FUZZY LOGIC BASED OPTIMUM PENSTOCK DESIGN: ELASTIC WATER COLUMN THEORY APPROACH

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ABSTRACT

Shock wave or surge events are disturbances in the water caused during a change in state, typically from one steady or equilibrium condition to another. The principle components of the disturbances are head pressure and flow changes at a point that causes propagation of pressure waves throughout the distribution system. The larger the magnitude of the velocity change and the larger the magnitude of the wave speed, the greater the change in head-pressure will be. Many factors related to small hydro power (SHP) water conveyance system or penstock design are subjective and difficult to quantify. Hence fuzzy logic can be one of the most powerful design decision making method of shock wave or shock wave or surge analysis of penstock. To the best of the authors knowledge this novel Fuzzy Logic approach of optimum water conveyance system or penstock designing by shock wave analysis for small hydro power generation is absent in renewable energy or fluid mechanics literatures due to its assessment complexity.

Keywords: hydro power, fuzzy logic, penstock, hydraulic transient, shock wave, surge analysis.

1. INTRODUCTION

The cost of clean-green-friendly hydroelectricity is relatively low i.e., Rs1.5/kW to Rs2.5/kW, compared to others and thus making it a competitive source of renewable energy. Hydro power became increasingly popular as an advantageous clean - green - friendly renewable energy resource. 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 thru hydro power [1, 2]. 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.

Penstocks and tunnels carry water from the intake to the hydro turbine generator and introduce shock wave to the system through hydraulic and geometric parameter changes in the water passageway. Shock wave events are disturbances in the water caused during a change in state, typically from one steady or equilibrium condition to another. Transient analysis of the performance of water conveyance system or penstock systems is often more important than the analysis of the steady state operating conditions that engineers normally use as the basis for system design [3, 4]. Transient pressures are most important when the rate of flow is changed rapidly, such as resulting from rapid valve closures or hydro-turbine stoppages. Such disturbances, whether caused by design or accident, may create travelling pressure waves of large magnitudes. These transient pressures are superimposed on the steady state conditions present in the line at the time the transient occurs. The severity of transient pressures must be determined so that the water mains can be properly designed to withstand these additional loads. Transient regimes in water distribution systems are inevitable and will normally be most severe at hydro-power stations at high elevation areas and remote locations that are distanced from dam or storage. Although transient conditions can result in many situations, the engineer is most concerned with those that might endanger the safety of a plant and its personnel.

2. MATERIALS AND METHODS

The principle components of the disturbances are pressure and flow changes at a point that causes propagation of pressure waves throughout the distribution system. The pressure waves travel with the velocity of sound (sonic speed), which depends on the elasticity of the water and that of the water conveyance system or penstock walls. As these waves propagate, they create transient pressure and flow conditions. Over time, damping actions and friction reduces the waves until the system stabilizes at a new steady state. Normally, only extremely slow flow regulation can result in smooth transitions from one steady state to another without large fluctuations in pressure or flow. In general, any disturbance in the water generated during a change in mean flow conditions will initiate a sequence of transient pressures waves in the water distribution system [5, 6]. Disturbances will normally originate from changes or actions that affect hydraulic devices or boundary conditions.

Determining how to prevent water hammer in water conveyance system or penstock at design and planning stage requires a fundamental understanding of fluid properties, governing equations and the design and operation of hydro power systems. Rapid pressure changes are a result of rapid changes in flow, which generally occur in a water conveyance system or penstock system after hydro-turbine shut-off, although it may also occur at start or at valve opening or closing. Because of the compressibility of water and the elasticity of water conveyance system or penstocks, pressure waves will then propagate in the water conveyance system or penstock until they are attenuated at a velocity, which is dependent upon water conveyance system or penstock material and wall thickness.

