Operation modes of a hydro-generator as a part of the inverter micro hydropower plant

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Abstract. The paper dwells on the selection problem of power equipment for a stand-alone inverter micro hydropower plant, in particular a hydro-generator, and evaluation of its operation modes. Numerical experiments included the modes calculation of hydroelectric units of the same type with various nominal power, supplied to the consumer according to the unchanged electric load curve. The studies developed requirements for a hydro-turbine and a synchronous generator in terms of a speed range and installed capacity, depending on the load curve. The possibility of using general industrial hydroelectric units with nominal power equal to half-maximum capacity of a typical daily load curve in rural areas was shown.

1. Introduction

Diversion micro hydropower plants (micro HPP) with upstream pipeline have become mostly widespread due to their low environmental impact and the possibility of using unregulated turbines combined with semiconductor ballast voltage regulation systems for a hydro-generator, which defines their high performance and low cost of the generated electric energy.

The development of power converter equipment allows designing competitive micro HPPs with a reversible converter and a power storage unit [1, 2]. Such power plants can achieve high-quality output voltage and increase the installed capacity utilization factor of the hydro-generator.

Complex processes of energy conversion of the inverter micro HPP hinder the selection of power equipment, particularly the hydro-generator, and evaluation of its operation modes. Research in this area is very relevant.

The research objective is a diversion micro hydropower plant with a reversible converter and a battery power storage unit. The goal of the research is to study the operation modes of a hydro-generator as part of a stand-alone inverter of micro HPP and to develop the requirements for hydro-turbines and a synchronous generator in terms of a speed range and installed capacity, depending on the electric load curve.

The research methodology rests on the study of power balance in a stand-alone power supply system based on a micro HPP and mathematical simulation of hydro-generator modes by means of the Matlab software package.

2. Operation modes of a hydro-generator

The load curve is a defining factor for operation modes of the stand-alone power supply system. A typical daily domestic load curve of rural households is shown in Figure 1, where P – active load, Q –

reactive load. As shown in the graph, the dark color indicates effective load (electric power) and the white one – ballast load (electric power converted into heat) of the power plant.

Widespread micro HPP with ballast regulation shall be selected due to the condition of providing the consumer with electric power during the maximum load hours, in this graph – evening maximum load is reached when P_m=1 PU. Obviously, the hydro-generator produces the effective load during these hours. The rest of the time its power is distributed between the effective load (according to the load curve) and the ballast load so that gross capacity remains equal to P_m. As follows from the curves shown in Figure 1, the hydro-generator is loaded with active power of the effective load on average at the level of 36-45% compared to its nominal load, depending on the season.

Figure 1. A summer daily domestic load curve.

Thus, using the ballast load of the heating elements, it is possible to use the entire installed capacity of micro HPP, but more than a half of it is used in the form of heat. The load power factor variability prevents the components of gross capacity from stabilizing, which leads to errors in both amplitude and frequency stabilization of the output voltage at micro HPP [3-5].

Figure 2. Operation modes of hydro-turbines of ballast and inverter HPP.

In addition to the inverter, the equipment of inverter micro HPP, due to the power storage unit, can be selected for a significantly lower nominal power, as shown in Figure 2, where P_b – characteristic curve of the hydro-turbine with ballast regulation; P_n – characteristic curve of the hydro-turbine of inverter micro HPP; 1 – working point on the curve of $P_b=f(n)$ of ballast micro HPP; 2 – operation mode of the hydro-turbine for the average load of P_{av}; 3 – operation mode of the hydro-turbine for the minimum load of P_{min}.

The figure shows a typical power dependence of the propeller hydro-turbine on speed rate n with constant parameters of the water workflow. The dependence is presented in relative units. The basis values refer to the maximum power of the hydro-turbine with maximum energy of the water workflow and its speed rate in an idling mode. The values of average P_{av} and maximum P_m consumed power correspond to points 1 and 2, respectively. The micro HPP with the ballast stabilization system requires a turbine with the characteristic curve of P_b that can supply consumers with electric energy during the maximum load hours (point 1 in Figure 1).

In accordance with the load curve, the average effective load of hydro-generator P_{av} is characterized by point 2, and the minimum load - by point 3 on the power curve of the turbine.

