HYDRO TURBINE EMULATOR FOR MICRO HYDRO POWER PLANTS

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REZUMAT. Aceasta lucrare prezinta un emulator de turbina hidraulica care faciliteaza analiza functionarii la nivel de laborator a microhidrocentralelor. Emulatorul este de fapt un sistem de actionare electrica cu control adecvat. Functionarea sa se bazeaza pe o bucla de control avand ca marimi de intrare cuplul electromagnetic estimat al motorului si gradul de deschidere al vanei de admisie a apei in turbine, iar ca marime de iesire turatia motorului. Cu ajutorul acestui emulator este testata functionarea unui generator asincron trifazat ce alimenteaza sarcini monofazate izolate.

Cuvinte cheie: microhidrocentrale, generator asincron, sisteme de actionare electrica.

ABSTRACT. This paper deals with a hydro turbine emulator for micro hydro power plants analysis at laboratory level. The emulator is actually an electric drive system based on an induction motor with adequate control. Its operation relies on a control loop having as input parameters the estimated motor electromagnetic torque and the turbine gate opening, while the output parameter is the motor imposed rotational speed. With the help of this emulator the behaviour of a three-phase induction generator supplying isolated single-phase loads is tested.

Keywords: hydro electric power generation, induction generator, induction motor drives.

1. INTRODUCTION

The environmental impact of the conventional power plants, along with the diminishing of fossil fuels has opened the gate to renewable energy sources for energy production. While large scale green energy (mainly wind and solar plants) constitute a significant part of some developed countries energetic systems (Spain, Denmark, Germany), smaller units (mainly micro hydro) can successfully supply isolated consumers. It is also the case of Romania, where the hydro-graphic network offers a significant potential for micro and small plants. Furthermore, the national energetic strategy for 2007-2020 states that “micro hydro power plants (MHPPs) represent a good alternative for supplying rural areas that are still not connected to the national utility grid”.

At research level, a comprehensive analysis of any renewable energy source behaviour starts with the modelling of the primary energy source. In the case of medium and large size power plants, besides the detailed hydraulic turbine model, the modelling should focus also on the hydraulic system (penstock, water tower), as well on the turbine governor [1-3], thus resulting a complex system with a significant number of variables. But when the study involves a micro hydro power plant that operates in autonomous mode, with an installed power of several kW, the hydro-mechanical part can be reduced to the turbine only, operating in fixed-speed or variable –speed regime [4].

When choosing the turbine for a micro hydro, aspects as cost, efficiency and maintenance should be taken into account. Usually, impulse turbines are employed, such as Pelton and Banki-Michell The latter appears to be very versatile, as it accommodates a large range for both head (from 1 to 200 meters) and flow (between 0.02 and 10 m^3/sec). It has an overall efficiency slightly lower then Pelton, but available on a much wider range of flows, mainly in the two-cell configuration.

This paper focuses on the behaviour of a simple hydro turbine emulator for micro hydro power plant with induction generator. The paper is organized as follows. In section II, the system configuration and control strategy are presented. Section III details the hydro turbine emulator. Section IV shows the experimental results, while conclusions are provided in Section V.

2. SYSTEM CONFIGURATION AND CONTROL STRATEGY

The basic diagram of the considered system is depicted in fig.1. It relies basically on a motor-generator group containing two three-phase induction machines.

