

SIMULATION AND LABORATORY MODEL OF SMALL HYDROPOWER PLANT

Richard OLEXA, Pavol FEDOR

Department of Electrical Engineering and Mechatronics, Faculty of Electrical Engineering and Informatics,
Technical University of Košice, Letná 9, 042 00 Košice, Slovak Republic, Tel. +421 55 602 2694, E-mail: richard.olexa@tuke.sk

ABSTRACT

This paper is dedicated to the description of all our research done so far in the field of simulation of small hydropower plants as well as in creating a functional laboratory model based on the proposed simulation models. Comparing to the common structures, we propose some different approaches in modelling parts of the small hydropower plants, e.g. fuzzy model of the hydraulic turbine efficiency. Moreover, this simulation model is created directly for the small hydropower plants, thus it simplifies parts, that are commonly used in other scientific papers and simulate the phenomenon connected to the big scale hydropower plants structure and physical description. As a necessary step in the process of creation of universal laboratory model of a small hydropower plant that should be used for design and tuning purposes of new approaches of controlling such systems, we discuss the research and development phase that led to the final construction of the depicted laboratory model.

Keywords: small hydropower plant, simulation model, asynchronous generator, laboratory model, MATLAB

1. INTRODUCTION

At the moment, the pressure put on all of the countries, especially in the European union connected to the usage of a renewable energy sources instead of fossil fuels and most recently instead of natural gas as well, leads many institutions and researchers to development of new, more efficient and simple solutions in this field.

Not only this, but a long lasting common aim to be more green or in other words, environmental friendly, was our reason for starting this research at its very beginning, too.

Firstly, an overview of the currently available scientific papers and work was done, i.e. defining a scale differences, comparing proposed simulation schemes of small hydropower plants, while adjusting these ideas to perform as efficient as possible for our modelling purposes. The vast majority of already-published papers describes modelling and simulation of a large scale hydropower plants, thus, consists of some phenomenon, or its model respectively, that are not needed to be incorporated in the model of a small hydropower plants, especially because of the missing technological parts that cause them, e.g. water hammer phenomenon; surge tank subsystem; etc. [1]

As mentioned, this paper is dedicated to the investigation of small hydropower plants, with a unit rating Power Generated P_G between 100kW to 5GW; run-of-river type, or only with a small reservoir, while the proposed simulation model and new modelling approaches are being applied. Moreover, the construction and the scheme definition of a laboratory model of a small hydropower plant for simulation, development and optimization purposes, was performed.

2. PROPOSED SIMULATION MODEL

Generally, small hydropower plant (SHP) is simulated using a model of five main sub-systems, i.e. the Governor – representing a turbine control system; the Servodrive, that serves as an actuator to regulate the flow of the water throughout the hydraulic turbine via controlling the valves, or guide vanes according to the Governor output signal; the simulation model of a Hydraulic Turbine – representing the

process of conversion of the energy; as well as a block for the Electric Generator and another one for the Grid. [1] The already-described scheme is depicted in the Fig. 1.

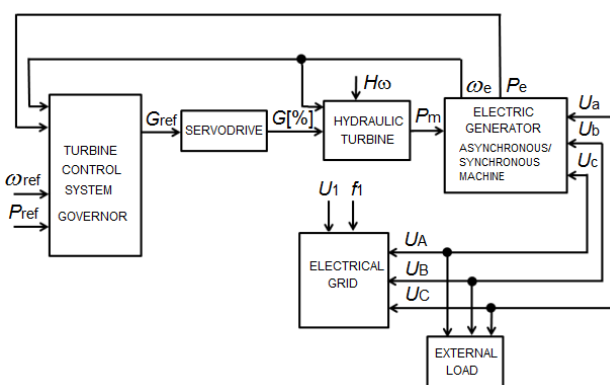


Fig. 1 Block diagram of Small Hydropower Plant [2]

In this model, there are all of the parameter normalized, i.e. they reach the value between 0 and 1, or between 0 and 100% respectively. Moreover, as stated before, it is possible to neglect all of the phenomenon characterized for a big scale hydropower plants for the purposes of our simulation, e.g. water hammer, travelling waves, etc., mainly due to the length of the penstock and the typical height of the water head usually available at the SHP.