Assuming that maximum power load is provided by the power storage unit, the hydro-turbine of inverter micro HPP of much less capacity can be selected, which is the average value of daily power load. The curve of the hydro-turbine of inverter micro HPP is indicated as P_{inv} in Figure 2.

It is obvious that the power balance of such plant shall consist of two alternating modes, depending on the ratio of the available capacity of the hydro-generator and the current power load. A charge and a discharge of the power storage unit are characterized by formulas

$$P_{gi} = P_{ni} + P_{chi} \qquad \text{and} \qquad P_{gi} = P_{ni} - P_{dchi}, \tag{1}$$

where P_{gi} – power of the hydro-generator on the i-th time interval; P_{ni} – power load on the i-th time interval; P_{chi}, P_{dchi} – charge and discharge power of battery power storage units.

The available capacity of the hydro-turbine is limited by the maximum point on its power curve. The power of charge P_{chi} and discharge P_{dchi} of the battery power storage unit provides the power balance and, to a certain extent, stabilizes the operation of the hydro-turbine.

The power storage unit can limit the range of the power load change at a point of $P_{av} \pm \Delta P$. Accordingly, the hydro-generator of lower installed capacity can be selected, with the same power load of a plant. The power curve of the hydro-turbine, which develops less power is shown in Figure 2 and indicated as P_{inv}. The working point, corresponding to the average power load is indicated as 2`. The speed rate of the hydro-generator will vary, to some extent, from n_{min} to n_{max}, depending on the range of the generated power.

The equation for the daily power balance can be shown as

$$W_g = W_n + W_{ch} - W_{dch}. \tag{2}$$

Obviously, at 100% efficiency of battery power storage units $W_{ch} = W_{dch}$ and (2) become equality of $W_g = W_n$. Taking into account the actual properties of storage units, charge power will always exceed discharge power.

In the joint load operation of the hydro-generator and the power storage unit, the capacity and power contribution of the hydro-generator in maximum load periods shall be limited to their available values. As it was mentioned above, the available capacity of the hydro-generator is limited to the maximum power curve of the turbine, and in case of batteries storage units – the capacitance and the recommended value of its discharge in a cyclic mode.

To control the flows of capacity and power, an intelligent system that monitors the current power load of the stand-alone power consumer and the state of battery storage units is required.

An operation mode of battery storage units, providing acceptable service life in a cyclic mode, shall be limited to the available capacitance to a maximum of 30 % of the total power charge. Thus, the storage units shall provide power for consumers during peak hours, contributing to the available generation level of micro HPP up to the consumption level. The value of this power shall not exceed

30 % of the power of a fully charged battery. The rest of the time, the storage units are charged to the nominal capacitance from the hydro-generator.

A selection of the operation mode is defined by the threshold of power load, denoting the need to include battery energy into the system power balance. The threshold defines the allowable value of the hydro-generator capacity, providing its stable operation under specific conditions [6, 7].

Using daily load curves (Figure 1) and the power curve of the hydro-turbine (Figure 2), the component of the system power balance can be defined.

Daily power, required by a consumer, is defined as

$$W_n = \sum_{i=1}^{48} P_{ni} t_i \,,$$

where P_{ni} – power at a half-hour interval; t_i – half-hour interval of time sampling; i –interval number.

Mean consumed power is equal to $P_n = W_n/48$. In view of the charging current of the storage unit, the hydro-generator shall provide the energy system with average power

$$P_g = P_n + P_{ch},$$

where P_{ch} – charge power.

The charge power can be characterized by the recommended value of charging current, which does not numerically exceed 10 % of the nominal capacitance of the battery. Then the charge power of the storage unit can be defined as

$$W_{ch} = \sum_{i=1}^{48} \left(P_{gm} - P_{ni} \right) \cdot t_i \,,$$

provided that $P_{gm} > P_{ni}$. Unless the inequality is satisfied, the charge power at the interval is equal to zero.

The amount of the charge power shall exceed the discharge power by the value of battery efficiency – η_{bat}:

$$W_{dch} = W_{ch} \cdot \eta_{bat} \,.$$

The discharge power is defined as

$$W_{dch} = \sum_{i=1}^{48} \left(P_{gm} - P_{ni} \right) \cdot t_i \,,$$

provided that $P_{gm} < P_{ni}$. Accordingly, unless the inequality is satisfied, the battery does not discharge, and the previously described charge of the storage unit occurs.