The basic idea is to define for each hydraulic component an equivalent electric component. In the case of water conveyance system or penstock segment, the electric equivalent circuit can be obtained using the momentum and mass conservation equations. A water conveyance system or penstock must always be divided into a series of N elementary water conveyance system or penstock segments with the elementary length. These equations lead to the electrical equivalent circuit. The water conveyance system or penstock of hydropower plant can be considered as a hydraulic transmission line. This hydraulic transmission line is considered to terminate by using an open circuit at the turbine and short circuit at the reservoir. To ensure stable frequency regulation under isolated condition, hydro turbine governors are designed to have relatively large transient droop with long resettling time because a change in gate position at the water conveyance system or penstock may produce short term power change [7, 8]. The block diagram of a generating unit with hydraulic turbine is shown in Figure-1.

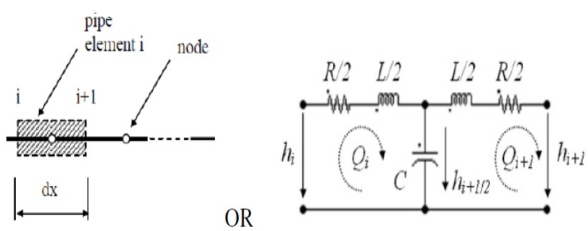

Figure-1. Electrical equivalent hydraulic model of a SHP penstock segment.

The static and dynamic properties of the hydro plant must be known to understand the nonlinear characteristic. A common test to visualize and approximate the nonlinearity in hydro plant characteristic is to test the static behaviour of the plant. The static behaviour is established by the relationship between the steady-state values of gate position and turbine developed power. The hydraulic turbine generating unit was in standstill and ready to start up as initial condition. The simulation start at first and then the hydraulic turbine generating unit received the signal two seconds later. Hence the effect of water hammer on mechanical power with change in the water conveyance system or penstock property can be achieved. The head pressure variation with time for surge is shown in Figure-2 and Figure-3.

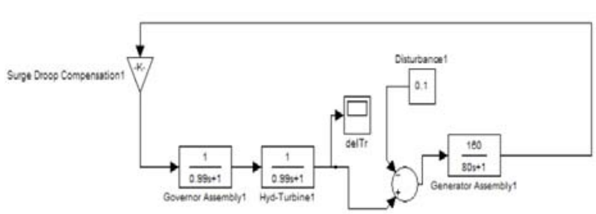

Figure-2. MATLAB simulation for a SHP penstock.

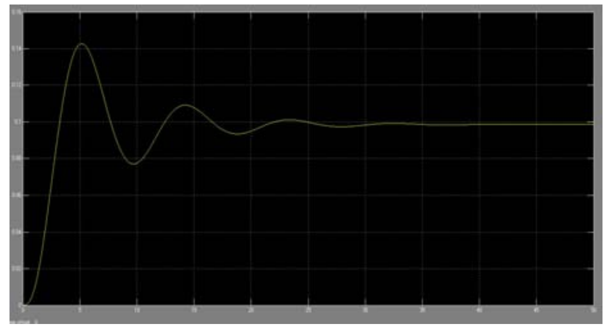

Figure-3. Pressure change vs time response of shock wave for a SHP penstock.

Among the numerous MCDA methods available for renewable energy system design and management analysis, the most prevalent are Macbeth, AHP, Promethee, Electre, and Fuzzy Logic [9, 10]. It uses a subjective assessments of relative importance converted to a set of overall scores (weights), arranging in this way the structure of the problem in a hierarchy way. Fuzzy logic can be one of the most powerful decision analysis method or tool in design decision making. In this paper, an applied hydro power design decision making problem is solved using fuzzy logic [11, 12].

There are significant amount of literatures available nowadays dealing with hydro power generation and its design issues. However, the research in the area of integrated aspects of hydro power generation - system design issue by A.I. is scarce and has been discussed here. In the present job an attempt has been made to solve the complexity prevailing in the hydro power generation system design issue by considering a new concept. The job has been emphasized to overcome the above mentioned shortcomings and simultaneously build up an efficient model that can handle multiple requirements. In recent years artificial intelligence such as fuzzy logic has emerged as a new computational approach that tries to extract ideas from a natural system, in particular the vertebrate immune system, in order to develop computational tools for solving complex engineering problems having imprecise and vague inputs and outputs [13, 14].

