TECHNICAL TRANSACTIONS | CZASOPISMO TECHNICZNE
ELECTRICAL ENGINEERING | ELEKTROTECHNIKA
1-E/2015

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CONTROL STRATEGY FOR MAXIMIZING CONVERSION EFFICIENCY OF A SMALL HYDROPOWER PLANT

STRATEGIA STEROWANIA MAŁĄ ELEKTROWNIĄ WODNĄ MAKSYMALIZUJĄCA SPRAWNOŚĆ PRZETWARZANIA

Abstract

An analysis of the energy conversion system which consists of a propeller water turbine, a permanent magnet synchronous generator and a power electronic converter is presented. The considered control strategy implements an optimizing technique that guarantees maximal average efficiency independently of hydrological condition changes through the constant search for optimal operation parameters. The water flow parameter, essential for objective function estimation, is eliminated by the dedicated control technique. The control method is implemented and tested in the model created in the Matlab/Simulink software. All characteristics and parameters were identified on a real small hydropower plant and on the special laboratory model.

Keywords: *small hydropower plant*, *variable speed operation*, *optimizing algorithm*

Streszczenie

W artykule analizowany jest tor przetwarzania energii, który składa się z turbiny śmigłowej, generatora synchronicznego z magnesami trwałymi oraz przekształtnika energoelektronicznego. Przedstawiono strategię sterowania opartą na metodach optymalizacji, która przez ciągłe poszukiwanie optymalnych parametrów pracy gwarantuje maksymalną sprawność przetwarzania niezależnie od zmiennych warunków hydrologicznych. Przez wybraną technikę sterowania wyeliminowano konieczność znajomości parametru przepływu wody niezbędnego do oszacowania funkcji celu. Strategia sterowania została zaimplementowana i przetestowana w modelu opracowanym z zastosowaniem oprogramowania Matlab/Simulink. Wszystkie charakterystyki i parametry zostały zidentyfikowane w rzeczywistym obiekcie małej elektrowni wodnej i na stanowisku laboratoryjnym.

Słowa kluczowe: *mała elektrownia wodna*, *zmienna prędkość obrotowa*, *algorytm optymalizacyjny*

DOI: 10.4467/2353737XCT.15.023.3823

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1. Introduction

The production of energy from renewable sources is of key importance for the energy security of Poland and European Union policy. According to the 2009/28/EC [1] directive, the European Union (Poland) should produce 20% (15%) of electrical energy from renewable energy sources by the end of 2020. The current share of these sources is estimated at 12.7% (9.5%) [2].

Small Hydropower Plants (SHPs) are objects rated up to 10 MW. Traditional solutions of energy conversion system for SHP are based on water turbines working at a constant speed (synchronous generators) or near constant speed (asynchronous generators). An interesting solution is to apply variable rotational speed operation to the system. The variable speed operation applied in hydropower plants improves the turbine operation range and increases energy conversion efficiency under changeable hydrological conditions [3]. This design simplifies a mechanical system but requires the application of a Power Electronic Unit (PEU) in the energy conversion system. The PEU is needed to match the generator and grid parameters and to control the power flow from the generator to the grid [3, 4]. Taking into account high efficiency under a wide range of loads, as well as a possible high pole number structure, the Permanent Magnet Synchronous Generator (PMSG) is the recommended type of generator. In Europe, and particularly in Poland, this type of solution is rare and is mainly of a prototype character [5, 6].

The variable speed operation can be especially effective in control demanding locations, where small changes in operation parameters significantly affect the energy production result. Such a situation especially concerns ‘run-of-the-river’ plants, where generating power depends on the actual hydrological conditions because the water storage is impossible or limited. Thus, changeable hydrological conditions throughout the year force the power plant to operate in a wide water flow and head range [7]. In this situation, the control strategy considerably affects the economic profitability of the SHP. Desirable regulation has to fulfill two main functions – maintaining the upper water level on a fixed level and adjusting the operation parameters in order to obtain the highest possible 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 based upon fixed settings and operational characteristics are ineffective. Furthermore, the coefficient quality of the second task (efficiency) requires the actual water flow parameter, the measurement of which is difficult and expensive.