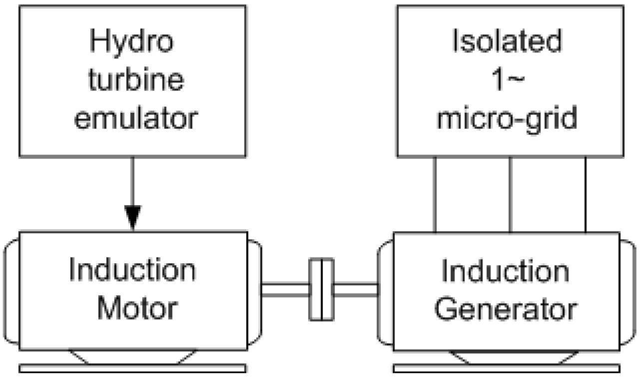

Fig. 1. System configuration

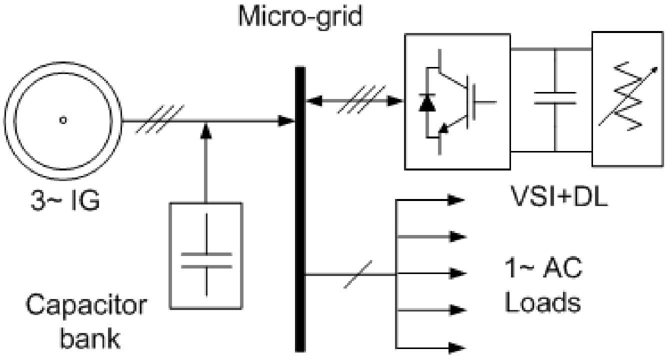

Fig. 2. The single-phase micro grid structure

The left-side machine, operating in motor regime, along with the turbine emulator, plays the role of the prime mover. The right-side machine operates as a generator and supplies a single-phase isolated micro-grid.

Usually, a low power MHPP is equipped with induction generator (IG) because it has several advantages compared with the synchronous one: price, robustness, good response to faults and overloads, simpler starting and low maintenance. A single-phase micro-grid is considered due to the fact that in isolated places low power single-phase consumers are usually encountered.

In order to supply such consumers, a single-phase induction generator can be used but its performance is low because this machine was designed for optimal motor operation and the power is limited to 3- 4kW. Three phase induction machines are available in a very wide power range; by comparing such a machine with a similar power single-phase one, the 3~ machine results to be cheaper, has higher efficiency and consequently a better power per weight ratio.

Some adaptations are required in order to supply single-phase loads with power from a three-phase induction generator. The main goal is to ensure stable operation, as it is the classical case of severe unbalance. Simple topologies rely on passive circuit elements to obtain balanced operation; the resulting configuration should take into the account the machine internal connection (star or delta). For star connected machines the balancing is done with the help of three capacitors, from which two of the same value, placed in parallel with the load [5]. For delta connected machines, the use of one capacitor results in several Steinmetz connections [6] and if three of the same value are used the C-2C connection is obtained [7].

The block diagram of the proposed stand-alone single-phase micro-grid is topology is given in fig.2. It includes a Δ connected induction generator equipped with a suitable capacitor bank, the single phase loads and the control system.

The control system is a combination between a Voltage Source Inverter (VSI) and a Dump Load (DL) circuit. By operating at constant synchronous frequency (excepting the start-up process), the VSI imposes the IG frequency. The dump load connected to the VSI DC side controls the voltage across the DC capacitor, maintaining the system voltage in a standard variation range by dissipating the exceeding active power.

An unbalances compensator block within the VSI control circuit deals with unbalances compensation. It redistributes the currents through the VSI and thus ensures balanced currents at the IG leads. A more detailed presentation of the control system can be found on a previous author’s research [8].

3. HYDRO TURBINE EMULATOR

Usually, the main characteristics of a hydraulic turbine are torque vs. speed, power vs. speed, efficiency vs. speed. In terms of torque, besides the fact that it has linear decreasing characteristic with speed, its value is also influenced by the turbine admission degree. By merging the torque and power variations with speed in one graph, the characteristic from fig. 3 resulted.

By assuming the turbine power constant, the torque vs. speed characteristic of an impulse turbine can be expressed through the following linear relation:

$$T = T_0 - m\Omega \qquad (1)$$

where T is the torque at the turbine shaft, m is the curve slope, T_0 the torque at 0 rpm and Ω the angular speed.

