of the measurement, past experiences and calculation in the workplace, their membership function and other parameters are obtained. The linguistic variables, their linguistic values and related fuzzy intervals are defined below. The triangular membership functions (trimf) for all inputs and output revealed.

Manual calculation for Spillway Gate Control:
Here we have defined following [4] fuzzy conditions:
Definitions of Water Level (M)-Input(1):
Low trimf (0 15 35); Medium trimf (30 45 65); High trimf (60 75 100)
Definitions of Flow rate (Kilo Cumec)-Input(2):
Low trimf (0 15 35); Medium trimf (30 45 65); High trimf (60 75 100)
Now let us consider following condition:
Water Level (63 M): Medium (0.1) & High (0.2)
Flow rate (32 Kilo Cumec): Low (0.15) & Medium (0.133)
Rules fired are 4, 5, 7 and 8
Strength of rule 4: [0.1 ^ 0.15] = 0.1
Strength of rule 5: [0.1 ^ 0.133] = 0.1
Strength of rule 7: [0.2 ^ 0.15] = 0.15
Strength of rule 8: [0.2 ^ 0.133] = 0.133
Now, C.O.G. = $\sum\mu i*\mu(i) / \sum\mu i$
Hence, C.O.G. =
(65*0.1+0.1*20+0.15*65+0.133*65) / (0.1+0.1+0.15+0.133)
C.O.G. = 55.5% i.e. “Partially Open” – Output.

Validating above calculation through MATLAB FIS Editor:

Inputs: Dam control methods need specific parameters and input variables to be measured to estimate degree of control indicators as shown in Fig-1(a) and Fig-1(b). Here two inputs are Dam Water Level and Inflow Rates.

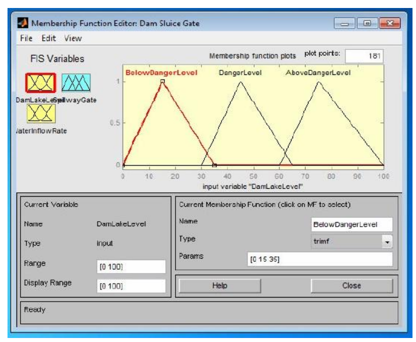

Fig-1 (a): Dam Water Level-Input

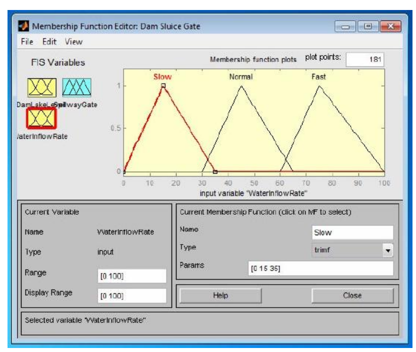

Fig-1 (b): Dam Water Inflow rate-Input

Rule Editor: In this study, total number of active rules obtained is equal to 9 rules (= $3^2 = p^q$; where p = maximum number of overlapped fuzzy sets and q = number of inputs) as shown in Fig-1 (c). The rules are based on “Mamdani Inference Method”.

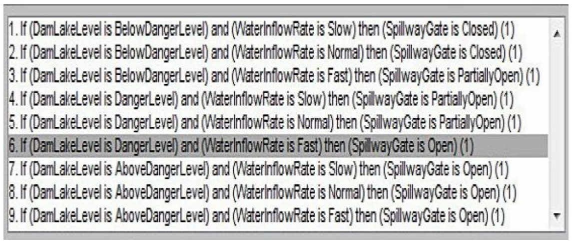

Fig-1 (c): Fuzzy Mamdani-Rule Editor

Output: Fig-1(d) shows the relation of 2 inputs i.e. "Water level" and "Water flow rate" for their 1 output i.e. "Spillway Gate open-ness".

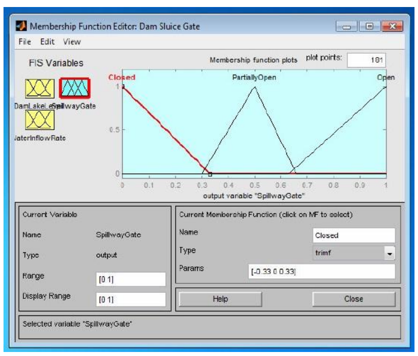

Fig-1 (d): Spillway Gate Opening-Output

Rule Viewer-Graphical: Fig-1(e) shows the relation of 2 inputs i.e. "Water level" and "Water flow rate" for their 1 output i.e. "Spillway Gate open-ness" through graphical rule viewer. Result shows 56% i.e. "Partially Open". Hence we find after validation that calculative accuracy of the fuzzy model is very reasonable as shown above.

