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LABORATORY MODEL OF SMALL HYDROPOWER PLANT WITH VARIABLE SPEED OPERATION

Abstract: The article presents the laboratory model of an energy conversion system based on the innovative construction of the permanent magnet synchronous generator and the AC/AC power electronic converter. Application of the converter allows to work with variable speed which gives higher efficiency in a wide range of speed. The innovative generator is specially designed to integrate with a propeller turbine. Turbine features, in the presented conversion system, are modeled by the asynchronous motor fed by a voltage source inverter. The vector controlled inverter allows to control the generator torque. The nominal power of the system is 30 kW.

Presented test bench was used to model the run-of-the-river Small Hydropower Plant with a water tank, guide vanes and properties of the propeller turbine. The static and dynamic features of specific elements were identified on the real power plant of an analogous construction. The whole system is supervised by the PLC controller (Embedded PC), monitored and controlled by the operator panel. Presented model allows to simulate the power plant operation under changeable water conditions as well as with different kinds of control method. It makes a very good research object and a teaching test bench.

1. Introduction

Renewable Energy Resources delivered almost 20% of global electricity supply in 2010. It is estimated that now it comprises one-quarter of global power capacity from all resources.

Hydropower is an important part of renewables, its capacity is accounted for approximately 83% of the total Renewable Energy Resources [1]. Moreover, its growth is rapid in recent years; the capacity installed in the year 2010 was the same as of the previous four years combined. There is still great potential for development because only 10% of the total viable hydropower has been used.

The large hydroelectric power plants are not so attractive any more due to the increasing concerns about environmental effects, long development time and capital costs. What is more, the most suitable sites for such development have been already exploited [2].

This situation creates big interest in a small scale development. The Small Hydropower Plants (SHP), up to 10MW, have great potential because of low administrative costs, small environmental impact, short construction time and low executive costs [3].

In general, the energy conversion system used in SHPs can be divided into two groups. The first is a conventional fixed speed power drive system with a synchronous or asynchronous generator directly coupled to the grid. The second group utilizes a Variable Speed Operation (VSO) concept with the using of Power Electronic Unit (PEU). The VSO can be realized by a double feed induction generator, where a stator is directly coupled to the grid and a rotor is supplied by the PEU. It allows to adjust the speed in a range of ±30% nominal speed. Another solution is to connect a generator through the PEU to the grid. Here, the frequency, voltage characteristic and power factor depend only on the design and control of PEU and no longer on a generator type. The variations from 30% to 200% of rated speed can be achieved. Such a system may contain an induction or synchronous generator. In the solutions described above, a mechanical gearbox is needed to match the turbine speed with standard generators speed (from 750 up to 1500 rpm). However, the gearbox can be avoided in solutions with a high pole number, what is possible in a permanently excited synchronous generator. The synchronous generator also has higher efficiency in a wide range of load then the induction generator [4].

Features mentioned above cause increasing interests in the energy conversion systems containing permanent magnet synchronous generator (PMSG) and PEU applying the VSO. Such a conversion system is presented in the paper [5] on example of the innovative SHP with two hydro-sets of 150kW total power. In addition, described hydro-set consists of PMSG integrated with the propeller turbine. This integration eliminates the external shaft and reduces the dimension of the hydro-set, thus creating a modular and compact structure.

This paper presents the laboratory test bench of an energy conversion system, analogous to this applied in the real object, which was used to model SHP. In the presented conversion system (Fig. 1) turbine features are modeled by the asynchronous motor (ASM) fed by the voltage source inverter (INV). The static and dynamic features of specific elements were identified on the real power plant and applied to the model.

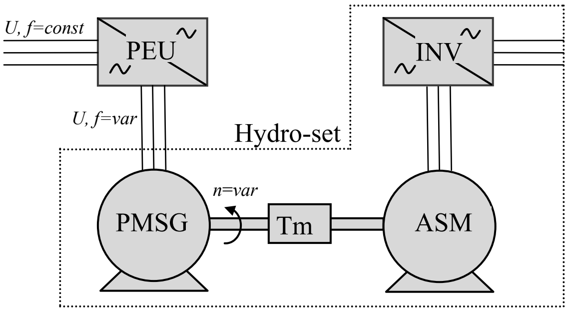

Fig. 1. Energy conversion system structure

2. Structure of energy conversion system

2.1 Hydro-set equivalent

As it was mentioned in the Introduction, the hydro-set consists of PMSG directly connected with induction motor (Fig. 1), which models the propeller turbine features. The vector controlled voltage source inverter allows to adjust the generator torque. To measure the actual torque the DataFlex torque meter is used. Figure 2 presents a photo of the laboratory hydro-set.