The mechanical power at the turbine shaft can be obtained by multiplying equation (1) with Ω:

$$P = \Omega \cdot T = \Omega \cdot T_0 - m \cdot \Omega^2 \qquad (2)$$

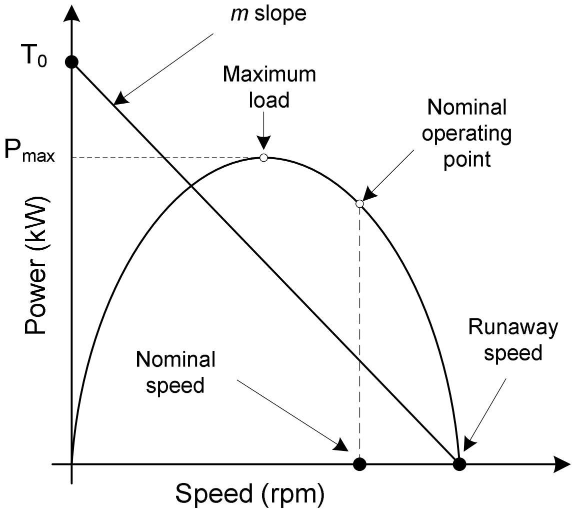

Fig. 3. Hydraulic turbine torque and power characteristics

By imposing the condition $\frac{dP}{d\Omega}=0$, the speed at which the turbine supplies the maximum power can be found; this will lead to:

$$\Omega_{|P_{\max}}=\frac{T}{2m} \tag{3}$$

If both torque and speed are given in per units (p.u.) and in steady-state regime the turbine power does not exceed its nominal power, the following relationship results, on which the turbine emulator is build:

$$T=2.5-1.5\Omega \tag{4}$$

In terms of practical implementation, the hydro turbine emulator is actually an electric drive based on an induction motor with adequate control. The electrical machine is a 3kW/1500rpm series motor, while the frequency converter is a Danfoss FC302 3kW; their parameters are given in Appendix A.

On the generator side, the induction machine is a series 2.2kW/1500 rpm able to deliver a maximum of 1.7kW electrical power in generator regime. Its parameters are also given in Appendix A. As VSI a FC302 Danfoss industrial inverter is employed, connected at the generator leads by a filter with Rf=0.1Ω and Lf=6,5mH. On the inverter DC side a 2500μF capacitor makes the connection with the DL. The DL circuit contains an IGBT transistor TD and a dumping resistance of 155Ω. The IG is magnetized by a stepped capacitor bank with four steps of 10, 20, 40 and 80 μF. The single-phase load consists in several resistors.

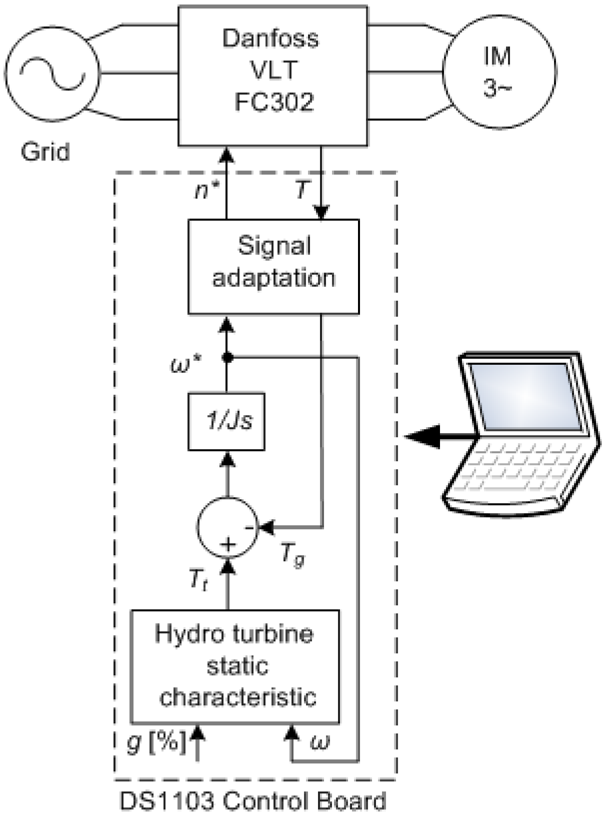

Fig. 4. Hydraulic turbine emulator

Data acquisition and control is ensured by a dSPACE DS1103 board. The control algorithm is built in Matlab/Simulink and implemented in dSPACE through a Real Time Interface. The ControlDesk program realizes the interface between the dSPACE system and the user. A monitoring and protection block generates error signals when monitored parameters exceed the nominal values. The block diagram of the turbine emulator is depicted in fig.4.