2.1. Turbine Control System – Governor

In general, Turbine Control System, or so called Governor serves in the scheme as a part performing two main functions, i.e. running up the hydraulic turbine, thus reaching the reference speed, taking the grid frequency and the number of generator's poles into account; and after connecting to the grid, this sub-system aims to control the power supplied by the SHP. In the Fig. 2, there is a well described and common scheme depicted that Munoz-Hernandez wrote in more detail about [3], where K_P - a proportional gain; K_I - an integral gain; K_D - derivative gain; and α - a permanent droop, that serves to boost the input signal of the controller coming from a power

controlling part of the scheme. Blocks of the Saturation placed in the diagram serves as some kind of an alternative to an anti-reset windup (ARW) protection.

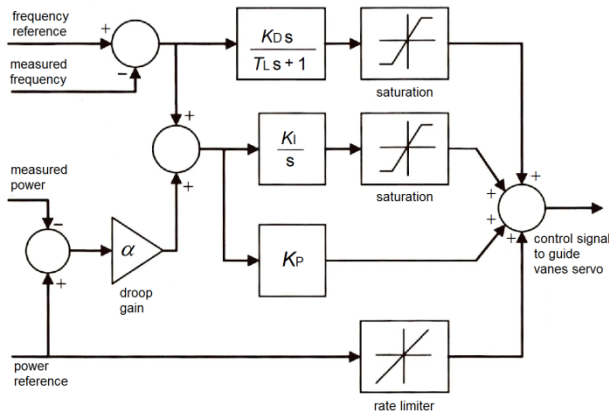


Fig. 2 PID controller representing the Governor Sub-System [3]

2.2. Servodrive

A second-order dynamic subsystem is used to represent a servodrive performing the opening and closing of the main water inlet gate. As mentioned in the previous parts of this paper, some of the phenomenon are being neglected in the proposed simulation model, especially due to the construction type, i.e. the scale of the simulated hydropower plant. On the other, even if this assumption is in line with other scientific literature, in some cases the water hammer phenomenon could possibly occur in the SHP. Usually, it happens if there is a fast opening or closing of the gate. Therefore, the saturators are being placed to limit the position and speed of the gate movement.

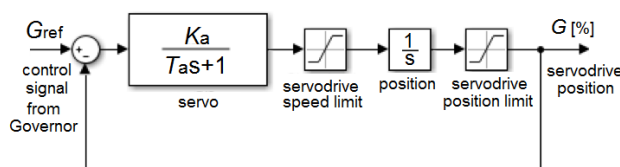


Fig. 3 Servodrive Sub-System (state variables are: speed of the water inlet gate opening and its position parameters K_a and T_a are calculated according to the type of an implemented servodrive used in the hydroelectric scheme) [2]

2.3. Hydraulic Turbine

The Hydraulic Turbine, considered as a heart of the hydropower plants, plays an important and irreplaceable role in these structure, because it converts a kinetic, or potential energy of the water, into the mechanical movement that is usually transferred to the generator via a common shaft. Obviously, such an important role requires an accurate model to be used in the simulation schemes in order to achieve realistic and relevant results.

However, there are some differences in modelling this part in the published scientific papers. Many of them consider this sub-system being able to be linearized. We are determined, that using a non-linear model would result in a better and more accurate simulation outcomes. On the other hand, there are various ways how to take a very important

turbine's efficiency into account. First approach is so called no load flow calculation method described in detail by the IEEE Working Group in 1992. [4] Another one is a direct efficiency calculation method, presented by Acakpovi and Essel [6]. Both of these ways were described and compared in the paper [1]. While creating the proposed simulation model of a SHP, we chose to use the first one, i.e. the no load flow approach. Afterwards, we developed a fuzzy model for better efficiency incorporation that is discussed in detail in the next chapters of this paper.

2.4. Electromechanical Subsystem

Tiwari, Munoz-Hernandez, Acakpovi, Sattouf and many others describe the most common ways of creating a model representing an electromechanical part of a SHP.