The control strategy presented in this paper solves the above mentioned problems by implementing optimizing methods and dedicated efficiency assessment methods avoiding the water flow parameter. The proposed solution 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 [8].

2. The structure of the SHP system

The analysed SHP system, presented in Fig. 1, consists of: guide vanes that control the water quantity Q flowing through the turbine; propeller turbine; permanent magnet synchronous generator (PMSG); power electronic unit (PEU); the controller.

As mentioned above, the regulation system of the ‘run-of-the-river’ plants has to fulfil two main functions. These tasks are performed by the two separate regulators.

The water level regulator maintains the upper water at a fixed level. The angle of the guide vanes α mainly influences the water flow quantity Q, thus, it was chosen as a control parameter. It is adjusted by the PI regulator based on the actual error ε between the actual H and set H_{set} water level.

The optimizing load controller has to select the optimal operation point of the system in order to obtain the highest possible efficiency of the whole energy conversion system. It adjusts the generator armature current I_g depending on the actual measuring parameters: water head H; guide vanes angle α; active power generated by the system P_s.

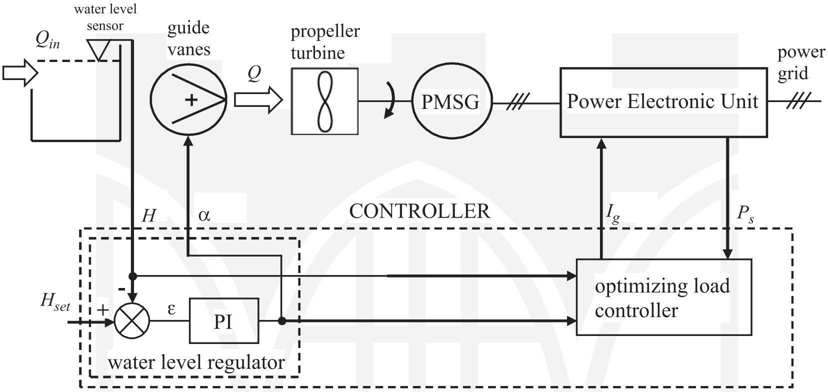


Fig. 1. Block diagram of the SHP system

3. Simulation model

The control process of the hydropower plant takes a long period of time due to the long-time constants of the water system. In order to accelerate simulation calculations, some simplifications are necessary. All elements of the energy conversion system are represented by their essential features: a steady state characteristics, time constants and efficiency functions.

The simulation model presented in Fig. 2 was created in the Matlab/Simulink software. The PI controller has a parallel form with the lower and upper saturation limit. The guide vanes block inserts the initial condition and rate limiter imitating the hydraulic system of position controlling.

The Hydroset subsystem (Fig. 3) models propeller turbine characteristics as a mechanical torque function T_t of guide vanes angle α, water level H and turbine speed n:

$$T_t = C_H \cdot \left(a_T(\alpha) \cdot n^2 + b_T(\alpha) \cdot n + c_T(\alpha)\right) \tag{1}$$

where:

C_H – water level coefficient [8],
$a_T(\alpha)$, $b_T(\alpha)$, $c_T(\alpha)$ – function coefficients approximated by a polynomial function of guide vanes angle [8].

