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OPTIMIZATION OF POWER OUTPUT OF A MICRO-HYDRO POWER STATION USING FUZZY LOGIC ALGORITHM

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Abstract- In this study the electric power generation from the Kayabogazi Dam has been investigated using Fuzzy logic algorithm to optimize the required power demand. In the implementation of the algorithm the real data recorded by the State Water Works (DSI) which is representing monthly average water flow to the Kayabogazi Dam has been used. An easy and operator friendly control algorithm has been developed to operate and control the projected turbines of the micro sized hydroelectric power plant. The control and operation of the projected small-scale hydro-electric power station will be realized by using fuzzy logic (FL) control and programmable logic controller (PLC).

Keywords: Fuzzy Logic, Small Hydro Plant, Renewable Energy.

I. INTRODUCTION

In today's fast developing and emerging world; due to increasing environmental concerns the importance of the renewable and alternative energy sources are increasing. As a stable and well developed technology small scale hydro power sources play a major role among the other renewable power generation sources such as wind energy, solar energy, wave energy, geothermal energy etc. The small-scale hydro power is one of the most reliable and cost-effective primary energy sources for renewable and sustainable electric power generation.

As an environmentally benign and well developed technology, small hydro power stations have higher capacity factor and efficiency, high level of predictability, varying only with the seasonal rainfall patterns. Another advantage of the hydro power versus other renewable energy sources such as wind or solar energy; is its availability is not sporadic; hence it does not need to be backed by other sources in order to avoid instability of the power system. The hydro-power technology is a long-lasting and robust technology and the turbines can serve long years depending on the water specifications. In literature [1-4], many studies are present in the renewable energy sector. Houri [1] in his study, evaluated the hydro power electricity generation in Lebanon.

Mamlook et al. [2], has used neuro-fuzzy programming method to compare various electricity generation options for several energy sources in Jordan and concluded that the hydro power is the best option with solar and wind systems. Mungwena [3], studied the Zimbabwe's hydropower potential in major dams using the general technique. Egre and Milewski [4], has exposed the diversity of hydro power projects, hence, they have determined that there is a wide variety of hydroelectric projects, each providing different types of services and generating environmental and social impacts of different nature and magnitude.

Turkey has an economic capacity of 128 billion kWh hydroelectric energy per annum. Only 36% of this capacity has been utilized to generate electricity from hydroelectric power plants corresponding to 46 billion kWh per year. In Turkey the vast majority of the electric hydroelectric power comes from large scale projects that generate more than 10 MVA of electricity. The rivers suitable for SHPs are generally have been utilized for agricultural irrigation purposes only. Having 433 billion kWh gross theoretical hydro-potential, Turkey has a share of only 1% of world hydro potential and with its 125 billion kWh economically exploitable potential, this share is about 15% in European hydro power potential. The total number of hydropower stations with less than 10 MW installed capacity is 93. Of these 89 are run-of water and the others are dam or lake hydro power schemes with a total installed capacity of only 83.8 MW [5-6].

In Turkey, generally if the installed capacity of a hydroelectric plant is less than 10 MVA, it is classified as "small hydro". Generally in industrial terms, mini- and micro-hydro typically refer to schemes below 2 MW and below 500 kW, respectively [7]. These are arbitrary divisions and many of the principles involved apply to both smaller and larger schemes.

II. KAYABOGAZI DAM

Kayabogazi Dam has been commissioned in 1988 by The State Hydraulic Works of Turkey (DSI) on Kocacay River for irrigation and flood control purposes. It is located 34 km east of town of Tavsanli of Kutahya province. As can be seen from Figure 1, the Kayabogazi Dam is an earth- and rock filled dam with a volume of

628,000 m^3. The dam is 237 m (777.5 ft) long and its crest is 38 m above the level of the river bed (924.75 m above sea level). At normal water elevation, the area of the reservoir is 4.20 km^2 with a volume of 38.00 hm^3. The proposed Kayabogazi hydroelectric power station is based on generation of power from 130 million m^3 of water currently used for agricultural irrigation only. For this reason, the data related to the water flow rate recorded by DSI between the years of 2007 and 2011 is evaluated. From the records, it is seen that the maximum level of water was regulated at 918 m.

The monthly average rate of water flow to the dam as total and production values is given in Table 1. As seen from the table, the incoming flow rate is not stable. The amount of monthly average of flow varied from 2.86 to 7.11 m^3/s. The total volume of the reservoir is 37.8 million m^3 and rather small. Since the physical size of the reservoir is not adequate in dry seasons, the volume of water cannot be regulated for more than a few months. In this case, the electric power generation will be highly dependent on the incoming water flow to the dam and will be subject to variations.