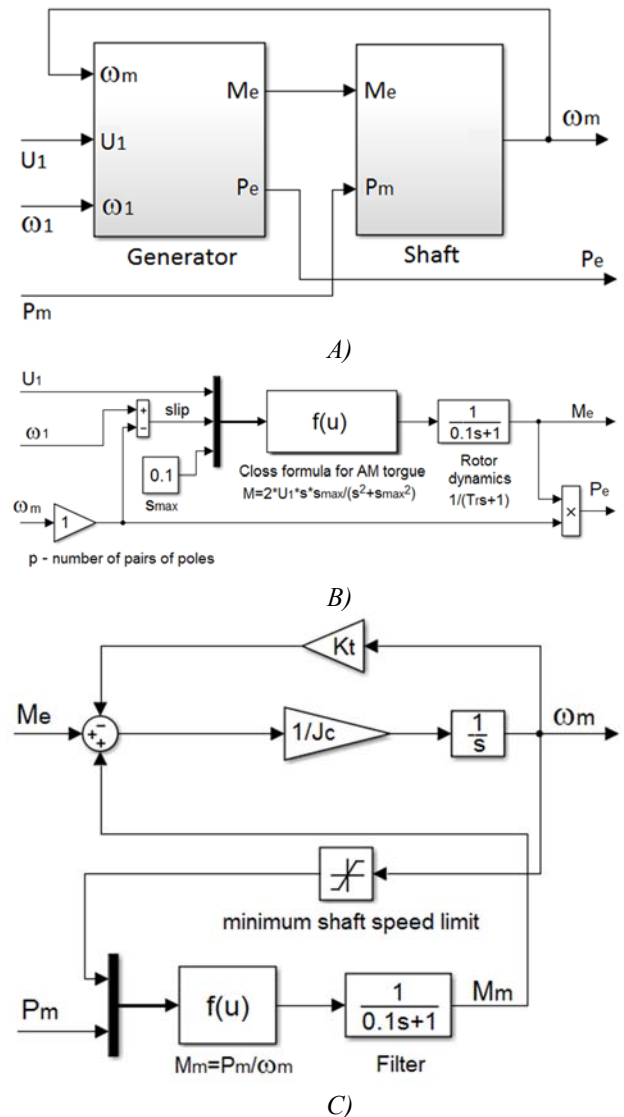


Fig. 4 Block diagram of Electromechanical Subsystem [2]

- A) Interconnection of the generator and the turbine (the common shaft)
- B) Asynchronous generator model
- C) Model of the mechanical system connected to the shaft

The proposed model considers an usage of an asynchronous generator described by the Closs formula. Considering the speed of changes in electrical and hydromechanical parts of the SHP, hydrodynamic

processes are considerably slower, thus for the simulation purposes it is sufficient to model a generator only in terms of a torque equation of the common shaft between the turbine and the generator, whereas the equation of the equilibrium (1) is valid. [2]

$$M_e + M_m - M_f = J_c d\omega_m/dt \quad (1)$$

$$M_f = K_t \omega_m \quad (2)$$

$$M_m = P_m/\omega_m \quad (3)$$

where: M_e is the torque of the generator, M_m the torque of the turbine and M_f is the frictional torque proportional to the mechanical angular velocity ω_m ; the constant K_t in the equation (2) represents the friction coefficient. The right side of the equation (1) represents the dynamic torque on the shaft, which accelerates the total moment of inertia on the shaft J_c . Thus, P_e is the generated electrical power on the shaft, which in case of an asynchronous machine is proportional to product of its torque and the rotor angular velocity ω_m . The before-mentioned assumption complies connection of models of the asynchronous electric generator and hydraulic turbine fixed on the common shaft (depicted in the Fig. 4), where T_r is the rotor time constant of the asynchronous generator corresponding to the rotor resistance. [3][5][11]

3. PROPOSED FUZZY EFFICIENCY MODEL OF A HYDRAULIC TURBINE AND LABORATORY MODEL OF SMALL HYDROPOWER PLANT

3.1. Fuzzy efficiency model of a hydraulic turbine

The approaches mentioned above are dependent on the accuracy of the calculation, as well as on the precise determination of the key parameters that are necessary for incorporating the turbines efficiency into the simulation model. However, these parameters are often not available or have to be determined, or calculated respectively, that leads to possible errors, as well as to making the data preparation phase long lasting and in many times, quite complicated.