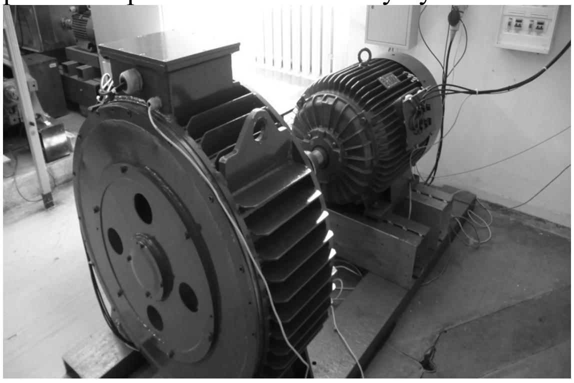

Fig. 2. Laboratory hydro-set of 30kW

The stator of PMSG has a classical 3-phase winding. However, its construction was custom-designed to match hydrological conditions (water flow, head) [5]. This generator allows to integrate the propeller turbine of 560mm diameter in the rotor. The permanent magnets are mounted to the external ring of the turbine. The generator has 5 pairs of poles thus the synchronous speed is 600rpm.

2.2 Power electronic converter

The main function of the PEU is to convert generator electricity of variable parameters (voltage and frequency) into electricity of constant frequency synchronized to the grid. In presented system the standard full-scale AC/DC/AC converter is used [6]. The PEU consists of an uncontrolled rectifier, direct-voltage intermediate circuit and inverter (Fig. 3 and Fig. 4).

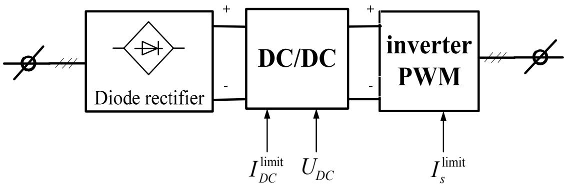

Fig. 3. PEU topology

A DC/DC boost module increases DC voltage up to U_{DC} value. The inverter uses the DPC-SVM algorithm (Virtual Flux – Direct Power Control with SVM modulator), which is based on the closed loop regulation of the instantaneous active and reactive power [5].

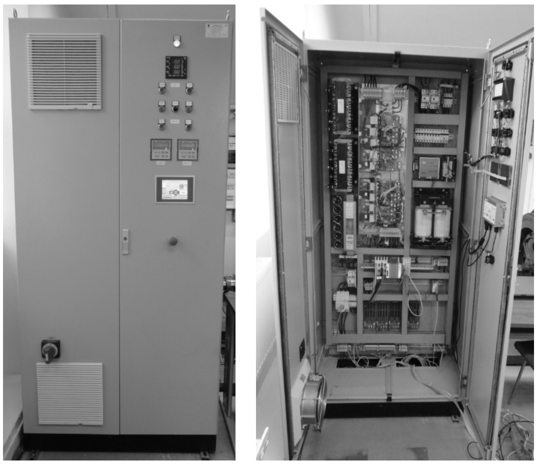

Fig. 4. Ready PEU of 30kW power (manufactured by Power Electronics Company "Twerd")

The control strategy of SHP has to realize the VSO by regulating the PEU parameters according to actual hydrological conditions. There are three parameters, which can be used in a control operation. The current limit I_{DC}^{limit} of the DC/DC boost regulator controls directly generator current, what corresponds to a torque of a synchronous machine. The current limit I_s^{limit} regulates a grid current i.e. power transferred from generator to the grid.

The U_{DC} reference voltage defines the minimal rotational speed n_c for which the DC/DC converter does not increase the generator voltage thus an I_{DC}^{limit} regulation is not possible. The influence of control parameters on the torque characteristic is presented in Fig. 5.

