Small Hydropower Plant Modelling and Controlling

Modelovanie a riadenie malej vodnej elektrárne

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***Abstrakt*— Výskum, optimalizácia a praktická implementácia malých vodných elektrární ako zdroja čiestej energie je jednou z aktuálnych otázok súčasnej energetiky, ktorú nie je možné riešiť bez podpory výkonných výpočtových prostriedkov vzhľadom na nelineárnu podstatu týchto systémov. V článku je predstavený prehľad najbežnejších simulačných modelov malých vodných elektrární spolu s modelmi jednotlivých podsystémov.**

Kľúčové slová*— *hydraulická turbína, systémy vodných elektrární, modelovanie a riadenie vodných elektrární, malá vodná elektráreň.

***Abstract*— 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.**

Keywords*— *Hydraulic turbines, hydropower systems, modelling and controlling hydropower plants, small hydropower plant.

I. INTRODUCTION

Nowadays, it is often heard about the need for recycling and greater environmental protection. However, not only the activists are the 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, researcher, and even for politicians.

The impact of current situation is for example very strong 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 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, plus we introduce some modelling techniques of individual parts of SHP to provide the sufficient simulation model of SHP for our follow-up research in the field of controlling SHP using a universal control scheme.

II. TYPES OF HYDROPOWER PLANTS

According to the literature [2]-[3]-[12], 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.

A. 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. [3]

B. 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.

[3] term this as a *hydrokinetic power*, which means that the pure RRHP are totally dependent on instantaneous state of the river flow.

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. [2]-[3]

C. *Amount of Power Generated*

The exact generated power P_G ranges for each of the following group of the hydropower plants can vary depending on the literature, and therefore combining the sources [2]-[3]-[14], the list below explores one of the most common definition in terms of the amount of generated power P_G.

1. Micro-Hydropower Plants – P_G up to 100kW
2. Small-Hydropower Plants – with a unit rating P_G between 100kW to 5GW
3. Big Scale Hydropower plants – P_G over 5GW [13]

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 $P_G = 100kW – 5GW$.Použite túto šablónu pre členenie a formátovanie vášho článku. Všetky okraje, šírky stĺpcov, riadkovanie a fonty sú predpísané, prosím nemeňte ich. Do hlavičky a päty dokumentu nevkladajte žiaden text.

III. 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 [3]-[12], 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.

A. *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.

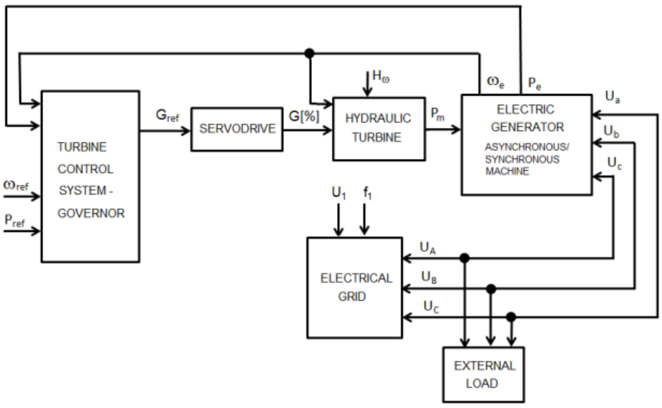

Fig.1 Block diagram of a Small Hydropower Plant [13]

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.

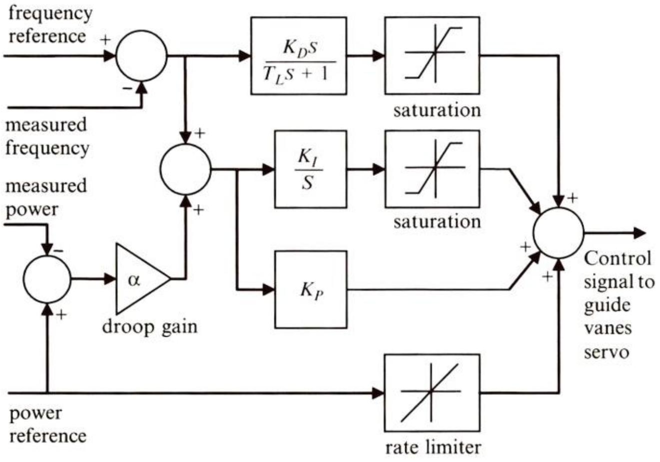

Fig.2 Block diagram of a PID governor for controlling power and frequency [3]

B. *Servodrive*

The sub-model of the *Servodrive* is often modelled as a second order dynamic system, which state variables are the 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 our sub-system of the Servodrive, while demonstrating the results obtained via the simulation using Matlab-Simulink software in *Figure 4*.