Figure 1. The Kayabogazi Dam [6]

Currently, in the operation of the Kayabogazi Dam any optimization or control methodology is not implemented. In this study in view of these constraints outlined above, the operation of the plant has been optimized to supply the required electric power demand (PD) to the existing medium voltage power grid.

Table 1. The average flow to Kayabogazi Dam between 2007-2011

Months	Monthly average water volume (m^3)	Average flow rate (m^3/s)	The output power of the turbine (kW)	Monthly electric energy generation (kWh)	Annual electric energy generation (kWh)
January	10274020	3.96	642	462331	5524736
February	14690988	6.07	984	661094	
March	18435600	7.11	1152	829602	
April	12825680	4.95	802	577156	
May	10874720	4.20	680	489362	
June	8988420	3.47	562	404479	
July	7759840	2.99	485	349193	
August	7449520	2.87	466	335228	
September	7667640	2.96	479	345044	
October	7529520	2.90	471	338828	
November	7412500	2.86	463	333563	
December	8863460	3.42	554	398856	

For this purpose an easy and operator friendly fuzzy logic (FL) based algorithm has been developed to operate and control the projected turbines of the micro sized hydroelectric power plant.

III. DETERMINING TURBINE TYPE AND CAPACITY

As can be seen from Table 2, the turbines used for high head applications are generally referred as impulse turbines, including Pelton, Turgo and cross flow designs. The impulse turbines differ from reaction turbines as the runner of an impulse turbine is driven by a high-speed jet of water and spins at or near atmospheric pressure. Due to their low operation speeds, impulse turbines are not suitable for the sites with low heads. Francis and variable pitch (Kaplan) turbines are of the reaction type and usually preferred in low to medium head hydro projects.

Table 2. Impulse and reaction turbines [7]

Head classification	Turbine type	
	Impulse	Reaction
High (>50 m)	Pelton Turgo Multi-jet	
Medium (10-50 m)	Cross flow Turgo Multi-jet Pelton	Francis (Spiral case)
Low (<10 m)	Cross flow	Francis (Open flume) Propeller Kaplan

The reaction turbine utilizes both flow and kinetic energy of the liquid and energy conversion takes place in an enclosed space at pressure above atmospheric conditions. In hydro-turbo turbines, the power produced is the product of net hydraulic head and the water flow which propels the turbine. For any given hydro scheme, the electrical power P produced by the alternator which is proportional to the product of net head H and volume rate Q of penstock can be written as [7]:

$$P = \eta \rho g Q H \tag{1}$$

where η is the total efficiency of the turbine (including the electrical generator), ρ is the water density and g is the gravity acceleration. The efficiency of the turbine is related to the effective head and water flow which varies in between 80% to 90% in good turbines. The major advantage of reaction turbines is that they can provide the necessary rotational speed for the modern generators at low heads.

The Francis turbine has a high maximum efficiency but relatively low part-load efficiency compared to either impulse wheel or the Kaplan turbine [7-8]. In this study, it has been considered that the turbine is located at the end of the existing penstock which has a diameter of 1.0 m and a length of 270 m. The net head is assumed as 18 m. By evaluating the net head and the amount of water flow on monthly basis; instead of using a single 1400 kW unit, installation of three units with the output power of 250 kW (T_1), 400 kW (T_2) and 750 kW (T_3) which comprise of Francis turbines and self excited synchronous generators has been proposed.

Hence apart from meeting the required *PD* it would be possible to generate electricity at low water levels due to low part-load efficiency of Francis turbines. In addition, during the maintenance of a single unit, the rest of the system may continue to generate electric power.

IV. FUZZIFICATION PROCESS

The concept of Fuzzy Logic (FL) was first introduced by Zadeh (1965) which is defined as the logic of human thinking. It deals with problems in engineering as a way of processing data which allows partial set membership rather than crisp set membership or non-membership by giving degrees of certainty to the answer of a logical question. In contrast to classical logic which is based on crisp sets of “true and false”, fuzzy logic views problems as a degree of “truth”, or “fuzzy sets of true and false. It provides a simple way to arrive at a definite conclusion and does not require precise, noise-free information and can be programmed safely. The output control of FL is a smooth control function a wide range of input data. [9-11].