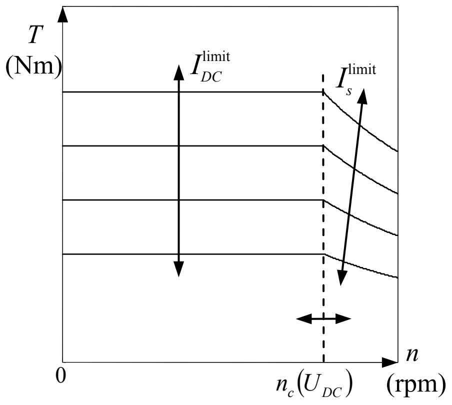

Fig. 5. PEU torque characteristics $T(n)$ *for different values of* I_s^{limit}, I_{DC}^{limit} *and* U_{DC}

Practical operations have showed that the best option is to control the hydro-set by the current limit I_{DC}^{limit} (generator torque) in order to achieve a stable operation [7]. The grid current limit should be set to the value that corresponds to the maximum power of the hydro-set to protect the PEU and turbine against a runaway speed condition. The optimal operation point of the hydro-set, ensuring the highest possible efficiency in certain water conditions, is selected based on a universal turbine characteristic [5].

3. Small Hydropower Plant model

The energy conversion system, described above, has been used to model SHP working at variable speed. The general block diagram of the control system is presented in Fig. 6.

Most of the SHPs are "run-of-the-river" plants, which provide little or no storage water. Therefore, a control system has to maintain the upper water level at a fixed value. Assuming lower water at zero level, the upper water level corresponds to the water head H. This task is implemented with a negative feedback control system, where the set point is the desired water head H^{ref}. The regulator (usually PI) adjusts the angle α of the guide vanes based on the actual error ε.

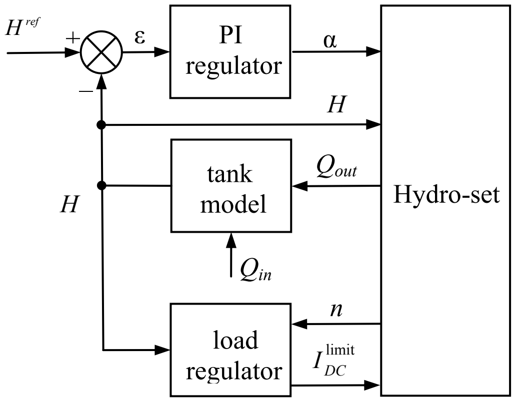

Fig. 6. Control system block diagram

The load regulator controls generator current, by the I_{DC}^{limit}, according to the actual generator speed and water head. This regulator keeps the operation point on the optimal working curve ensuring high turbine efficiency [5].

Tank model is needed to calculate the water head resulting from the water inlet of river (Q_{in}) and the turbine flow through the turbine (Q_{out}). In the presented system a distributed river is modelled as a concentrated water tank. Simple derivative of the water tank volume V gives a flow balance (1).

$$\frac{dV}{dt} = Q_{in} - Q_{out}, \qquad H = \frac{V}{S} \tag{1}$$

Assuming a constant tank area S the water head H may be easily calculated.

In order to obtain real behavior of the hydro-set, the static and dynamic features of a turbine and guide vanes, which control the water flow, needs to be modeled (see Fig. 7).

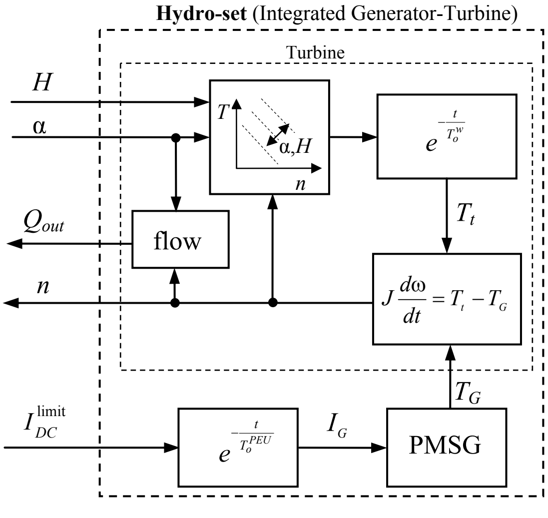

Fig. 7. Hydro-set block diagram

Static features are characterized mainly by the turbine torque characteristic as a function of speed $T(n)$ for different values of the guide vanes angle α. This characteristic can be approximated by a linear function of a slope and intercept depending on a turbine construction (dimensions and shape of blades) as well as actual hydrological conditions (water head, speed and guide vanes angle). This function has been identified on the real plant and can be described by the function (2) presented in Fig. 8.

$$T_t^r = -1.2 \cdot n^r + H^r\left(0.237 \cdot \alpha^{0.544}\right) \qquad (2)$$

where: $T_t^{\,r}$ – relative torque (T_t/T_{tN})
n^r – relative speed (n/n_N)
H^r – relative head (H/H_N)