3. THEORY AND CALCULATIONS

The effects of the water hammer vary, ranging from slight changes in pressure and water velocity to sufficiently high pressure or vacuum through to failure of fittings, water conveyance system or penstock damage [15, 16]. Allevi's Equation, which originates from Newton's laws of motion, describes the pressure change that results from a rapid change in water velocity.

Allevi's equation

$$H_1 - H_0 = \frac{a}{g}(v_0 - v_1)$$

Where:
H_1 is the new head in meters
H_0 is the steady state head in meters at velocity v0.
a is the velocity of the shock wave in meters per second.
g is a constant of 9.82m/s^2 for gravity
v_0 is the initial steady state velocity in meters per second
v_1 is the new velocity in meters per second

The magnitude of the sub-pressure that the water conveyance system or penstock will experience will therefore depend on the water conveyance system or penstock line profile, i.e., the distance between the minimum pressure line and the water conveyance system or penstock line profile. Water conveyance system or penstock length will influence the reflection time and the inertia of water inside the penstock. The longer the water conveyance system or penstock is, the longer the reflection time, that is, the time it takes for the wave to reflect at the outlet and return to the starting point. In addition, the longer the penstock, the larger the mass of water that will affect the moment of inertia of the water column. The higher the moment of inertia, the longer the hydro-turbine will continue to rotate after shut-off. A higher moment of inertia minimizes pressure drops before the reflecting wave raises the pressure again. Allevi's equation states that the magnitude of water hammer is directly proportional to the velocity of the wave propagation. Wave propagation velocity depends on the elasticity of the water conveyance system or penstock walls and the compressibility of the liquid. The type of filling and packing method used around the water conveyance system or penstock line has a direct impact on the external pressure on the water conveyance system or penstock lines. Due to the pressure changes created by water hammer, there will be oscillations of the water conveyance system or penstock in the ground, therefore the filling around the water conveyance system or penstock will have a great effect on the wear of the penstock. Sharp stones, for example, will tear the water conveyance system or penstock exterior. Water hammer can have devastating effects on the hydro-turbine system. These include instant water conveyance system or penstock failure, weakening of water conveyance system or penstock sections, fatigue and external wear. Devices used to actively protect the hydro-turbine station against the effects of water hammer are dependent upon power supply. Therefore these methods only protect the water conveyance system or penstock line during normal hydro-turbine stops.

Methods of active protection include variable frequency drives, soft starters and slow-closing valves. Passive protection equipment operates without the need for additional power supply and can therefore be used to protect the water conveyance system or penstock system in the event of a power failure. Air chambers, surge towers and air inlet/release valves are methods used to provide passive protection. By analyzing the formula, it is clear that the larger the magnitude of the velocity change and the larger the magnitude of the wave speed, the greater the change in pressure will be. Fuzzy logic can be one of the most powerful design decision making methods [17, 18]. The main advantage of the fuzzy logic method is to control the processes that are too complex to be mathematically modeled. The membership functions must be optimally determined to design an efficient Fuzzy Logic system for a problem. Many factors related to Run-off River or hydro power are subjective and difficult to quantify 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 fuzzy logic system 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 fuzzy logic system.

4. RESULTS AND DISCUSSION-A CASE STUDY

Considering a project of "Fuzzy Logic approach to shock wave in water conveyance system or penstock design and selection of a small hydro power generation project in the Himalayan region within India".

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 expert's 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 then tabulated or defined. The most popular triangular membership functions for all inputs and outputs revealed. As they are 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. In shock wave analysis of SHP water conveyance system or penstock design and selection the two inputs are: water velocity change and wave speed change for the output-Surge Pressure change.