A flow chart of the algorithm is shown in Figure 2. The inputs of the system are power potential (*PP*) of the water and electric *PD*. The output of the system is electric power generation (G) versus input variables. The first step in FL is to gather and convert a crisp set of input data to a fuzzy set using linguistic variables rather than numerical values, fuzzy linguistic terms and membership functions. Membership function is the mathematical function which defines the degree of an element’s membership in a fuzzy set [9].

There are different forms of membership functions such as triangular, trapezoidal and Gaussian shapes. As seen from Figure 3, two trapezoid and three triangular shapes were formed to define fuzzy membership functions using *PP* of water, which ranges from 0 to 1150 kW. In the fuzzy membership functions which are shown PP_1, PP_2, PP_3, PP_4 and PP5 correspond to very low, low, moderate, high and very high *PP* of water respectively. Membership degrees corresponding *PP* for trapezoid shapes were calculated by using membership functions in Equation (2) [9]:

$$\mu(x_i)=\begin{cases} \dfrac{x_i-a}{b-a}, & a \le x_i \le b \\ 1, & b < x_i < c \\ \dfrac{d-x_i}{d-c}, & c \le x_i \le d \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

Similarly the membership degrees corresponding *PP* for triangular shapes were calculated by using membership functions in Equation (3) [9]:

$$\mu(x_i)=\begin{cases} 0, & a \ x_i \le a \\ \dfrac{x_i-a}{b-a}, & a \le x_i \le b \\ \dfrac{c-x_i}{c-b}, & b \le x_i \le c \\ 0, & c \ge x_i \end{cases} \tag{3}$$

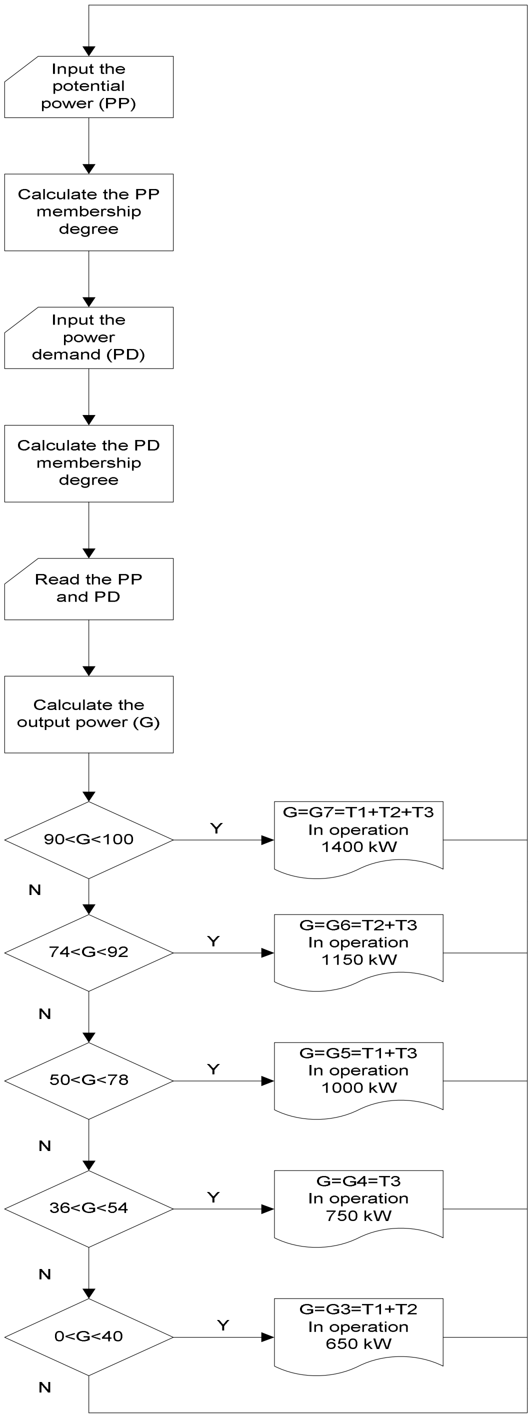

Figure 2. A flow chart of the FL algorithm

where *a*, *b*, *c* and *d* are limits of the membership function. For instance, PP_2=0.30 and PP_3=0.69 can be calculated for *PP*=640 kW. Two trapezoid and three triangular shapes were also chosen to express the second crisp input for *PD*. Five membership functions were formed for *PD* between 0 and 1150 kW (Figure 4). In the fuzzy membership functions which are shown as PD_1, PD_2, PD_3, PD_4 and PD_5 correspond to very low, low, moderate, high and very high electric *PD* respectively. Membership degrees were calculated using Equations (2)-(3). For instance, PD_1=0.48 and PD_2=0.48 can be obtained for *PD*=500 kW.

