FUZZY APPROACH OF MODELING A HYDRAULIC TURBINE EFFICIENCY

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Research, optimization and practical implementation of a Small Hydropower Plants as a source of clean electricity are one of the actual tasks in the current energetics, which is virtually impossible to solve without powerful computer support due to the strongly nonlinear nature of such systems. The article presents an overview of the most common simulation model schemes of Small Hydropower Plants, whereas explores the sub models of its individual subsystems. The most important subsystem and a so-called heart of the hydropower plant is the hydraulic turbine, which efficiency calculation is analytically demanding and dependent on parameters that are often obtained only by a theoretical estimation. In this article, a fuzzy system was used to create its model based on a measured operating data of the turbine flow rate and the height of its water column without any need of knowing exactly the turbine parameters. Such a model is applicable in practice, e.g. in the designing process of an energy-optimized hydro-turbine control, as well as for the effective determination of the deterioration rate. The correctness of the results was verified by simulation measurements in the MATLAB software.

KEYWORDS

hydraulic turbines, hydropower systems, modelling and controlling of hydropower plants, small hydropower plant, fuzzy model of turbine efficiency

1 INTRODUCTION

Nowadays, it is often heard about the need for recycling and greater environmental protection. However, not only the activists are the only ones who speak about this topic. Even ordinary people started to pay attention to the polluted air and nature, and therefore being environmental friendly becomes one of the biggest concerns for scientists, researchers, and even for politicians.

The impact of the current situation is very strong, e.g. in the automotive industry. More and more electric cars are being produced, bought and moreover, there are already some restrictions for combustion engines vehicles in terms of entering centers of the big cities.

As a result of the above-described situation, the car producers have already started transferring their financial resources to the research and development of electric cars. However, did we realize how the "green" electricity is being produced? Fossil fuels are still commonly used to produce electricity, thus we should search for another, more ecofriendly source of energy to replace the old coal power plants.

Because of it, this paper explores the current knowledge in using one of the renewable energy sources – water. Next parts of this paper are dedicated to the brief description of a technology used in hydropower plants, esp. in small hydropower plants (SHP), which potential in Slovakia is still not fully used. Moreover, the paper introduces some modelling techniques of individual parts of SHP to provide the sufficient simulation model of SHP with a description of various methods commonly used in the development of a simulation model of small hydropower plants, as well as a proposed fuzzy model of hydraulic turbine's efficiency is being described.

2 TYPES OF THE HYDROPOWER PLANTS

According to the literature [Wagner 2011, Munoz-Hernandez 2013, Giesecke 2005], there are many of criteria used to divide the hydropower plants, i.e. according to hydroelectric scheme; amount of generated power; type of the generator; type of the hydraulic turbine; etc. The first two before-mentioned criteria are important in defining and differentiation of small hydropower plants.

2.1 Hydroelectric scheme – Reservoir Hydropower Plants

The main characteristic of Reservoir Hydropower Plants is a reservoir located in an upland or mountainous area. Usually, the reservoir store a large amount of water and keeps its potential energy available to use throughout the year. Such a construction is used for various purposes, i.e. keeping the grid requirements; controlling the grid frequency; flood protection.

So called Pumped Storage Hydropower Station (PSHS) is one of special forms of this hydroelectric scheme. As a name suggest, the PSHS is able to pump the water between its two reservoirs placed at significantly different vertical levels. Thereby, the PSHS gives the option to keep the grid requirements when needed; e.g. during the peak load, the water is released from the upper reservoir so that the hydropower plant generates the power and contributes to the grid; and on the other hand, at the times of low demand, the water is drawn back from the lower reservoir to the upper one by motors/pumps using the electricity from the grid. It means that PSHS operates on a closed cycle. This way of operation could seem to be inefficient and unprofitable. However, the price difference between the peak load and low demand periods of time makes a price return despite the inefficiency involved [Munoz-Hernandez 2013].

2.2 Hydroelectric scheme – Run-of-River Hydropower Plants

As the name suggest, the Run-of-River Hydropower Plants (RRHP) are located at rivers, or at the surroundings of rivers. By this type of hydroelectric scheme, there are another two sub-categories; i.e. Pure RRHP and Hybrid RRHP.