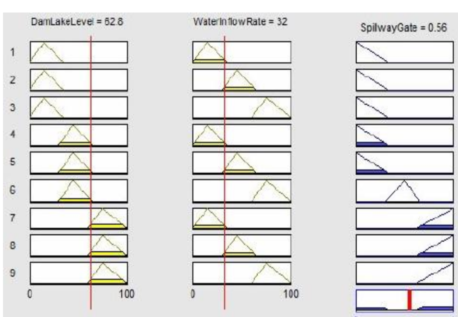

Fig-1 (e): Fuzzy Rule Viewer-Graphical

Surface Viewer-Graphical: Fig-1(f) shows 3-D plot of "Spillway Gate open-ness" as a function of "Dam Lake Level" and "Water Inflow Rate".

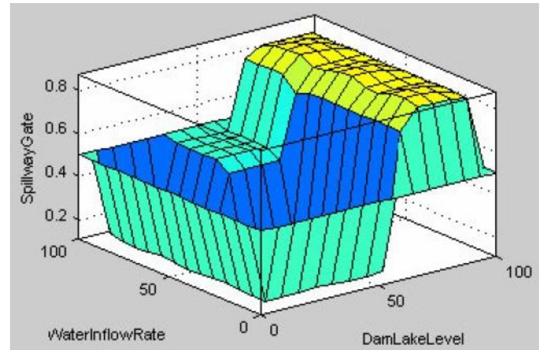

Fig-1 (f): Fuzzy Rule Viewer-3D Surface

4.2 Case-2:

Efficient Turbine Valve Control: Similarly, according to the experts' poll and based on obtained data of the measurement, past experiences and calculation in the workplace, their membership function and other parameters are obtained similarly as above. The linguistic variables, their linguistic values and related fuzzy intervals are also illustrated. The triangular membership functions for all inputs and output revealed. TSA is used to choose the most appropriate parameter values characterizing the fuzzy membership functions.

Input: Turbine Valve control methods need specific parameters and 2 input variables i.e. "River Head" and "River Flow Rate" to be measured to estimate degree of control indicators as shown in Fig-2(a) and Fig-2(b).

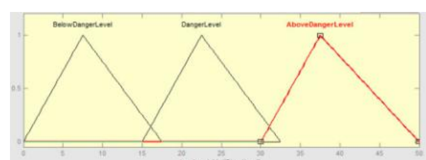

Fig-2 (a): River Head-Input

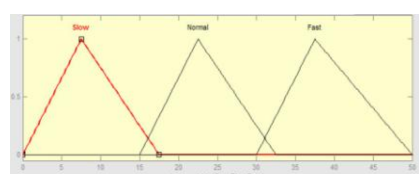

Fig-2 (b): River Flow Rate-Input

Rule Editor: In this study, total number of active rules obtained is equal to 9 rules (= 3^2) as shown in Fig-2 (c). The rules are based on "Mamdani Inference Method".

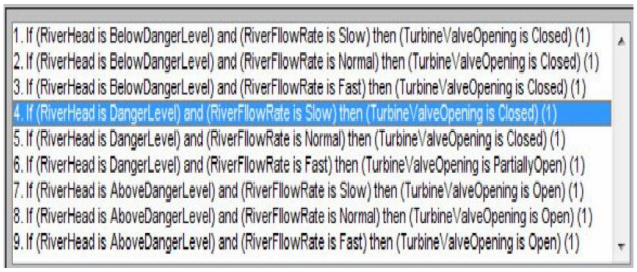

Fig-2 (c): Fuzzy Mamdani-Rule Editor

Output: Fig-2(d) shows the relation of 2 inputs i.e. "River Head" and "River Flow rate" for their 1 output i.e. "Turbine Valve open-ness".

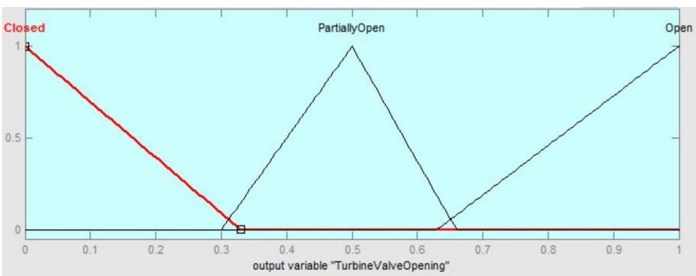

Fig-2 (d): Turbine Valve Opening-Output

Rule Viewer-Graphical: Fig-2(e) shows the relation of 2 inputs i.e. "River Head" and "River Flow rate" for their 1 output i.e. "Turbine Valve open-ness" through graphical rule viewer as 73.3% i.e. "Open" position.