Therefore, we started considering some other possibilities, how to get rid of the uncertainty created by the above-described process of hydraulic turbines efficiency incorporation. The solution proposed is based on the usage of Fuzzy logic. Such an approach allows to take into account the actual condition of a SHP, e.g. the wearing of the turbine's blades, its runner, or a change in the blades inner area, i.e. A_{blades} parameter, which is one of the key values in the calculation defined by Acakpovi et al. [6], whereas in the Fig. 5 and Fig. 6, there is an obvious change in the maximum possible turbine's efficiency, cause only by the change of an already mentioned parameter.

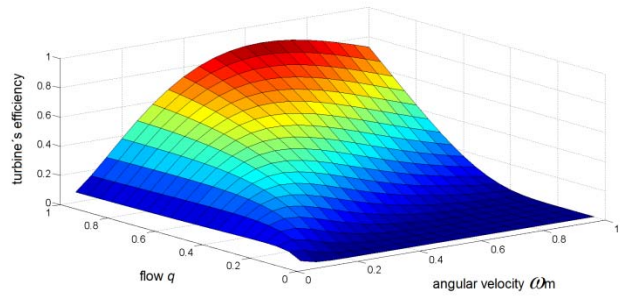


Fig. 5 3D illustration of a turbine's efficiency ($R_{blades}=1.9\text{m}$ and $A_{blades}=9\text{m}^2$), where maximum turbine's efficiency gained is approx. 88% [1]

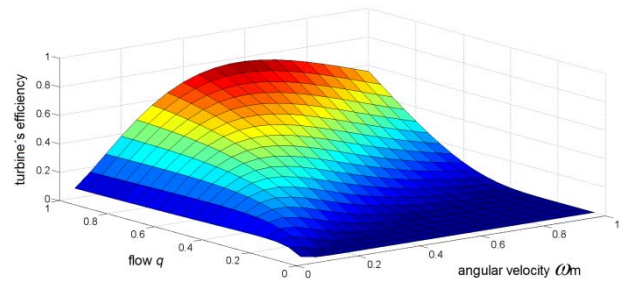


Fig. 6 3D illustration of a turbine's efficiency ($R_{blades}=1.9\text{m}$ and $A_{blades}=8\text{m}^2$), where maximum turbine's efficiency gained is approx. 77% [1]

That all means it is possible to create a so called hydraulic turbine's efficiency image, while using the measured data of the water flow q ; $\Delta\omega$ and the turbine's efficiency at the steady state operation points, as stated below in the Table 1.

Table 1 Different steady state operation points and the measured turbine's efficiency

Efficiency [%]		q [p.u.]				
		0.2	0.4	0.6	0.8	1
ω_m [p.u.]	0.2	12.77	30.36	36.23	37.83	37.97
	0.4	2.74	26.40	49.60	64.41	73.24
	0.6	0.35	13.64	40.90	66.92	87.22
	0.8	0.04	5.68	27.20	56.26	84.31
	1	0.00	2.11	16.07	42.03	72.49

Process of finding the fuzzy interference structure and the usage of an *Anfisedit* software tool provided by

MATLAB is discussed in more details in the paper. [1][10] As a result of the proposed determination process of a hydraulic turbine's efficiency, a graphical representation of this fuzzy system is shown in the Fig. 7.