The pure ones are characterized by not having any pond as a kind of a small reservoir and hence by using the running water to power the hydraulic turbine directly. Hernandez et.al. term this as a hydrokinetic power, which means that the pure RRHP are totally dependent on instantaneous state of the river flow [Munoz-Hernandez 2013].

On the other side, the hybrid scheme includes a small pond smoothing the short-term flow variation at the turbine. It even gives the operator an option to increase the amount of power generated during the peak demand time periods of the day.

In some cases, the penstock can be used to enable the pond to be placed at the higher vertical level, and thus to increase the available head [Wagner 2011, Munoz-Hernandez 2013, Sladecek 2019].

2.3 Amount of Power Generated

The exact generated power PG ranges for each of the following group of the hydropower plants can vary depending on the literature, and therefore combining the sources [Wagner 2011, Munoz-Hernandez 2013, IEEE 1988], the list below explores one of the most common definition in terms of the amount of generated power PG.

1. Micro-Hydropower Plants – PG up to 100kW
2. Small-Hydropower Plants – with a unit rating PG between 100kW to 5GW
3. Big Scale Hydropower plants – PG over 5GW [Fedor, 2019]

Assuming all the before-stated criteria and differentiations, this article aims to explore a modelling process of a small-scale hydropower plants of the run-of-river hydroelectric scheme with unit rating PG = 100kW – 5GW.

3 SIMULATION MODEL OF A SMALL HYDROPOWER PLANT

In general, the simulation model of a small hydropower plant (SHP) consists 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. In Figure 1, there are all the previous-stated main sub-systems depicted, creating the basic simulation model of SHP.

The vast majority of the scientific papers and literature use a model, wherein all the parameters are being normalized, i.e. their value is between 0 and 1, or in other words between 0 and 100%.

The phenomenon of the water hammer, cavitation and traveling waves are deeply explored in literature [Munoz-Hernandez 2013, Giesecke 2005, Hlavac 2018], while including even the way how to simulate and model their impact on the functionality of hydropower stations and how to reduce it. On the other hand, in case of the SHP, where the length of the penstock, and the height of the water head available are small, the impact of these phenomenon can be neglected.

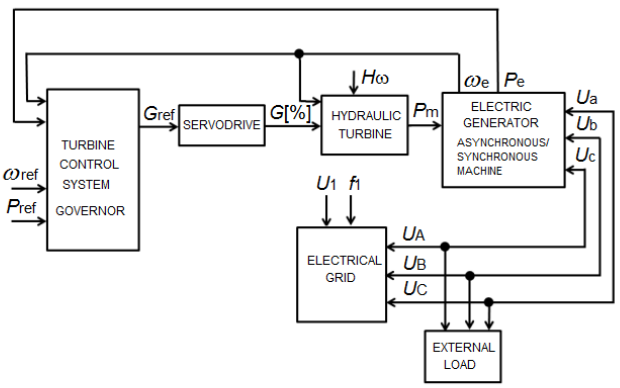

Figure 1. Block diagram of a Small Hydropower Plant [Fedor 2019]

3.1 *Governor – Turbine Control System*

Basically, the Governor, or the Turbine Control System has two main functions, i.e. running up the turbine and reaching the mechanical speed close to the grid frequency considering the number of poles of the electric generator; and after being phased into the grid, i.e. after the synchronization, the Governor controls the power supplied by hydropower plant to the grid.

Usually, PID or PI controllers are being used for controlling such a nonlinear and complex system of hydropower plants. In Figure 2, there is block diagram of a PID governor system for controlling the power and the frequency of a controlled hydropower station, where the included variables are: 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. The function of saturations placed in the Figure 2 is mainly to give the model of a PID controller an option to keep the output value in the preset range during the operation, and to act as a basic alternative of an anti-reset windup (ARW) protection.