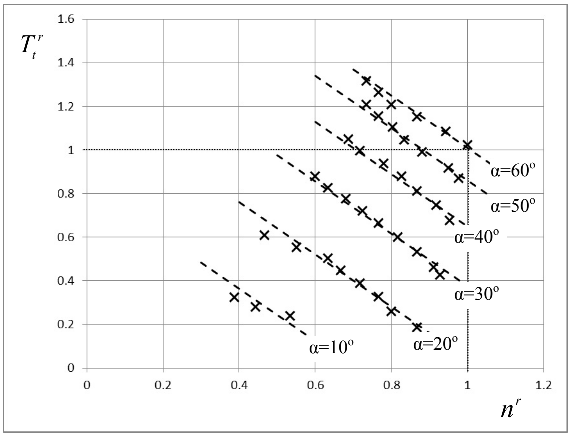

Fig. 8. Real turbine torque characteristics (in releative units) for a given guide vane angles and nominal water head (H^r=1)

Hydrological features are defined by the flow block which calculates the turbine flow Q_{out} .In general, the flow is proportional to the turbine speed for a given guide vanes angle (see Fig. 9). This relation can be approximated by the formula (3).

$$Q_{out}^r = 0.0166 \cdot \alpha \cdot n^r \qquad (3)$$

where: $Q_{out}^{\,r}$ – relative flow (Q_{out}/Q_{outN})

Dynamic behavior of the hydro-set is caused by many elements. The most significant are the PEU and the dynamics of water. The first one is defined by the time constant T_o^{PEU} and depends on the PEU regulators sets. The result of the laboratory test, which identifies this time constant, is presented in Fig. 10.

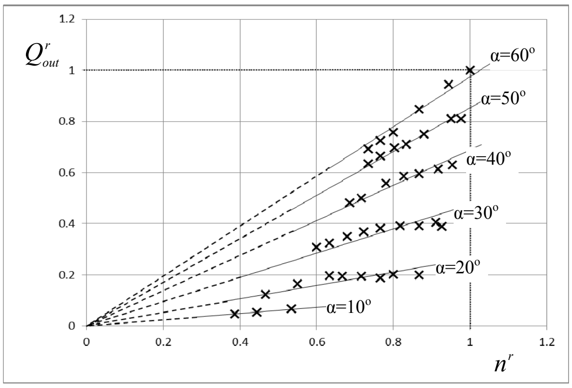

Fig. 9. Turbine flow in relation to speed and guide vanes angle

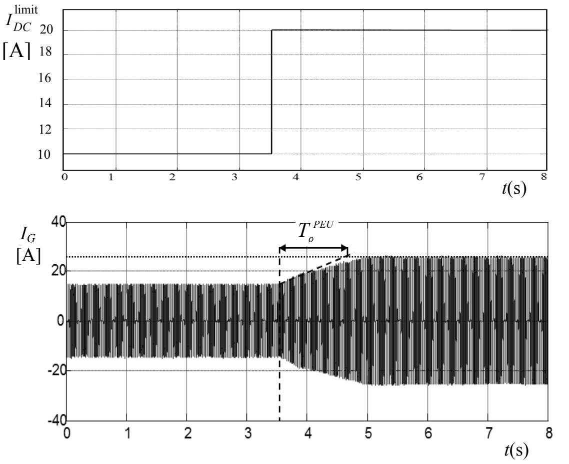

Fig. 10. I_{DC}^{limit} step response of PEU (generator current) in laboratory test bench ($T_o^{PEU} \approx 1s$)

The second parameter, marked by the T_o^w, is a function of the water head and the volume of the inlet channel. The tests of real hydro-set operation have allowed to identify this parameter (see Fig. 11).

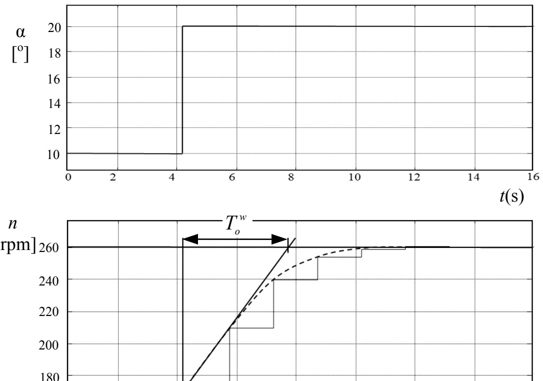

Fig. 11. Angle step response of turbine speed in real SHP ($T_o^w \approx 3.5s$)

The time constant resulting from the inertia coefficient of the rotor J is relatively small comparing to the previous constants.