The hydro turbine emulator operation relies on a control loop in which the input parameter is the induction motor electromagnetic torque *T*, which is estimated by the frequency converter, while the output parameter is the motor imposed rotational speed. The other input parameter, which is directly controlled by the user, is the turbine gate opening *g(%)*.

4. EXPERIMENTAL RESULTS

Based on the aspects detailed in the previous section, the experiments focus on two main directions. The first one is the induction generator loading while the second one represents the system response to a perturbation such a significant load being switched ON/OFF.

About the system start-up, some clarifications should be made. Because the induction generator operates in parallel with the voltage source inverter (VSI), at any moment they should be synchronized. Thus, the best solution is to have the VSI connected from the beginning at the IG leads; in this manner it will enhance the generator start-up. A more detailed presentation of the start-up process can be found on a previous author's research [9].

Right after its start-up, the generator operates lightly loaded, just like in the case of a real generator connected to the grid. The generated power is then boosted by slowly increasing the admission vane opening. For our turbine emulator the procedure implies the increase of the *g[%]* parameter with the help of its corresponding button from ControlDesk. As can be seen in fig.5, this process begins at t=7s and lasts for about 20s. Thus, the turbine torque increases from 0.1 to 0.65 (p.u.). The emulator static characteristic implies that any torque (and consequently mechanical power) increase is done by increasing the speed of the driving motor. This is why the motor-generator group speed increases from 1506 rpm to 1546 rpm, as results from the bottom of fig.5.

Returning to the turbine torque, one might notice that it increases up to 0.65 (p.u.). The maximum mechanical power at the driving motor shaft is 3kW, which corresponds to a torque value of 1 (p.u.). In the mean time, the generator is actually a 2.2kW motor, where this nameplate power represents its nominal shaft mechanical power. In terms of torque, it means that it should never be above 0.73 (p.u.). At 0.65 (p.u.) torque, the mechanical power is around 1.95kW, and for a generator efficiency of 80%, the available electrical power at the IG leads is around 1.6kW. The IG active and reactive power variations are presented in fig.6. This explains the active power increase from 250W to 1.6kW from the upper part of fig.6.

As for the reactive power variation (bottom of fig.6), some clarifications are necessary. As the induction generator is connected in Δ, its line voltage is 230V and thus its capacitance requirements increase by 3 times with respect to the star connected machine. The generator requires around 132μF at nominal loading. The capacitor bank was set to 130μF from the experiments beginning. Thus, when lightly loaded, the generator seems to "deliver" around 300var. This is due to the fact that the IG reactive power is measured at the coupling point between the IG and the VSI, while the capacitor bank is connected at the IG leads. Thus, the corresponding 300var represent the exceeding reactive power that circulates towards the VSI. When the generator is loaded up to almost its nominal power, the reactive power decreases and becomes slightly negative, due to the fact that now the VSI supplies the rest of 50 μF.