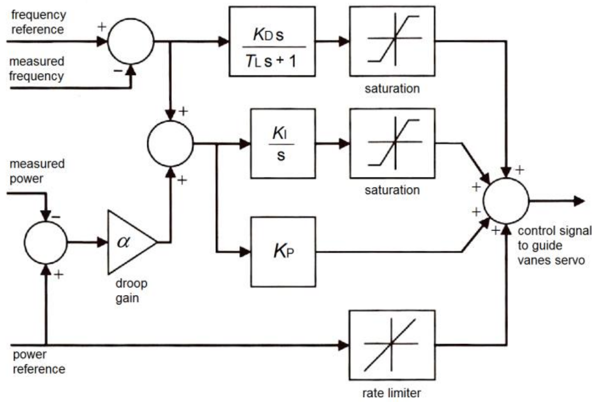

Figure 2. Block diagram of a PID governor for controlling power and frequency generated [Munoz-Hernandez 2013]

3.2 *Servodrive*

The sub-model of the Servodrive is often modelled as a second order dynamic system, which state variables are: speed of the guide vane opening and its position. The before-mentioned phenomenon of water hammer and cavitation occurs even in some cases of SHP, esp. when there is a fast change in the position of the servodrive. Therefore, the saturation block is being placed in the simulation model to limit the speed of the servodrive (see Figure 3), and thus to ensure the safe operation. Another saturation block is used to set the operation range of the guide vane's position to keep the turbine operating in the most efficient and safest way.

In Figure 3, we present one of the possible ways of modeling a sub-system of the Servodrive.

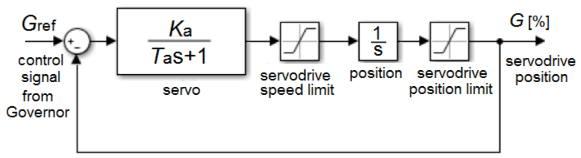

Figure 3. Block diagram of the Servodrive subsystem *(parameters Ka and Ta are calculated according to the type of an implemented servodrive used in the hydroelectric scheme)*

3.3 *Hydraulic Turbine*

The Hydraulic Turbine is considered as a heart of the hydropower plant and it is mostly because of its important function in the whole process of electrical energy production. Therefore, using its accurate model is necessary to achieve realistic and relevant results. The turbine converts a kinetic or potential energy of the water into a mechanical rotation, that moves the generator's rotor via the common shaft.

For modelling purposes, the proposed subsystem of Hydraulic Turbine does not differ according to the type of the hydraulic turbines. However, the turbine characteristics, or in other words incorporating its efficiency into a model is one of the most important part in proper modelling of the turbine as a part of SHP.

Figure 4 shows the block diagram of the hydraulic turbine subsystem that was created based on the turbine's theoretical and mathematical description mentioned in the literature [Sattouf 2014, IEEE Working Group 1992].

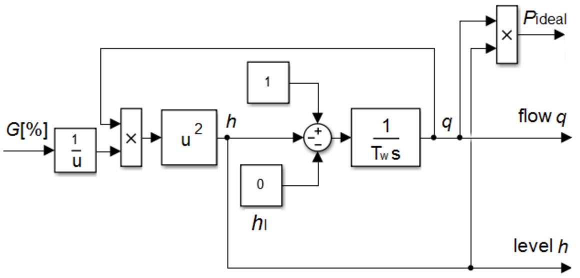

Figure 4. Block diagram of the hydraulic turbine

Modeling the penstock, as a part of the depicted model's structure, was done assuming the incompressibility of the water and under the assumption that the penstock is strong enough with a length *L* and a cross-sectional area *A*. The loss of the water column caused by the penstock characteristic is so far neglected.

$$\frac{\mathrm{d}\bar{q}}{\mathrm{d}t} = (\bar{h_0} - \bar{h} - \bar{h_l})g\frac{A}{L} \tag{1}$$

Equation 1 represents the basic formula used in the hydraulic turbine's simulation model development.

Table 1. List of the parameters used in the equation (1)

Symbol	Quantity	Unit
q	Turbine's flow	[m^3/s]
A	Cross-sectional area of the penstock	[m^2]
L	Length of the penstock	[m]
g	Gravitational acceleration	[m/s^2]
h_0	Static water head (water column)	[m]
h	Water head (at the turbine's inlet area)	[m]
h_l	Loss of the water head caused by the friction in the penstock	[m]

Using the per-unit values of the parameters in the equation (1), the equation (2) is:

$$\frac{\mathrm{d}q}{\mathrm{d}t} = \frac{(1-h-h_l)}{T_\mathrm{W}} \tag{2}$$

where the parameter of h_l, representing the loss of the water head, is being neglected. Plus, the coefficient of T_W used in the equation (2) is a time constant. It is usually called in the literature as a water time constant, or a water starting time. To determine the value of the T_W, the equation (3) is used. [Sattouf 2014]

$$T_\mathrm{W} = \left(\frac{L}{A}\right)\frac{q_{base}}{h_{base}g} \tag{3}$$

where: h_{base} – the total static head available; and q_{base} – the water flow in case of guide vane opening position *G*=1 (see equation 4).

$$q = G\sqrt{h}\text{, i.e.: } q_{base} = 1\sqrt{h_{base}} \tag{4}$$

Obviously, the turbine's water flow *q* is a function of guide vane position *G* and a water head *h*. Thus ideally, the mechanical power of the hydraulic turbine would be characterized as a turbine's water flow multiplied by the water head available (in case of 100% turbine's efficiency).

