Dariusz Borkowski 
Cracow University of Technology

OPTIMIZING CONTROL ALGORITHM OF ENERGY CONVERSION SYSTEM FOR SMALL HYDROPOWER PLANT WORKING AT VARIABLE SPEED

Abstract: The paper presents the control algorithm dedicated to a variable speed energy conversion system in a small hydropower plant. The energy conversion system consists of propeller water turbine, permanent magnet synchronous generator and power electronic converter.

The main purpose of the algorithm, apart from the water level controlling, is to achieve the highest possible efficiency of the system. The changeable hydrological conditions, in the form of significant variations in a river’s flow and head throughout the year, requires to operate in a wide water flow and head range. Applied optimizing techniques guarantee maximal average efficiency independently of hydrological condition changes, by constant searching of the optimal operation parameters.

The presented control method is implemented and tested in the energy conversion model, created in the Matlab/Simulink software. All characteristics and parameters were identified on the real small hydropower plant and on the special laboratory model.

Keywords: small hydropower plant, variable speed, control algorithm, PM generator

1. Introduction

Small Hydropower Plants (SHP), as a decentralized energy sources located close to their customers, improve grid stability by diversifying the electricity system and reducing transmission losses. In Poland a fast development of SHP, from 400 objects in year 2000 to 700 power plants in year 2010, has been registered. Moreover, according to the “Energy policy of Poland until 2030 year” the threefold increase of installed capacity is planned. Production of energy from renewable sources has a key importance for the energy security of Poland and European Union policy. According to 2009/28/EC [1] directive the European Union (Poland) should produce 20% (15%) of electrical energy from renewable energy sources by the end of year 2020, while the current share of this sources is estimated at 12.7% (9.5%) [2].

SHPs are objects rated up to 10 MW. The main division criterion is the type of energy conversion system, that is elements complex used to convert energy from water through mechanical energy (water turbine) into electrical energy (electrical generator) supplying power system. Traditional solutions of energy conversion system for SHP are based on the water turbines working at constant speed (synchronous generators) or almost constant speed (asynchronous generators).

An interesting solution is to apply the system used in wind power plants, which due to the huge wind variations works with variable rotational speed. This design significantly simplifies the mechanical system but requires a Power Electronic Unit (PEU) in the energy conversion system to match the load and control the power flow from the generator to the grid [3], [4]. The Permanent Magnet Synchronous Generator (PMSG) is the most likely candidate from among the generator types used in SHPs because of its potential for a high pole number (a gearbox is not needed for variable speeds) and a high efficiency under a wide range of loads. The PEU, which control the turbine load torque by setting a given generator current, allows to operate the turbine in a wide range. In Europe and particularly in Poland that type of solutions are rare and have mainly the prototype character [5]. However, significant and promising features following from applying variable speed operation as well as accessibility of high power electronic converters cause increasing interests of such solutions in SHPs.

In the recent years some innovative solutions integrating the propeller turbine and the synchronous generator have appeared on the market. It eliminates the complexity of designing and maintaining mechanical systems for gearbox, shaft and rotor blade control. Applying the variable speed operation in this
system improves its features and makes it more attractive nowadays [6]. The profitability of SHPs depends largely on their location and the hydrological characteristics at that location [7]. SHPs are primarily “run-of-the-river” plants, defined as providing little or no water storage. Thus, the operation state of the power plant (e.g. generating power) depends on the actual hydrological conditions. Due to the changeable hydrological conditions throughout the year, it is recommended to operate in a wide water flow and head range [8]. It significantly increases the annual average efficiency of generation system. Using variable speed operation allows to work in a such changeable conditions with high efficiency of the turbine. Management of the energy conversion system with the PEU, due to the specific features of water turbine (quite different then wind turbine), should be based on the dedicated control strategies ensuring proper exploitation and the optimal parameters of turbine operation. Desirable regulation has to adjust the operation parameters due to the actual conditions in order to obtain the highest possible efficiency of the whole energy conversion system. Dedicated optimization algorithm presented in this paper fulfills this requirements. It is implemented and tested on the simulation model created in the Matlab/Simulink software. The energy conversion model is based on the real system installed in the SHP of 150 kW nominal power [6]. All characteristics and parameters are identified in this object and in the 30 kW laboratory model [9].

2. Energy conversion system structure
The energy conversion system, analysed in this paper, contains guide vanes, which control the water quantity flowing through the turbine, propeller turbine integrated with permanent magnet synchronous generator (PMSG) and the power electronic unit (PEU). The block diagram of the system is presented in Fig. 1. The controller adjust the guide vanes angle α depending on the actual measuring parameters: water head H, rotational speed n as well as current and voltage of the grid \((I_s, U_s)\).

3. Identification of elements features and system parameters
In order to create the simulation model of energy conversion system all elements have to be analysed and represented by its essential features. Due to the fact, that this model will be using to test the control method, particular elements will be represented by a steady state characteristics, time constants and efficiency function. This simplification is necessary to accelerate the simulation calculations.