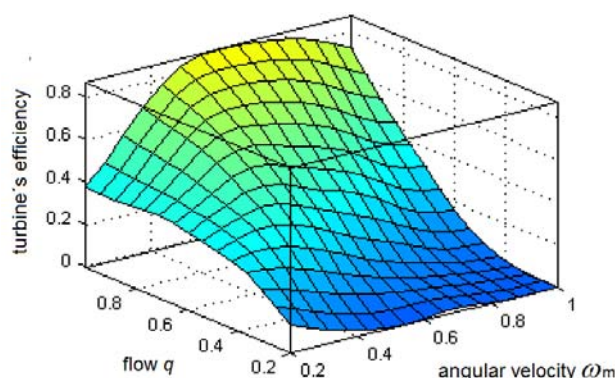


Fig. 7 An example of a fuzzy representation of the hydraulic turbine's efficiency [1]

3.2. Laboratory model of small hydropower plant

At the very beginning of the determination of the laboratory model's structure, we had to decide how would the laboratory model perform all the functionalities of each of the already-mentioned main simulation model subsystems, i.e. turbine-control system, or so called governor; servo drive that adjust the position of the main water inlet gate, or of the guide vanes respectively; hydraulic turbine; electric generator; plus the fifth part could be considered as an electrical grid.

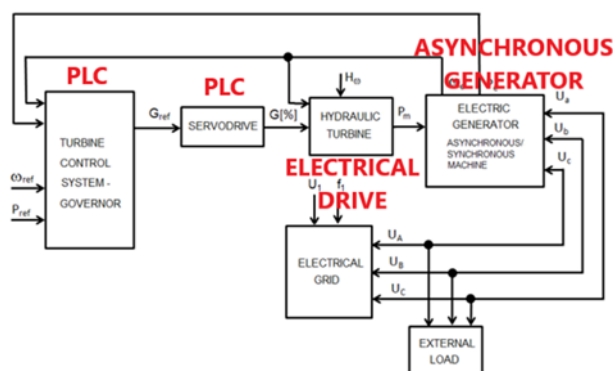


Fig. 8 Block diagram of Small Hydropower Plant + Highlighted elements [7]

In the Fig. 8, there is the same scheme as in the Fig. 1, but with the difference of highlighting the part of the laboratory model overtaking the subsystem's role. Each of the elements proposed to be a part of the laboratory model is described in the following subsections *A-C*.

A. PLC – Programmable Logic Controller – B&R Power Panel 500 series

This, all-in-one solution depicted in the Fig. 9 was chosen according to its ability to combine a controlling features with the HMI (Human Machine Interface)

functions in one device. This programmable logic controller is used to take over the control system part, shown in the Fig. 8; servo drive subsystem, as well as all the calculation connected to the operation of the simulated behavior of the hydraulic turbine.

The control mechanism is performed by using the functional block for the PID controller while using the calculated and tuned parameters obtained in MATLAB, or set up by the user. Implementation of the servo drive subsystem is done as well via programmed structure that supposed to give an input value for the hydraulic turbine part, i.e. the inlet water gate vane position $G[\%]$. All the calculations that are performed in the MATLAB model of the hydraulic turbine subsystem is then processed by the PLC (programmable logic controller) with an output of the turbine velocity [rpm] that serves as an input value for the electrical drive while using the B&R ACOPOSinverter 8I66 series.

Moreover, a build-in TFT display serves as an HMI where the user has various options to adjust the process values and thus to affect the operation, or the simulation process respectively. Examples of these parameters are: current water head value; demanded generated power (reference value); no-load flow value, i.e. the value that determines the efficiency of the turbine; or so called turbine gain (A_1 parameter – Turbine's Gain). Moreover, it displays all the process data needed for the safe operation and simulation purposes. [7]



Fig. 9 B&R Power Panel 500 – HMI display, placed on the front panel of the switchboard Electrical drive – ABB 3GAA101520-ADE662

B. Electrical drive – ABB 3GAA101520-ADE662

We chose a three-phase cage motor to perform the functions of the hydraulic turbine simulation model subsystem in the proposed laboratory model of a SHP, especially when it comes to a rotational movement of the turbine, or the movement of the common shaft respectively. Its velocity, or the input voltage value, is calculated according to the actual demanded generated power specification, as well as according to the parameters of the exact parameters of the simulated hydraulic turbine. Because of the fixed coupling between the motor and generator, the model represents an image of a real SHP operation. (see Fig. 10) Since it has an embedded encoder, the actual position and speed are easy to be used in the model, or in the PLC program respectively.