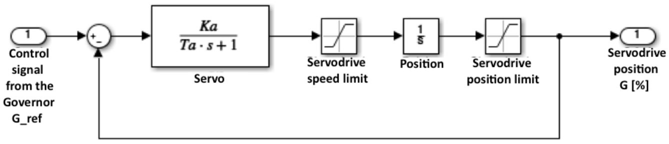

Fig.3 Block diagram of the Servodrive subsystem
(parameters *Ka* and *Ta* are calculated according to the type of servodrive used in the hydroelectric scheme)

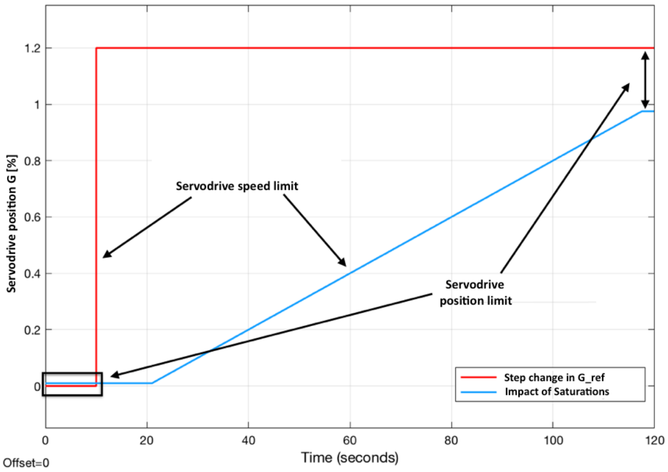

Fig.4 Servodrive position as a reaction to the step change in *G_ref* = 1.2 at the time *t* = 10s
(Speed limit saturation = 0,01 in both directions; Servodrive position limit saturation = 0,01(lower one) and 0,975(upper one); *Ka* = 3,33 and *Ta* = 0,07s)

C. *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, and therefore 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.

The *Eq. 1* characterize the relation of the actual flow of the water *q* and other input parameters, i.e. *h* - a current *water head*; h_l – head losses that are usually neglected in SHP modelling; and so called *Water Time Constant*, which calculation is described by the *Eq. 2*.

$$\frac{dq}{dt} = \frac{(1-h-h_l)}{T_w} \tag{1}$$

$$T_w = \left(\frac{L}{A}\right)\frac{q_{base}}{h_{base}g} \tag{2}$$

where: *L* – the penstock length; *A* – penstock cross-sectional area; *g* – gravitational acceleration; h_{base} – the total static head available; and q_{base} – the water flow in case of *G = 1 (Eq.3)*.

$$q = G\sqrt{h}, \text{ i.e.: } q_{base} = 1\sqrt{h_{base}} \tag{3}$$

One of the basic ways how to model 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 *Eq. 4* describes the relation between the variables.

$$P_m = A_t h(q - q_{nl}) - DG\Delta\omega \tag{4}$$

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 $\Delta\omega$ represents the *speed deviation*. [1]-[11]

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 *Eq. 5* serves to calculate the A_t parameter according to the paper [1].

$$A_t = \frac{\text{TURBINE POWER [MW]}}{(\text{GENERATOR\_POWER [MVA]}.h_r(q_r - q_{nl}))} \tag{5}$$

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

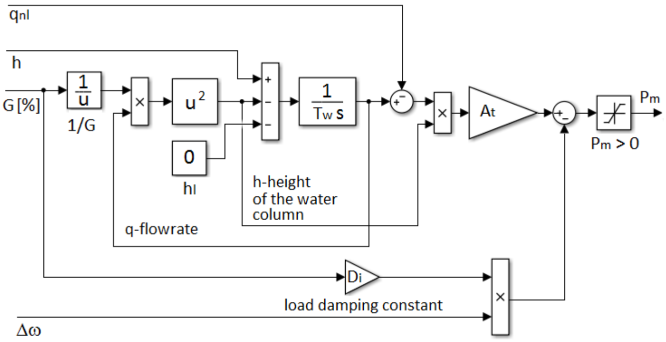

Fig.5 Block diagram of a Hydraulic Turbine Subsystem

Another way how to take into account the turbine 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* [9].

D. *Electro-Mechanical Subsystem*

As the name suggest, it is possible to model the electric generator and the grid in one subsystem. The literature [1]-[3]-[6]-[9]-[10]-[11] describes most common ways of modelling the electromechanical part of the SHP, while distinguishing between the islanding mode of operation and the operation, when the SHP supplies the national grid system.

IV. CONCLUSION

Computer models of power systems make it possible to significantly simplify and speed up their design, as well as save costs in their implementation. The computation of hydro turbine efficiency is analytically demanding and dependent on parameters which are often obtained only by theoretical estimation. Knowledge of the "efficiency image" of a particular hydro turbine is essential for its optimal power control.

ACKNOWLEDGMENT

„This work was supported by the Slovak Research and Development Agency under the contract No. APVV-16-0206"

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