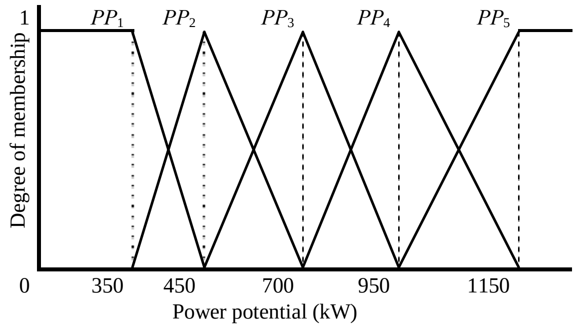

Figure 3. Fuzzy membership functions and membership degree of *PP*

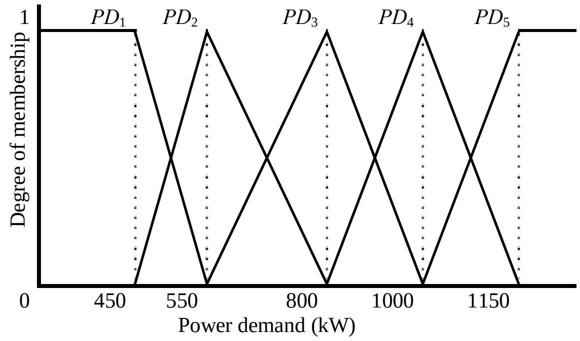

Figure 4. Fuzzy membership functions and membership degree of *PD*

A. Fuzzy Inference

The second step in fuzzy processing is fuzzy inference. In a FL controlled system, a rule base is constructed to attain the output variable by using the membership values and their definitions. A fuzzy rule is a simple IF-THEN rule with a condition and a conclusion, which consist of outputs of fuzzification corresponding to *PP* and *PD* linguistic inputs. Four linguistic outputs were used in the rule base (G_3, G_4, G_5, G_6 and G_7) as shown in Table 3. As can be seen from Figure 2 for the output of G_3 only T_3 turbine, for the output of G_4 a combination of T_1 and T_2 turbines, for the output of G_5 a combination of T_1 and T_3 turbines, for the output of G_6 a combination of T_2 and T_3 turbines and for the output of G_7 all three turbines will be in operation.

The evaluations of the fuzzy rules and the combination of the results of the individual rules are performed using fuzzy set operations. Relations obtained from the rule base were interpreted using minimum operator, "and". The outputs obtained from rule base were interpreted using maximum operator, "or". The fuzzy rules used in the current work are as follows:

If $PP=PP_1$ and $PD=PD_1$ then $G=G_3$ where five outputs of *PP* and five outputs of *PD* were available.

Table 3. Database of triangular membership function

	PD_1	PD_2	PD_3	PD_4	PD_5
PP_1	G_3	G_3	G_3	G_3	G_3
PP_2	G_3	G_4	G_4	G_4	G_4
PP_3	G_3	G_5	G_5	G_5	G_5
PP_4	G_3	G_5	G_6	G_6	G_6
PP_5	G_3	G_5	G_6	G_7	G_7

B. Defuzzification

After the inference step, the overall result is a fuzzy value. This result should be defuzzified to obtain a final crisp output so that the actual system can use these variables. For this process, the resulting fuzzy output is converted to a crisp output according to the membership function of the output variable.

For this purpose, the centroid of each membership function for each rule is first evaluated. The final output *COG* (G), is then calculated as the average of the individual centroid, weighted by their heights as follows [9]:

$$COG=\frac{\sum_{x=a}^{b}\mu_A(x)\cdot x}{\sum_{x=a}^{b}\mu_A(x)} \tag{4}$$

where *COG* is defuzzification output and $\mu_A(x)$ is minimum/maximum value of membership degree of input values. The output membership functions, G_3, G_4, G_5, G_6 and G_7 were converted to output power degrees, which were between 0 and 100 (Figure 5).