SHP penstock design optimization-cognitive modelling

Here we have considered following fuzzy conditions:

Definitions of water velocity change

Low trimf (0 15 35); Medium trimf (30 45 65); High trimf (60 75 100)

Definitions of wave speed change

Low trimf (0 15 35); Medium trimf (30 45 65); High trimf (60 75 100)

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Now let us consider following condition:

Water velocity change (63 Unit): Medium (0.1) and High (0.2)

Wave speed change (32 Unit): Low (0.15) and Medium (0.133)

Rules fired are 4, 5, 7 and 8 as shown:

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

Output C.O.G. = ∑μi*μ (i) / ∑μI

= (65*0.1+0.1*20+0.15*65+0.133*65) / (0.1+0.1+0.15+0.133)

C.O.G. = 56% (Approx) i.e., "Critical".

Validation - MATLAB FIS simulation

Inputs: Water conveyance system or penstock shock wave need specific parameters and input variables to be measured to estimate "Head Pressure change". Here two inputs are "Water Velocity change" and "Wave Speed change" as shown in Figure-4 and Figure-5.

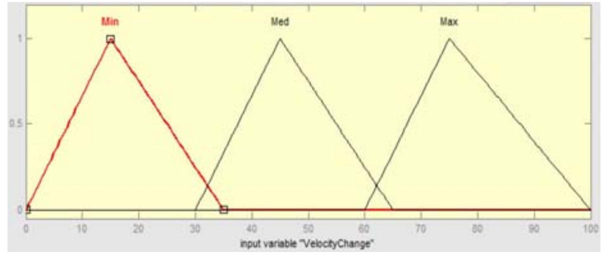

Figure-4. Water velocity change-Input.

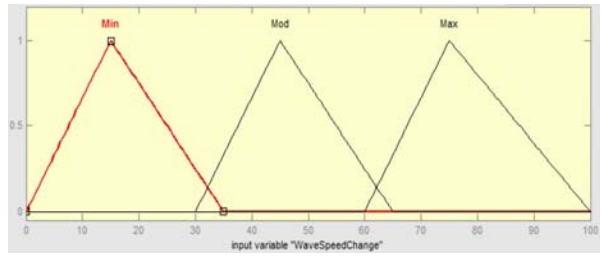

Figure-5. Wave speed change-Input.

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 Figure-6. The rules are based on "Mamdani Inference Method". Considered hypothetical rules to obtain optimum inputs and output as well as reasonable and realistic results for them.

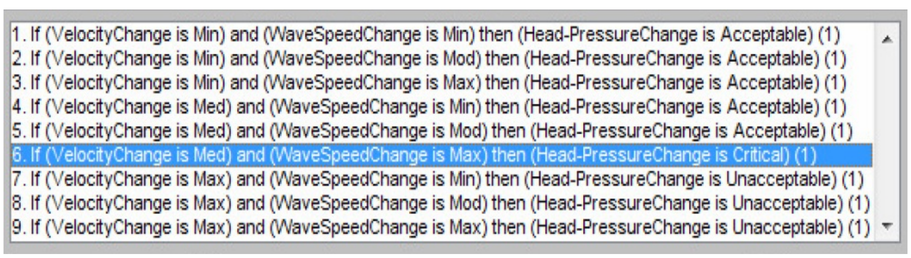

Figure-6. Fuzzy mamdani-rule editor.

Output: Figure-7 shows the relation of 2 inputs i.e., "Water Velocity change" and "Wave Speed change" for their 1 output i.e., "Head or Surge Pressure change".

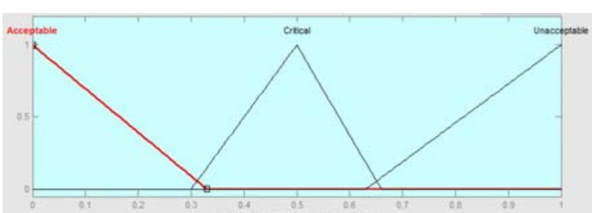

Figure-7. Head-pressure change-output.

Rule viewer-graphical: Figure-8 shows the relation of 2 inputs i.e., "Water Velocity change" and "Wave Speed change" for their 1 output i.e., "Surge Pressure change" through graphical rule viewer. Result shows 57% i.e., "Critical - Output". Hence we find after validation that calculative accuracy of the fuzzy model is very reasonable as shown.