4. Laboratory tests

The SHP model, presented in the previous paragraph, was implemented in the laboratory energy conversion system. The mathematical relations and automatic operations were defined in the PLC controller (CX 1030 – Beckhoff Embedded PC). The visualization and control operations were realized in the TwinCAT program and are available through a touch panel.

The parameters of modeled SHP are following: P_N=14kW, Q_N=1m^3/s, H_N=2m, n_N=450rpm, η_N=0.71, T_N=318Nm, α_N=60^o, S=250m^2, T_o^w=1.5s.

The visualization consists of few screens. The main screen (Fig. 12) presents the elements of SHP: water tank, guide vanes, hydro-set and the PEU. The guide vanes angle and generator current can be controlled manually by an operator and automatically by the control system (presented in Fig. 6). In addition, the hydrological conditions may be changed by adjusting a water inlet of a river and an actual water head.

The characteristic screen (Fig. 13) shows the actual steady-state torque characteristics of the turbine (presented in Fig. 8) and the generator controlled by the PEU (presented in Fig. 5). There is also indicated the operation point of the hydro-set, which in a steady state is situated in the cross point of the torque characteristics. The dotted lines define the optimal operation curve for a given water head.

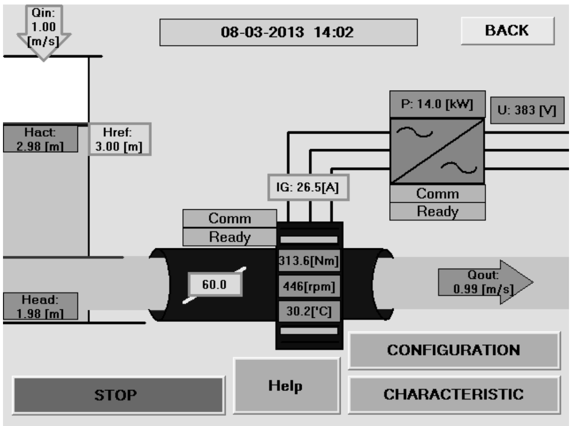
Qin: 1.00 [m/s]
08-03-2013 14:02
Hact: 2.98 [m]
Href: 3.00 [m]
P: 14.0 [kW]
U: 383 [V]
IG: 26.5[A]
313.6[Nm]
446[rpm]
30.2[°C]
60.0
Qout: 0.99 [m/s]
Head: 1.98 [m]

Fig. 12. Main screen of SHP monitoring and control system

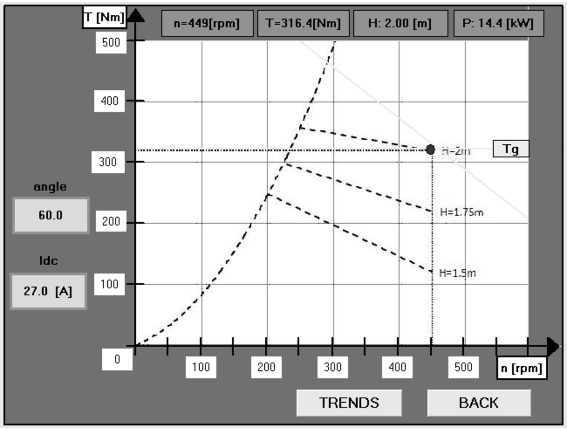
n=449[rpm]
T=316.4[Nm]
H: 2.00 [m]
P: 14.4 [kW]
angle 60.0
Idc 27.0 [A]

Fig. 13. Characteristic screen with steady state torque characteristics of turbine and generator controlled by the PEU

The static features of the SHP model are presented in the figures below on the power-speed (Fig. 14a) and the torque speed plane (Fig. 14b) for a given guide vanes angle and nominal water head. The optimal operational curve is also shown (solid line).