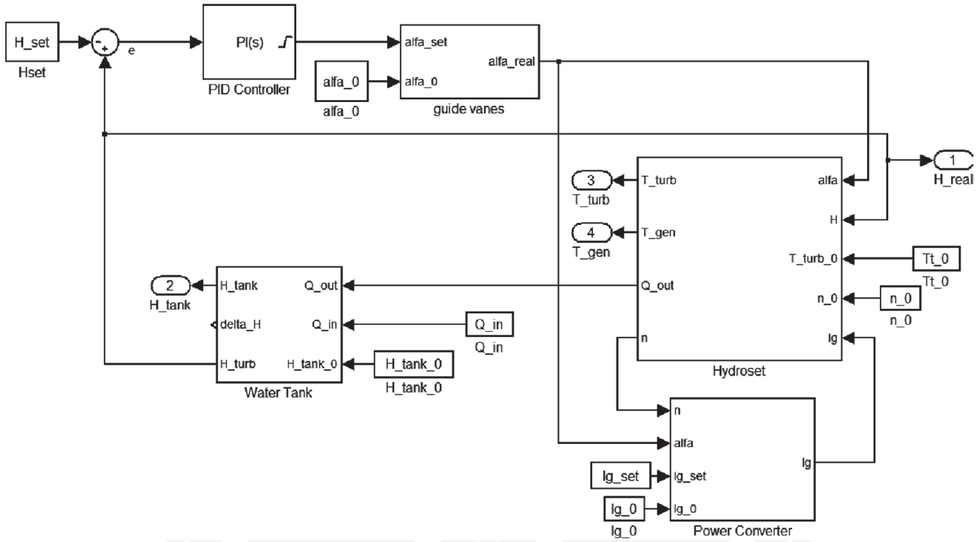


Fig. 2. Simulation model of SHP created in Matlab/Simulink

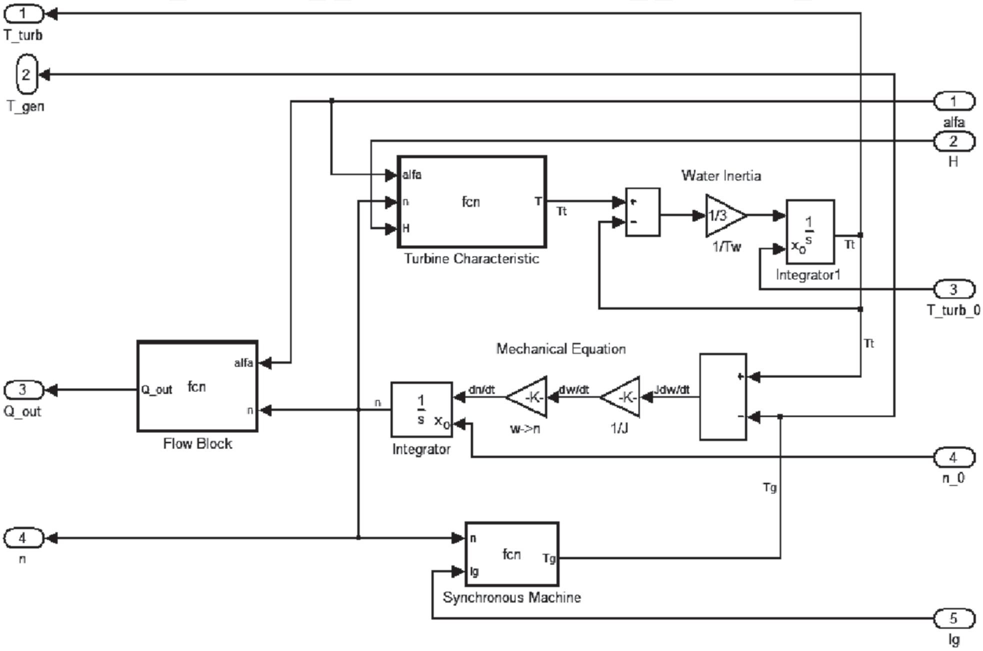


Fig. 3. Block diagram of Hydroset subsystem

The synchronous generator can be treated as a first order inertial object, where the generator armature current can be regarded as the system input, to which turbine torque is the system output. Taking into account linear relations between armature current and electromagnetic torque, the value of object gain is constant and independent on the generator speed.

The generator torque T_g and turbine torque T_t are compared in the mechanical equation from which the turbine speed n can be calculated. The parameter J is equal to the sum of the turbine and generator inertia.

$$J\frac{\mathrm{d}n}{\mathrm{d}t} = \frac{30}{\pi}\left(T_t - T_g\right) \tag{2}$$

The flow block calculates the water flow Q as a linear function of speed n with coefficients in the form of polynomial functions of angle:

$$Q = a_Q(\alpha)\cdot n + b_Q(\alpha) \tag{3}$$

All coefficients were calculated from the universal characteristic of the real propeller turbine (known as a hill chart) that presents efficiency isolines on a water flow-speed plane [9]. Dynamic behaviour of the turbine is caused by many elements, the most significant being the dynamic of the water mass. This time constant is a function of the water head and the volume of the inlet channel. The tests of real turbine operation allowed us to identify this parameter to be estimated at 3.5 seconds [9].