SIMULATION MODEL OF HYDRAULIC TURBINE'S EFFICIENCY: NO LOAD FLOW CALCULATION METHOD

However in reality, there are many other factors affecting the turbine's efficiency. Therefore, one of the basic ways how to model a turbine's efficiency is to use so called variable of no load flow q_{nl}, which is considered as a parameter characterizing the constant power losses. The equation (5) describes the relation between the variables.

$$P_m = A_t h(q - q_{nl}) - DG\Delta\omega \tag{5}$$

where: P_m is mechanical power at the shaft; *q* represents an actual flow throughout the turbine; *D* is considered as a Damping coefficient; *G* is the above-mentioned Guide Vane Opening Position [%]; and *Δω* represents the speed deviation [IEEE Working Group 1992, Sattouf 2014].

The IEEE Working Committee considers the parameter A_t as a some kind of Hydraulic Turbine's Gain, which calculation differs in the scientific papers. The equation (6) serves to calculate the A_t parameter according to the paper [IEEE Working Group 1992].

$$A_t = \frac{TURBINE\ POWER\ [MW]}{(GENERATOR\_POWER\ [MVA]h_r(q_r - q_{nl}))} \tag{6}$$

where the h_r is the rated head needed for the rated flow q_r.

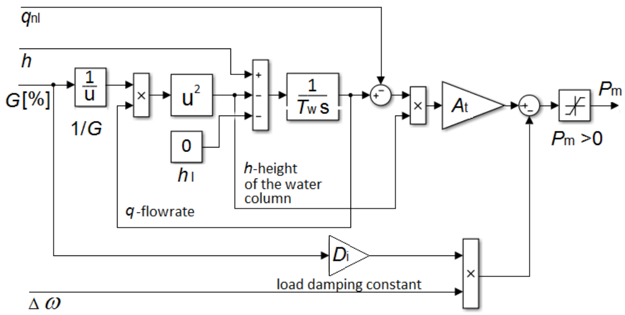

Figure 5. Block diagram of a Hydraulic Turbine Subsystem

SIMULATION MODEL OF HYDRAULIC TURBINE'S EFFICIENCY: DIRECT EFFICIENCY CALCULATION

Another way how to take into account the turbine's efficiency is to calculate its concrete value. Acakpovi; Essel and Fifatin explore this topic in detail in their scientific paper of Review of Hydropower Plant Models [Acakpovi 2014]. This way of modeling a hydraulic turbine's sub-systems is based on the very basic formula (equation (7)) for mechanical power calculation.

$$P_m = \eta\rho q g h \tag{7}$$

where *η* represents a hydraulic turbine's efficiency; *ρ* is a water density (usually used value of 1000kg/m^3); *q* represents an actual turbine's flow; *g* is a gravitational acceleration (9.81m/s); and *h* that is an actual water head available. In the simulation model, the values used are in the per-unit form.

This efficiency calculation method requires to know exactly some of the turbine's characteristic parameters, e.i. radius of the turbine's blades R_{blades} [m] and the size of the blades area A_{blades} [m^2]. The actual values of its mechanical angular velocity ω_m, as well as the actual turbine's water flow *q*, are as well necessary the correct calculation.

$$\eta_t(\lambda, q) = \left[\frac{1}{2}\left(\frac{90}{\lambda_i} + q + 0{,}78\right) exp\left(\frac{-50}{\lambda_i}\right)\right](3{,}33q) \qquad (8)$$

The equation 8 shows the relation between the turbine's efficiency value and all the above-mentioned parameters, where λ_i is defined as:

$$\lambda_i = \left[\frac{1}{(\lambda+0{,}089)} - 0{,}0035\right]^{-1} \qquad (9)$$

and λ is defined as:

$$\lambda = \frac{R_{blades}A_{blades}\omega_m}{q} \qquad (10)$$

Therefore, the input signal (value) to the calculation of the hydraulic turbine's efficiency in this case would be the actual turbine's water flow q and the mechanical angular velocity of the turbine ω_m. Using the mathematical description shown and described above, gives all the necessary data for creating a sub-model of the hydraulic turbine's efficiency (see Figure 6). Thus, this sub-model could replace the A_t coefficient and so called no-load flow value q_{nl} used in the before-mentioned method.