C. Asynchronous generator – ABB 3GA101520-ADE

This electrical drive is very similar to the one used as a simulator of hydraulic turbines behavior (subsection B). The only difference is that there is no encoder present at the machine. Thus, it is used as a generator, whereas the power generated is fed into the grid via a recuperative converter, or to the grid directly.

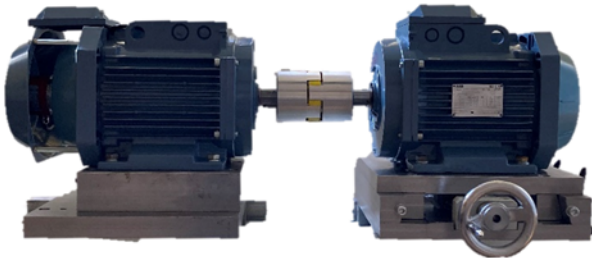


Fig. 10 Laboratory Model: Controlled Electrical Drive: Hydraulic Turbine (Left) and Asynchronous generator (Right) with the fixed coupling and common shaft

Additionally, the ABB CT PRO XT 40 current transformers are put in the scheme to transform the primary currents to secondary ones for c.a. measurements. Such a topology gives us the opportunity to monitor fast changes that could occur in the electrical part of the SHP and process them quickly with B&R X20AP3131 module, which measures active, reactive and apparent power individually for each phase as well as all of them collectively. In addition, this module provides the RMS values for voltage and current on the 3 phases. Definitely, for such fast changing parameters we need to secure fast processing as well. Therefore, a B&R PLC X20 CP1686X is included in the scheme and the communication of both PLC included in the scheme is done via OPC UA standard. [7]

4. DISCUSSION AND CONCLUSION

The authors have presented the complex simulation scheme of small hydropower plant in the MATLAB environment, while considering other unique options of improving the already-published ways of simulating these systems, i.e. the fuzzy model of hydraulic turbine's efficiency. The use of the fuzzy modeling was chosen and applied mainly to show how the turbine's efficiency changes due to the wearing of the turbine itself. Thus, this should be incorporated in the model of the small hydropower plant however, the appropriate form has to be set. Using an *Anfisedit* tool in MATLAB is proposed to serve this purpose, i.e. create such like a turbine's efficiency maps, that would be used in the simulation process based on the preset conditions and turbine's wearing level.

To sum up, referring to the research done in the field of modeling the small hydropower plants, the authors have designed and described proposed laboratory model of an SHP that should allow the users to easily develop and verify potentially new control schemes and methods, e.g. fuzzy controller as a replacement of a usually used control scheme mentioned before in the paper, etc.

Future research and development of this model should be aimed to provide a fully prepared model for a design and a verification of a control mechanisms of small hydropower plants. First step is to convert the already designed MATLAB model into the PLC program, verify it and thus create a simulator, that should basically shorten up the time necessary to design and build new small hydropower plant projects.

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BIOGRAPHIES

Richard Olexa was born in 1995 in Kosice. In 1991 he graduated (Ing.) with honors at the department of Electrical Engineering and Mechatronics of the Faculty of Electrical Engineering and Informatics at Technical University of Kosice, Slovakia. He is currently in the third year of his PhD studies, focusing mainly on the small hydropower plants systems, especially concerning its modeling a

simulation models.

Pavol Fedor was born in Kosice in 1956. He received the MSc degree in Technical Cybernetics from Technical University of Košice in 1980 and Ph.D degree in 1986 at the same University. During 1980 – 1988 he served as an Assistant Professor of Electrical Drives at the Technical University of Košice at the Department of Electrotechnics, Mechatronics and Industrial Engineering. He currently works as a Professor of Power Electronics at the same university. During 1996 – 1998 he was involved in research for continuous line control in USS firm, Kosice. He has extensive experience in installing of control systems in industry. In theoretical area his current research activities are focused on the development of control structures by means of Lyapunov's second method for electrical drives and multi-input multi-output systems.