The PEU controls the generator electromagnetic torque T_g by its rms armature current I_g. The applied block (Power Converter) models the full-scale AC/DC/AC power converter consisting of: an uncontrolled rectifier; a DC-DC boost converter, which increases the DC voltage; the DC/AC converter with a DPC-SVM algorithm (Virtual Flux – Direct Power Control with SVM modulator) [4, 6]. The generator armature current corresponds to the rectifier DC current and is adjusted by the DC-DC boost converter. The time constant of the PEU is estimated to be about 1 second [8]. The efficiency of the PEU is sensitive to the value of the transferred power. It also changes depending on the generator speed but in a small range, thus, this variation has been neglected [6].

4. Optimizing control strategy

Due to the continuously changeable hydrological conditions, as well as the turbine features caused by silt deposited in the channels, algorithms based on the fixed settings and operational characteristics are ineffective [10]. For that reason, the special method using an optimizing algorithm has been implemented. The procedure starts from the non-optimal current value and tries to improve the conversion efficiency η by applying the gradient method.

$$\Delta I_g = k\cdot\frac{\partial\eta}{\partial I_g} \tag{4}$$

The quality coefficient (efficiency of the energy conversion system) is defined by the following formula:

$$\eta = \frac{P_s}{9.81 \cdot Q \cdot H} \tag{5}$$

where:
P_s – active power generated by the system,
Q – water flow through the turbine,
H – water head.

The control algorithm based on this quality coefficient is relatively fast and independent of the water flow regulator. However, it requires the actual value of the water flow which may be measured using very expensive devices. In some cases, these measurements are very inaccurate. One of the solutions to this problem is to simplify the quality coefficient. Let's assume that changes of the water flow of the river are slow compared to the regulation process (Q = const). Another assumption concerns the water level regulation. Let's activate the optimizing algorithm only after the PI regulator obtains the desired water level. In this situation, it is possible to write:

$$\frac{\partial \eta}{\partial I_g} \overset{Q,H=const}{=} \frac{\partial P_s}{\partial I_g} \tag{6}$$

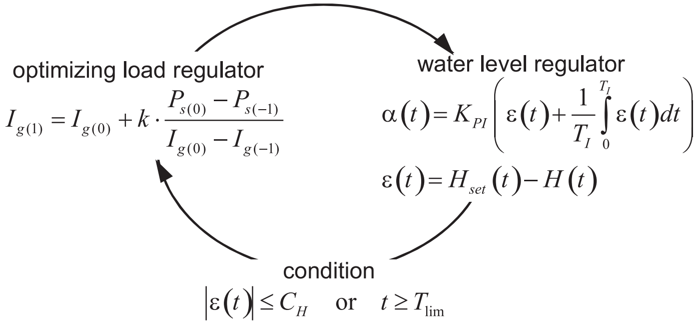
Using the discretization Euler method of an order one, the formula (4) with substitution (6) may be written as follows:

$$I_{g(1)} = I_{g(0)} + k \cdot \frac{P_{s(0)} - P_{s(-1)}}{I_{g(0)} - I_{g(-1)}} \tag{7}$$

where the subscript brackets indicate the step number of optimizing algorithm l.

The procedure (Fig. 4) changes the initial values of current I_g following the direction of the gradient components multiplied by a positive factor k. The next step of optimizing the regulator is activated only when the water level error is smaller than or is equal to the limit value C_H (constant water level assumption). This time interval T_s (called inter-optimizing period) may be different after each step due to the varying initial conditions. However, it should be relatively small compared to changes of the river water flow to satisfy the constant water flow assumption. This is the way that the time limit ($T_{\lim}$) was added. The example operation of the algorithm is presented in Fig. 5.