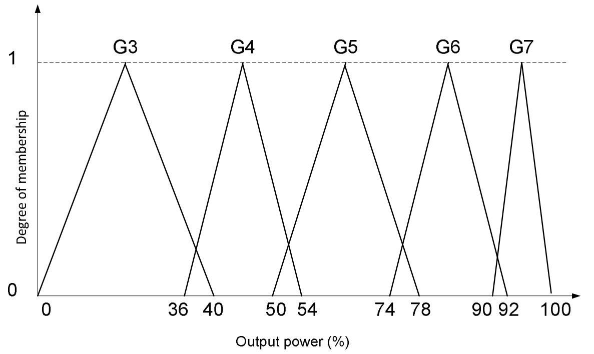

Figure 5. Linguistic membership functions of output power

V. RESULTS

The FL algorithm was tested for different input values of *PP* and *PD* by using Matlab software. The fuzzy membership functions of *PP* and *PD* are illustrated in Figures 3 and 4 respectively. For the *PP*=400 kW and *PD*=300 kW, linguistic membership functions of output power has yielded 20% of output power. This leads to the operation of G_3 which consist of T_3 turbine only. For slightly higher input values of *PP* and *PD* which are 500 kW and 600 kW respectively the membership function for the output power has yielded 48.8%.

In this case the T_1-T_2 turbine remained in operation. For the values of *PP*=800 kW and *PD*=900 kW, the output power corresponded to 73.3%. In this case the G5 output, consisting of T_1 and T_3 turbines, was instructed to operate. For higher values of *PP* and *PD*; for example 1000 kW and 1150 kW of input values respectively, the algorithm has given the output power as 87.5%.

In this case for the G_6 output T_2 and T_3 turbines will be in operation; and even higher input values of *PP* and *PD* for example 1250 kW each, the algorithm has given the output power as 95%. In this case for the G_7 output all T_1, T_2 and T_3 turbines will be in operation.

VI. SELECTION OF FUZZY CONTROLLER

In this study the fuzzy block of ABB Programmable logic controllers (PLCs) has been used to implement the fuzzy algorithm via ladder logic programming (LLP). In recent years, with the increase in microprocessor performance, the PLC’s began to perform more complex sequential control as well as to manipulate analogue inputs and outputs at low cost [24]. The PLC uses a programmable memory to store commands and specific functions that include switching, timing, counting, arithmetic operations and data handling. They have the ability to communicate with other PLCs or computer equipment in the network to perform functions such as supervisory control and data acquisition, process monitoring and downloading or uploading of programs. They are robust, reliable, and reusable, could withstand a harsh industrial environment such as extreme temperatures or dust in the air. The PLC operates the turbines with regards the water potential of the dam and power demand from the station by executing the fuzzy algorithm created with the LLP.

A. PLC Program

Figure 6 shows the basic structure of the system. In the implementation of the algorithm the water potential of the dam and power demand of the local load has been measured by using flow and current sensors. This information has been sent to the PLC at 4-20mA level using coaxial cables. In the figure S_1, S_2 and S_3 represent the switches for the synchronous connection of the alternators and S_4 indicates the circuit breaker for the connection of the station to the regional grid at medium voltage (MV) level. The MV_1, MV_2 and MV_3 motor driven electric valves which control T_1, T_2 and T_3 turbines are operated according to required power demand and water potential of the dam by the Fuzzy algorithm run within the PLC. Figure 7 illustrates the flowchart of the fuzzy algorithm.

In the implementation of the algorithm, initially all the electric driven valves are opened and consequently all the turbines are put into operation. In this stage, in view of the water potential of the dam the highest power generation capacity has been defined and power station starts to operate with the required number of turbines. After the operation of the turbines the grid breakers has been closed and the load demand has been monitored by the PLC using load current information.