3. Results and discussion

The study of the described hydro-generator modes has been conducted using a mathematical model, implemented in Matlab by means of the following elements: a synchronous generator with damper winding and an excitation system corresponding to hydroelectric units with the capacity of 85 kVA, 60 kVA and 42.5 kVA, a generic diode bridge was used as a rectifier, an inverter was based on IGBT-transistors shunted by reverse diodes. The maximum power load corresponds to the nominal power of the hydro-generator, which is 85kW. An unregulated turbine was simulated by a transfer function taking into account the water-hammer effect, specific to hydro-turbines [8, 9]:

$$W_t(s) = \frac{1 - a_{dis} T_w s}{1 + 0.5 a_{dis} T_w s} \,,$$

where T_w – time constant of the hydro-turbine; a_{dis} – initial opening of the turbine distributor.

Numerical experiments included the modes calculation of hydroelectric units of the same type with various nominal power, supplying the consumer according to the unchanged electric load curve. The calculation results in the form of graphs, interconnecting the hydroelectric unit speed rate and developed power, are shown in Figure 3.

The graphs are given in relative units for three hydroelectric units with different nominal power, such as $1 - 85$ kVA; $2 - 60$ kVA; $3 - 42.5$ kVA. The graphs show that the operation mode of ballast micro HPP is in the vicinity of the nominal mode: $P = 1$ PU, $n = 0.6$ PU. Deviations from the nominal mode are defined by the stabilizing error of gross capacity of ballast and effective load. In view of the operation mode stability of the hydro-generator, the general industrial power equipment, designed for constant speed rate, can be used.

In case of using inverter micro HPP without the power storage unit, the nominal power of the hydroelectric unit remains unchanged compared to the ballast power plant, but the speed range of the hydroelectric unit varies from 0.6 to 0.92 PU in accordance with Figure 3. Consequently, general industrial electric generators cannot be used under the terms of the mechanical strength. Using special generators with the variable speed rate usually leads to micro HPP appreciation.
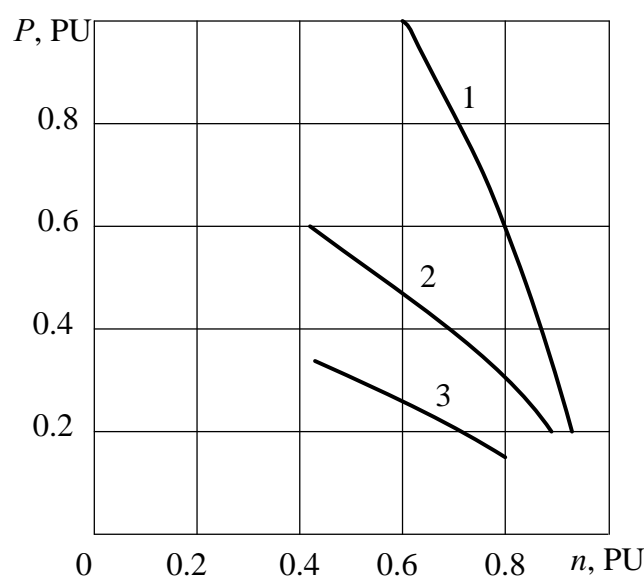

Figure 3. Operation modes of hydro-generators.

The power storage unit as a part of inverter micro HPP allows eliminating the peak load operation of the hydro-generator. Accordingly, its nominal power can be reduced. The curves 2 and 3 in Figure 3 characterize hydro-generator operation modes with nominal power of 0.7 PU and 0.5 PU relative to the basic one.

The current values of power load, with the exception of maximum loads, are within 0.2–0.35 PU (Figure 1). The speed rate of the hydro-generator with the nominal mode of $0.7P_m$ varies from 0.88 PU to 0.75 PU (Figure 3). The hydro-generator with nominal power of $0.5\ P_m$ operates in the frequency range from 0.7 PU to 0.55 PU.

4. Conclusion

Thus, assuming the hydro-generator nominal speed rate of 0.6 PU, it becomes possible to use general industrial electrical equipment, allowing an increase in the speed rate relative to the nominal value under the terms of mechanical strength of 20 %.

Therefore, the studies of hydro-generator operation modes as a part of stand-alone inverter micro HPP, allowed establishing the application of general industrial hydroelectric units with nominal power equal to half-maximum capacity of the typical daily load curve in rural areas.

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