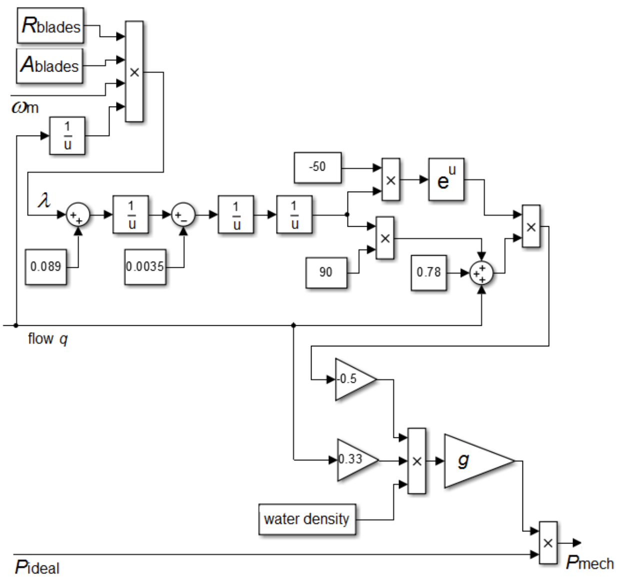

Figure 6. Turbine's efficiency calculation sub-model

FUZZY MODEL OF HYDRAULIC TURBINE'S EFFICIENCY

All the previous-mentioned ways of calculating the turbine's efficiency are based on a quite complicated and not always accurate calculations, mainly because of the need of detailed parameters knowledge, or only estimated parameter's values.

The next steps in our research in the field of Modelling a Small Hydropower Plants are in considering other possibilities in terms of universal, but still accurate and fast efficiency calculation. In Figure 7 and 8 respectively, there is an obvious difference in the maximum possible efficiency of the turbine, caused only by the wearing of the turbine's blades, or its runner, and thus by the change in the blades inner area A_{blades}, which is one of the key values in the calculation defined by [Acakpovi 2014]. This relation between the turbine's wear rate and its efficiency is strongly nonlinear and therefore, it is often difficult to implement this phenomenon into the simulation model.

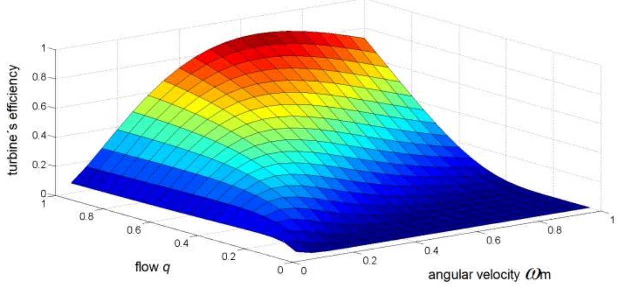

Figure 7. The efficiency of the hydraulic turbine *(R_{blades}=1.9m and Ablades=9m²) – Maximum turbine's efficiency is approx. 88%*

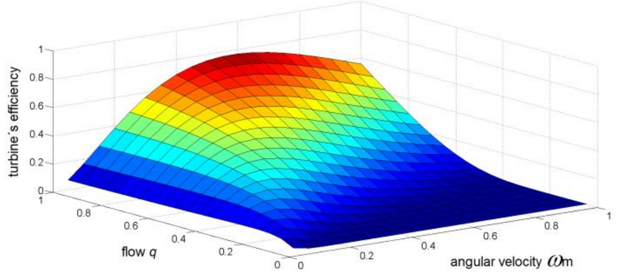

Figure 8. The efficiency of the hydraulic turbine *(Rblades=1.9m and Ablades=8m²) – Maximum turbine's efficiency is approx. 77%*

Therefore, so called efficiency "image" of the hydraulic turbine is possible to reach via measuring the water flow q; turbine's mechanical speed $\Delta\omega$ and the turbine's efficiency at the steady state operation points, as stated below in the Table 2.