3.1. Power electronic unit
Applied Power Electronic Unit (PEU) is the full-scale AC/DC/AC power converter consisting of: an uncontrolled rectifier, DC-DC boost converter which increases the DC voltage and the DC/AC converter with DPC-SVM algorithm (Virtual Flux – Direct Power Control with SVM modulator) [4], [6]. The main controlling parameter is \(I_{DC}^{lim}\) which tunes the DC current by the PI-\(I_{DC}\) regulator (Fig. 2).
It is also changing depending on the generator speed but in a small range, thus this variation has been neglected.

The second controlling parameter – limit of the grid current $I_{glim}$, which limits the generated output power, is set to the value that corresponds to the maximum power to protect the PEU and turbine against a runaway speed condition [6].

### 3.2. PM synchronous generator

The synchronous generator can be treated as an inertial object of a first order, where the generator current can be regarded as the system input, to which turbine torque is the system output. Taking into account linear relations between stator current and electromagnetic torque the object gain is constant and independent on the generator speed. The delay and inertia of this object can be neglected comparing to the dynamic parameters of the PEU, see Fig. 5. The PMSG efficiency is relatively constant over a wide range of loads, what is visible in Fig. 4.

### 3.3. Propeller turbine

Turbine properties can be visualised by a universal characteristic (known as a hill chart) that presents efficiency isolines on a water flow-speed plane. The real characteristic has been identified in the power plant and approximated [9] (Fig. 6).
Dynamic behaviour of the turbine is caused by many elements, but the most significant is dynamic of the water mass. This time constant, marked by the $T''$ is a function of the water head and the volume of the inlet channel. The tests of real turbine operation have allowed to identify this parameter estimated at 3.5 seconds [9].

4. Simulation model of SHP implemented in Matlab/Simulink software

All features described in the previous chapter have been implemented in the Matlab/Simulink software (Fig. 7). In addition the water tank model [9] and guide vanes model, which limits the speed of position changing, have been created. The main task of the regulation system is to maintain a constant hydrological conditions i.e., maintain the upper water $H_p$ at a fixed level. Usually this is realizing by negative feedback control system. The regulator (usually PI) adjusts the control input (the angle $\alpha$ of the guide vanes) based on the actual error $e$. The DC current is the parameter that controls the speed by setting the generator torque. Its value is set depending on the hydrological conditions in order to obtain the desirable operation point.

5. Optimizing algorithm

The main criterion of a control parameter, i.e. the DC current, from the economic point of view, is the maximum efficiency of the whole energy conversion system. The control of “run-of-the-river” plants is difficult due to the continuously changeable hydrological conditions as well as turbine features caused by silt deposited in channels. Algorithms basing on the fixed settings and operation characteristics are ineffective [10]. From that reason, the special methods which will be adapting control parameter automatically to the actual conditions have to be defined. It can be done by the using of the optimizing nonlinear algorithms. The procedure starts from non-optimal current value and tries to improve the production efficiency $\eta$ by applying the gradient method.
The efficiency of energy conversion system is defined by following formula:

\[ \eta = \frac{\sqrt{3} \cdot U_s \cdot I_s}{9.81 \cdot Q \cdot H} \]  

(3)

where: \( U_s \) - grid voltage, \( I_s \) - grid current, \( Q \) - water flow, \( H \) - water head

Using the discretization Euler method of an order one the formula (2) may be written as follow:

\[ I_{DC(l)} = I_{DC(0)} + k \cdot (\eta_{(0)} - \eta_{(-1)}) \]  

(4)

where, the subscript brackets indicate the step number of optimizing algorithm \( l \).
6. Summary

The changeable hydrological conditions and variable turbine parameters due to the ageing process as well as river pollution requires adaptive control. This paper presents the procedure based on gradient method which tunes the generator current, through the DC current of the PEU, in order to obtain the highest possible efficiency. The controller uses the standard PI regulator which provide desired upper water level and the steady state conditions in which the optimizing algorithm is activated.

The gradient descent method, applied in this paper, can provide small step changes resulting in short periods of unsteady states. Thus the optimal operation point may be obtained relatively fast. The drawback of this technique is the limitations of target to the local extreme (minimum or maximum). Fortunately, the efficiency characteristic (quality function) of the investigated system is the convex function which means that any local extreme is the global extreme.

Presented simulation results confirm the algorithm effectiveness and application possibility on the real system.

7. Bibliography


Author
Dariusz Borkowski, Ph.D.
Cracow University of Technology,
Faculty of Electrical and Computer Engineering,
Institute of Electromechanical Energy Conversion,
31-155 Kraków, Warszawska 24 St.
tel. +48 12 628-26-59, email: dborkowski@pk.edu.pl

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Fig. 10. Steady state algorithm steps (square markers) on the water flow – rotational speed plane (total efficiency isolines – solid line, guide angle lines – dashed line, maximal efficiency line – dash-dot line)