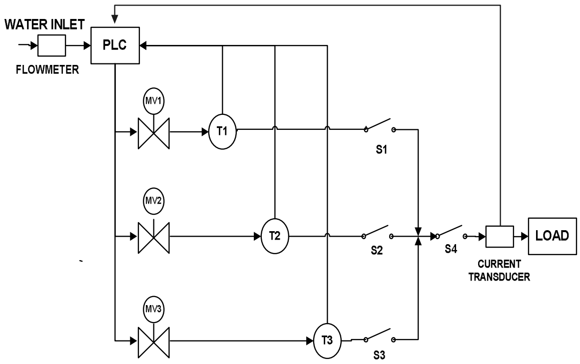

Figure 6. Single line diagram of the PLC operated system

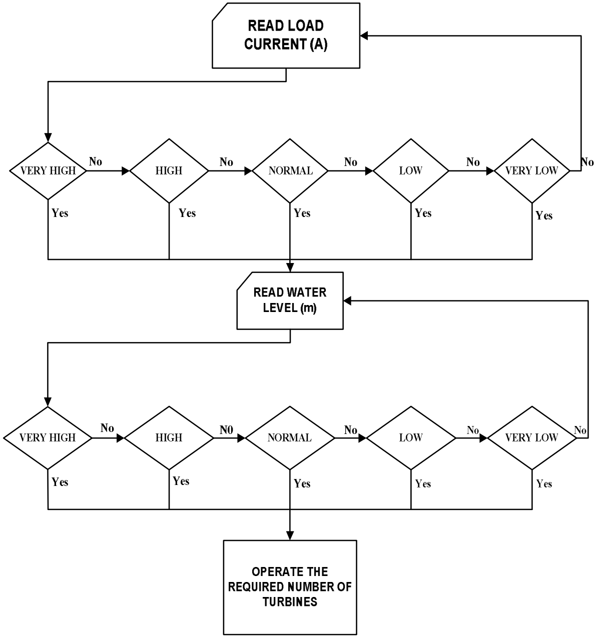

Figure 7. Flowchart of the fuzzy algorithm

In this stage the time span until the loads connected to the system stabilize has been observed and defined. At the end of the predefined time span if the loads has not been stabilized, then the time span restarts by the PLC (in this study it is taken as 120 seconds). After this process the fuzzy logic algorithm becomes active within the continuous loop. As can be seen from Figures 8-9, the fuzzy algorithm within the PLC, operates the turbines by monitoring the load current and water level of the reservoir. In this process, the water level of the reservoir and the power demanded by the regional grid continuously monitored. By executing the fuzzy logic algorithm within the PLC the required number of turbines were put into operation.

VII. CONCLUSIONS

In recent years due to the harmful effects of conventional power stations to the environment, installations utilizing renewable energy sources have been subject to renewed interest both in developing and in industrially developed countries. In this study by using existing infrastructure of Kayabogazi Dam and without extensive civil engineering work electric power generation has been investigated. Due to unstable water regime of the dam; instead of a single turbine; installation of three smaller units has been proposed. The operation of the turbines for the power potential and power demand constraints has been optimized using a FL algorithm. The algorithm can easily be implemented to the hydro-plant using programmable logic controller (PLC). Hence at low water levels the electric power generation can be achieved in reliable and economic way.

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REFERENCES

[1] A. Houri, "Prospects and Challenges of Using Hydropower for Electricity Generation in Lebanon", Renewable Energy, Vol. 31, pp. 1686-1697, 2006.

[2] R. Mamlook, B.A. Akash, M.S. Mohsen, "A Neuro-Fuzzy Program Approach for Evaluating Electric Power Generation Systems", Energy, Vol. 26, pp. 619-632, 2001.

[3] W. Mungwena, "Hydropower Potential on Zimbabwe's Major Dams", Renewable Energy, Vol. 25, pp. 455-462, 2002.

[4] D. Egre, J.C. Milewski, "The Diversity of Hydropower Projects", Energy Policy, Vol. 30, pp. 1225-1230, 2002.

[5] "Licensed Hydraulic Power Plants", Electricity Generation Co. Inc. (EUAS), www.euas.gov.tr/_Euas/Images/Birimler/musterihizme/lichidro.pdf,Turkey, 2006.

[6] Y. Aslan, O. Arslan, C. Yasar, "A Sensitivity Analysis for the Design of Small Scale Hydropower Plant: Kayabogazi Case Study", Renewable Energy, Vol. 33, No. 4, pp. 791-801, April 2008.

[7] O. Paish, "Small Hydro Power: Technology and Current Status, Renewable and Sustainable Energy Reviews, Vol. 6, pp. 537-556, 2002.

[8] G.W. Frey, "Hydropower as a Renewable and Sustainable Energy Resource Meeting Global Energy Challenges in a Reasonable Way", Energy Policy, Vol. 30, pp. 1261-1265, 2002.

[9] I. Guler, A. Tunca, E. Gulbandilar, "Detection of Traumatic Brain Injuries Using Fuzzy Logic Algorithm", Expert Systems with Applications, Vol. 34, pp. 1312-1317, 2008.

[10] A.S. Kannan, R. Kayalvizhi, "A Novel Design of a Fuzzy Coordinated SSSC Controller for Integrated Power Systems", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 8, Vol. 3, No. 3, pp. 6-16, September 2011.

[11] A. Barati, S.J. Dastgheib, A. Movaghar, I. Attarzadeh, "An Effective Fuzzy Based Algorithm to Detect Faulty Readings in Long Thin Wireless Sensor", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 10, Vol. 4, No.1, pp. 52-58, March 2012.

BIOGRAPHIES

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