Table 2. Measured efficiency at different steady state operation points

Efficiency [%]		ω_m				
		0.2	**0.4**	**0.6**	**0.8**	**1**
q	**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*

The data from Table 2 can be used for searching fuzzy inference structure (FIS) of the modelled efficiency describing the measured relation between [ω_m, q] → h_t,.

The fuzzy model is designed based on this data by standard cluster analysis tools with adaptive approach resulting in improved quality of simulation modelling and reduced time needed for the development process [Bacik 2015, Krenicky 2011, Perdukova 2013]. The adaptive neuro-fuzzy interference system *Anfisedit* (included in the *Matlab* software) was chosen out of the large number of available methods in the field of adaptive fuzzy system development [Fedor 2013]. The basic characteristics of cluster analysis is the reduction of total number of fuzzy rules and a good initial setting of rule parameters. The subtractive clustering [Fedor 2016] was used, as well as robust data analysis method, with the following parameters: *Range of influence = 0.5*, *Squash factor = 1.1*, *Accept ratio = 0.45*, and Reject *ratio = 0.005*.
As a result, we obtained static Sugeno type fuzzy system with twelve rules, as depicted in a Figure 9.

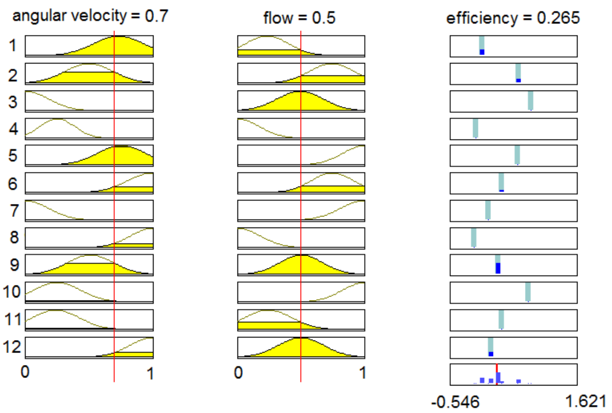

Figure 9. The fuzzy model of the hydraulic turbine's efficiency – Sugeno type with 12 rules

As a result, a graphical representation of the before-mentioned fuzzy system is depicted in the Figure 10.

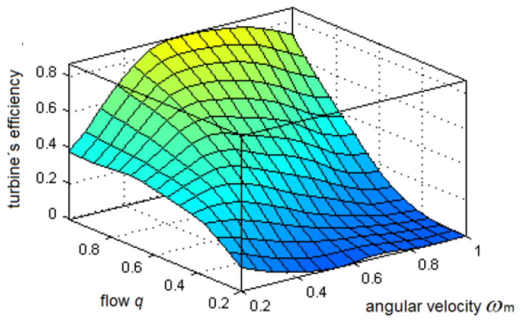

Figure 10. Possible fuzzy representation of the hydraulic turbine's efficiency

3.4 *Electro-Mechanical Subsystem*

As the name suggest, it is possible to model the electric generator and the grid in one subsystem. The literature [IEEE Working Group 1992, Munoz-Hernandez 2013, Tiwari 2015, Acakpovi 2014, Sattouf 2014] describes the most common ways of modelling the electromechanical part of the SHP, whereas distinguishing between the islanding mode of operation and the operation, when the SHP supplies the national grid system. One of possible model representation is described below.

An electric generator is usually an AC electric machine of synchronous, or asynchronous type. If a detailed model of such a machine must be created, a non-linear characteristic of these dynamic systems of higher order must be considered. Internal electromagnetic dynamic phenomena of such machines lie within the millisecond range. On the other hand, the hydrodynamic processes in the turbine are considerably slower and therefore, in most cases, it is meaningful to meaningful to create an electromechanical model of the generator in terms of a torque equation of the common turbine and generator shaft. The hydraulic turbine and the generator are mechanically coupled via a common shaft for which the equation of equilibrium (11) is valid [Fedor 2016].