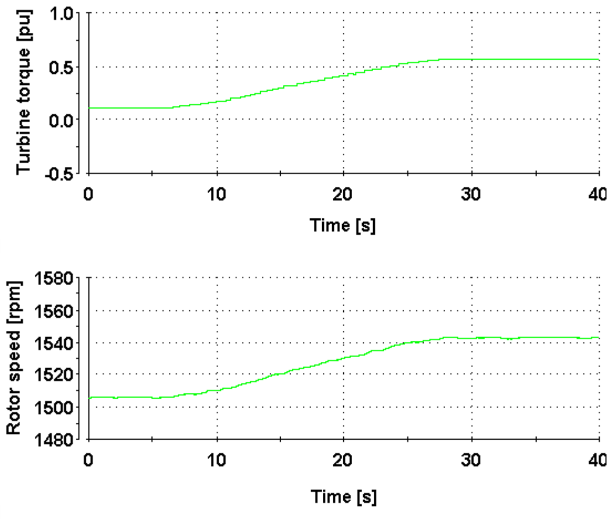

Fig. 5. The turbine torque and rotor speed variations

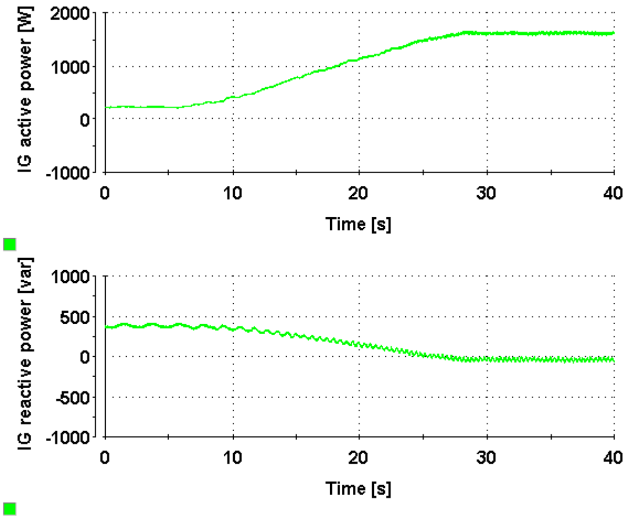

Fig. 6. The IG active and reactive power variations

In order to investigate the system overall behaviour during transitory regimes, a significant resistive load of 950W is connected at t=5s and disconnected 6s later. In this situation, the generator is a little less loaded then in the previous case, delivering around 1.4kW; thus the considered consumer has a power of 2/3 from the total available active power. In terms of torque oscillations one might see that they are insignificant, around the value of 0.55 (p.u.). Both torque and speed variations are depicted in fig.7. In the case of the rotational speed, during the load connection period the value decreases from 1538 to 1536; this represents around 0.1% from the nominal value.

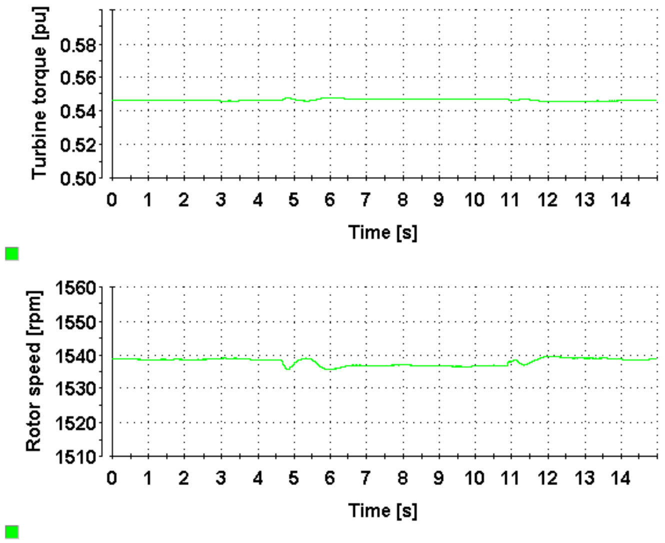

Fig. 7. The turbine torque and rotor speed variations during the transitory regime

On the generator side, the main interest parameters are the voltage and frequency. While the frequency hardly varies, the voltage drops up to 215V when the load is connected and rises to 245V when it is switched OFF, but these variations are rapidly mitigated by the control system, as can be seen in fig.8.

Although the single-phase load is connected between A and B phases, the currents through the generator remain balanced (see the upper part of fig.9). The balancing algorithm mentioned in section 2 proves its effectiveness because, by redistributing the currents through the VSI (see bottom of fig. 9), the currents through the generator remain balanced, and thus avoiding unwanted torque oscillations.