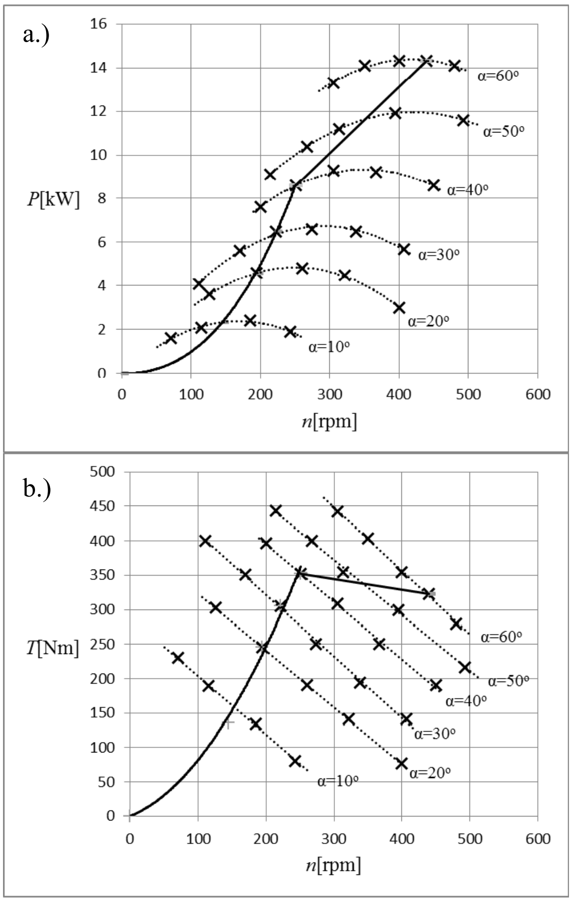

Fig. 14 Power (a.) and torque (b.) characteristics of the laboratory SHP model with the optimal operational curve (solid line).

To present the dynamic behavior of the hydro-set and control system operation some tests results are presented below. Due to the fact that real hydrological conditions are changing very slowly the dynamics can be visible in operational functions such as hydro-set starting. The automatic starting process is shown in Fig. 15 by two graphs: water parameters (a.) and hydro-set parameters (b.). The initial value of the water head equals 3.05m while the target water head is 3m. The water head regulator (PI) controls the guide vanes angle α to obtain the reference water head H^{ref}. In the same time the independent load regulator adjusts the generator current I in order to place the operation point on the optimal curve (Fig. 13).

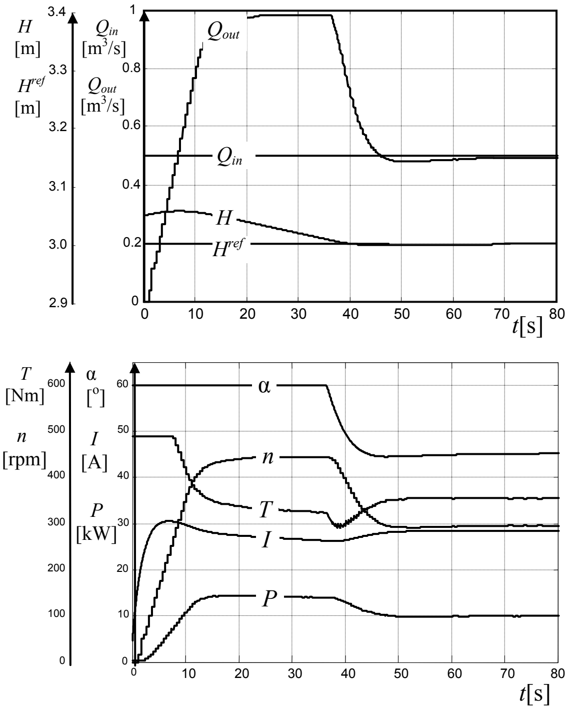

Fig. 15. Starting process of the hydro-set: a.) water flow and head (initial value of water head equals 3.04m), b.)hydro-set parameters

5. Conclusions

The paper presents the laboratory model of SHP with variable speed operation. The propeller turbine is modeled by the torque characteristic realized by asynchronous motor fed by the vector controlled voltage inverter. Other hydrological features (water dynamic, flow and water head calculations) are implemented in the PLC controller in the form of the mathematical formulas. All parameters were identified in the real SHP.

Analyzed model allows to investigate the energy conversion system based on the permanent magnet synchronous generator and the AC/DC/AC converter in a water power plant application. A possibility of setting specific hydrological conditions (water head, flow) gives opportunity to test and verify the stability and effectiveness of the control methodology. Furthermore, the influence of the converter on the generator and turbine operation can be also analyzed.

Presented laboratory model of SHP constitutes an interesting object from both research and teaching point of view.

7. Bibliography

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