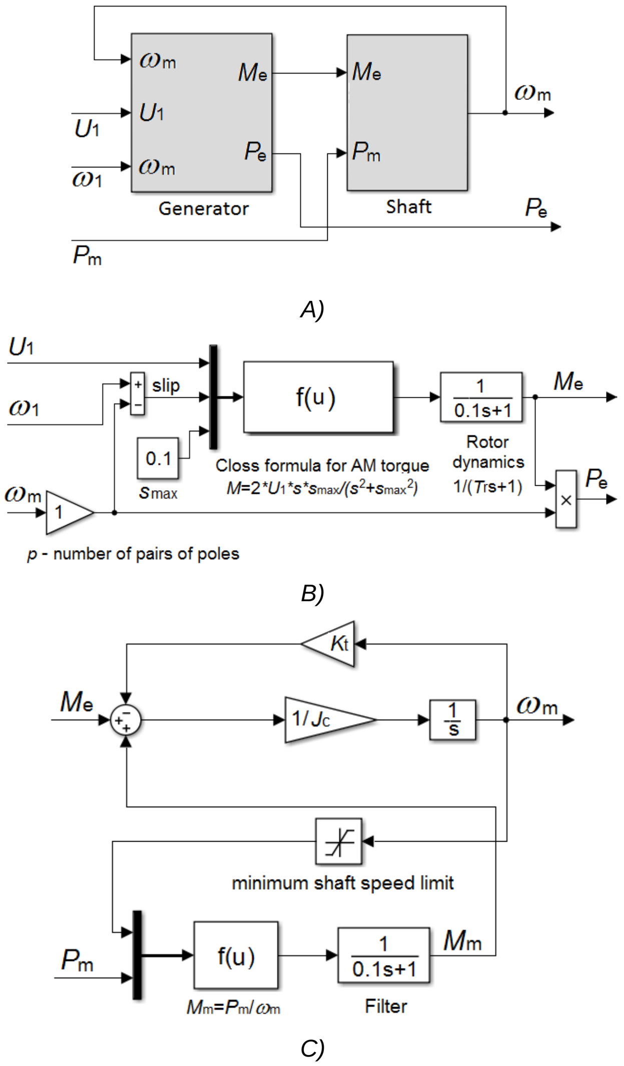

Figure 11. Block diagram of the electromechanical subsystem "GENERATOR-LOAD" [Fedor 2019]

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

$$M_e + M_m - M_f = J_c d\omega_m/dt \tag{11}$$

$$M_f = K_t \omega_m \tag{12}$$

$$M_m = P_m/\omega_m \tag{13}$$

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 (12) represents the friction coefficient. The right side of the equation (11) 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 Figure 11), where T_r is the rotor time constant of the asynchronous generator corresponding to the rotor resistance [Vo 2020].

Time respond of mechanical quantities during the turbine starting process to the angular velocity close to grid frequency (the value f1 = 0.6 corresponds to the frequency 50 Hz) are shown in the Figure 12 [Fedor 2019].

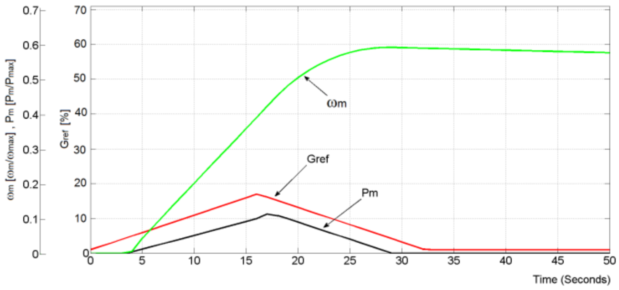

Figure 12. Turbine starting to the frequency of the grid [Fedor 2019]

4 CONCLUSIONS

Computer models of energy systems make it possible to significantly simplify and speed up their whole design and development process, as well as to save financial costs in their implementation. The calculation of a hydraulic turbine's efficiency is analytically demanding and often depends on the parameters, which are determined only by a theoretical estimation.

The knowledge of so called efficiency image of a hydraulic turbine is essential for it optimal energy control. The presented article describes a brief overview of the current knowledge and ways in the field of modeling small hydropower plants, as well as it describes a proposed fuzzy model of hydraulic turbine, whereas taking into account its efficiency. The mentioned fuzzy model can be obtained from a measured data of turbine's water flow, and the water head available. It is shown, that the model has practically reached the same accuracy as the analytical models did. Such a model can be used in the design and development process of an optimal energy control of hydraulic turbines, as well as in the effective determination process of an actual turbine's wear rate.

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