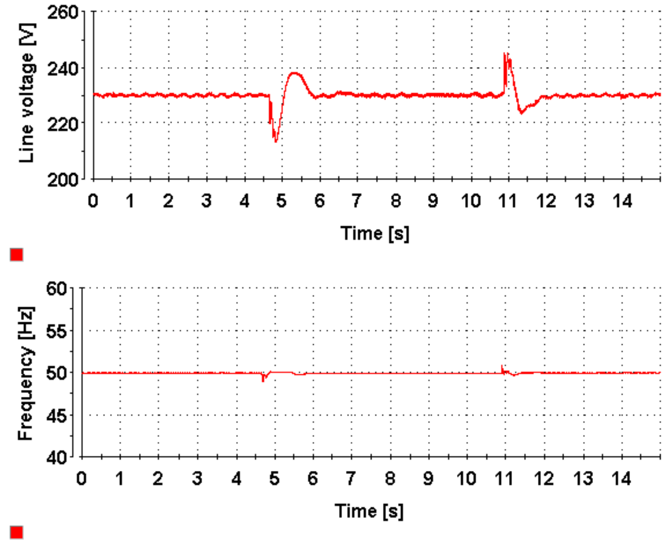

Fig. 8. The IG voltage and frequency variations during the transitory regime

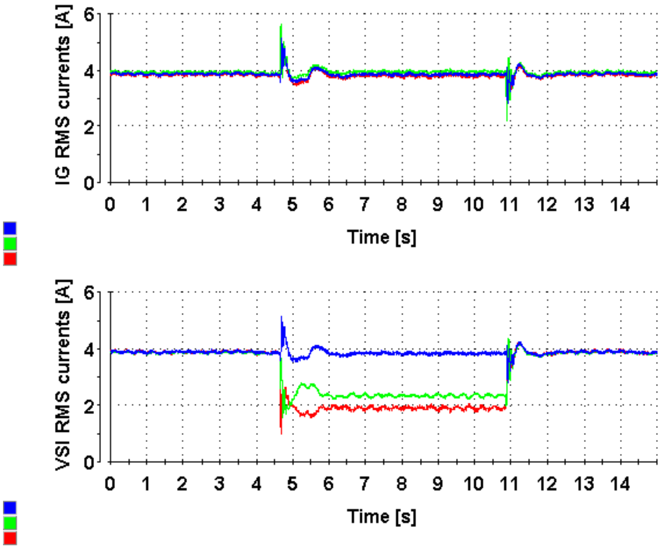

Fig. 9. The IG and VSI cuurent variations during the transitory regime

5. CONCLUSIONS

- ✓ The main goal of this paper was to propose and test the bahavior of a simple hydro tubine emulator build for research purposes.
- ✓ The experimental results showed that the proposed emulator is reliable.
- ✓ The investigations focused also on the generator loading and on the overall system behaviour during a transitory regime.
- ✓ The experimental results showed that on the mechanical side the main parameter variations are rather insignificant, while on the generator side the control system ensures good voltage and frequency regulation, while balancing the three-phase IG currents when single-phase loads are connected into the system.

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APPENDIX A

The driving motor parameters
Nominal power: 3kW;
Connection type: Star;

Nominal voltage: 400V;
Nominal frequency: 50Hz;
Nominal current: 6.8A;
Power factor: 0.82;
Efficiency: 0.8.

The frequency converter parameters
Nominal (shaft) power: 3kW;
Output power: 5kVA;
Nominal supply voltage: 380-440V;
Nominal current: 7.2A
Efficiency: 0.98.

The induction generator parameters
Nominal power: 1.7kW;
Connection type: Delta;
Nominal voltage: 230V;
Nominal frequency: 50Hz;
Nominal current: 7.4A;
Power factor: 0.8;
Efficiency: 0.8.

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