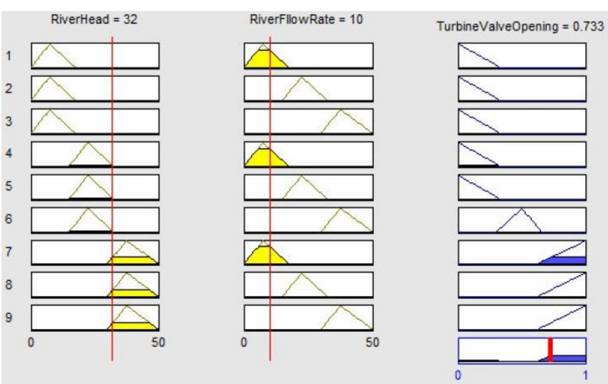

Fig-2 (e): Fuzzy Rule Viewer-Graphical

Surface Viewer-Graphical: Fig-2(f) shows 3-D plot of 2 inputs "River Head" and "River Flow rate" for their 1 output i.e. "Turbine Valve open-ness".

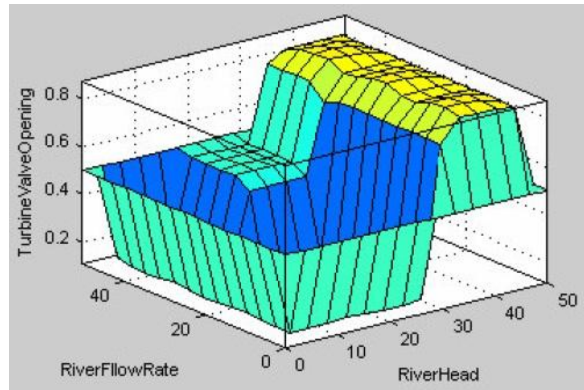

Fig-2 (f): Fuzzy Rule Viewer-3D Surface

5. DISCUSSION

The main aim of the hydro power generation and dam or reservoir control system is to keep the system within predetermined ranges by adjusting the flow through a spillway gate at the dam and inflow through turbine valves in any condition for safety as well as efficient hydro electricity generation. Because of the uncertain changes during flood or overflows, fast and effective manual control of the reservoir is very difficult. Similarly as of the uncertain changes in load demand effective governor control is very difficult. In all hydro power generation, a constant frequency value is desired against the varying load value. But the main problem on hydro power generation is to keep the constant frequency value because these plants get affected quickly by a small change in the regime of river. System frequency varies depending on the difference between demand and generated power. Furthermore, human beings are emotional and forgetful. So, humans may reach incorrect decisions under extreme conditions. Therefore, this disadvantage must be solved entirely by automation. Triangular fuzzy membership functions are used because of their simplicity as well as their simplicity over PID controls. The rule base is intuitively constructed by firing optimum no. of rules using FLC.

The predictive accuracy of the fuzzy model is very reasonable as shown in either manual calculation or MATLAB FIS Editor. It was well understood that the data scarcity in modelling reservoir operation influence the estimation of proper release policies. But still from the very approximate data, the model is capable of generating reasonably accurate result. These results demonstrate that the fuzzy logic is a very useful method for assessing and not enforced to evaluate with a crisp number.

6. CONCLUSION

The present study intends to contribute for the improvement of fuzzy logic application through use of MATLAB FIS editor or manual calculations for hydro power generation. Hydro electric power generation is one of the earliest known renewable energy sources and hence have a significant role in the economic-social development of countries and they have found special importance due to their relatively clean-green-friendly characteristics. The model here is fundamental importance to understand physical system. In this paper, an efficient and accurate method based on fuzzy control is proposed for the hydro power generation and reservoir operating system in dams for safe and efficient performance. The drawbacks of the human based control system do not exist in this method. Moreover, the parameters of the membership functions are optimized by using a TSA and the degree of automation of the fuzzy control system may increase. We have also seen that the FLC rule base is intuitively constructed by firing optimum no. of rules using “Delphi Method”. Initially, variables, membership functions and rule base were defined randomly. Then, “Tabu Search Algorithm” (TSA) is used to choose the most appropriate parameter values characterizing the fuzzy membership functions. The predictive accuracy of the fuzzy model is very reasonable. This work can be extended to develop a method for relating fuzzy logic-linguistic variables with various efficient control of other renewable energy generation in future.

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The authors declare that there is no conflict of interests.

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