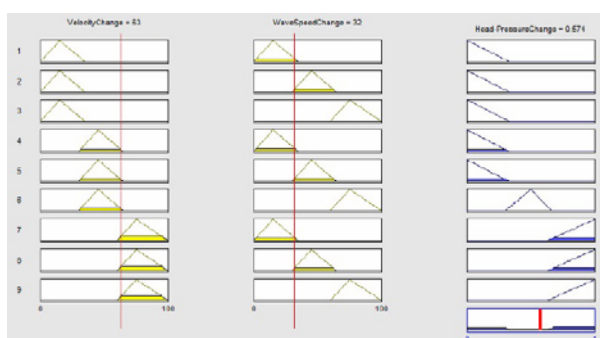

Figure-8. Fuzzy rule viewer-graphical.

Surface viewer-graphical: Figure-9 shows the 3D relation of 2 inputs i.e., "Water Velocity change" and "Wave Speed change" for their 1 output i.e., "Head Pressure change".

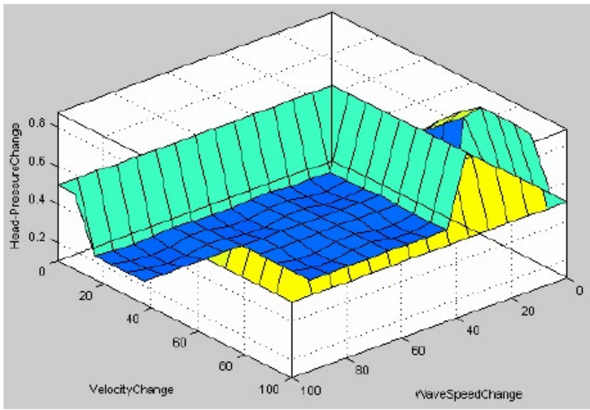

Figure-9. Fuzzy rule viewer-3D surface.

5. CONCLUSIONS

The present study intends to contribute for the improvement of Fuzzy Logic application thru use of MATLAB for surge analysis of hydro power generation. Hydro electric power generation is one of the earliest known renewable energy sources and hence has 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, shock wave analysis method based on MCDM or Fuzzy Logic is proposed for the small hydro power water conveyance system or penstock design. Optimization of the membership functions is an important factor, for the success of optimum hydro electric generation and reservoir control during various power demands and overflows. User does not need much domain knowledge on hydro power design 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 other renewable energy generations design process in future.

REFERENCES

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

[2] A. Flamos, *et al.* 2011. Hydro energy: techno-economic and social aspects within new climate regime. Int. J. Renewable Energy Technology. 2(1): 32-62.

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

[4] Gagan Singh and D.S. Chauhan. 2011. Simulation and Modeling of Hydro Power Plant to Study Time Response during Different Gate States. IJAEST. 10(1): 42-47.

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

[6] M.N. Rao. 2011. Implementation of a small hydro power project in India: Issues and lessons. Int. J. Renewable Energy Technology. 2(1): 53-66.

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

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

[9] L.A. Zadeh. 1975. The concept of a linguistic variable and its application to approximate reasoning. Information sciences. 8(3): 199-249.

[10] L.A. Zadeh. 1996. Multicriteria decision analysis or Fuzzy Logic = computing with words. IEEE Transactions on fuzzy systems. 4(2): 103-111.

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

[12] P. Adhikary, P.K. Roy and Asis Mazumdar. 2012. Selection of Penstock material for SHP - A Fuzzy Logic Approach. IJAST™. 6(2): 521-528.

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

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

[15] 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.

[16]S. Mishra, S.K. Singal and D.K. Khatod. 2012. Effect of Variation of Penstock Parameter on Mechanical Power. IJES. 2(3): 110-114.

[17]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.

[18]P. Adhikary, P.K. Roy and Asis Mazumdar. 2013. Fuzzy Logic based user friendly Pico-Hydro Power generation for decentralized rural electrification. IJETT. 4(4): 507-511.