The simulated situation assumes the nominal water head and zero initial parameters. The water flow characterises a step change from 90% to 100% of nominal value in the 20th algorithm step. It can be noticed that the error value ε equals the limit value $C_H = 1 \cdot 10^{-5}$ in most of the periods. The rest of the periods have a higher error because they exceed the time limit $T_{\lim} = 1000$ s.



$$I_{g(1)} = I_{g(0)} + k \cdot \frac{P_{s(0)} - P_{s(-1)}}{I_{g(0)} - I_{g(-1)}}$$

$$\alpha(t) = K_{PI}\left(\varepsilon(t) + \frac{1}{T_I}\int_0^{T_I}\varepsilon(t)dt\right)$$

$$\varepsilon(t) = H_{set}(t) - H(t)$$

$$|\varepsilon(t)| \leq C_H \quad \text{or} \quad t \geq T_{\lim}$$

Fig. 4. Algorithm of control strategy

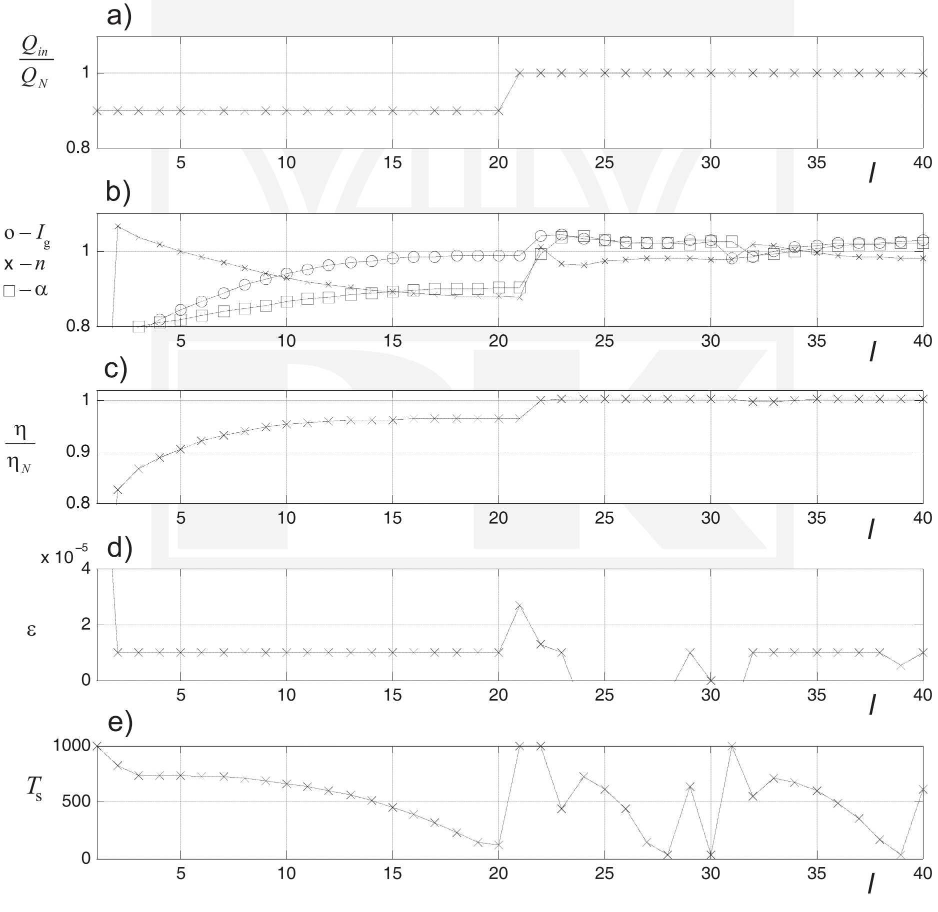


Fig. 5. Relative system state variables: a) water flow,, b) generator current (circle), speed (cross) and guide angle (square), c) total efficiency, d) regulator error, e) inter-optimizing period; for a certain algorithm step

Figure 6 presents the example inter-optimizing period between the 25th and 26th step of the optimizing algorithm. It is clearly visible that each step causes the impulse response of the system to the change of generator armature current.

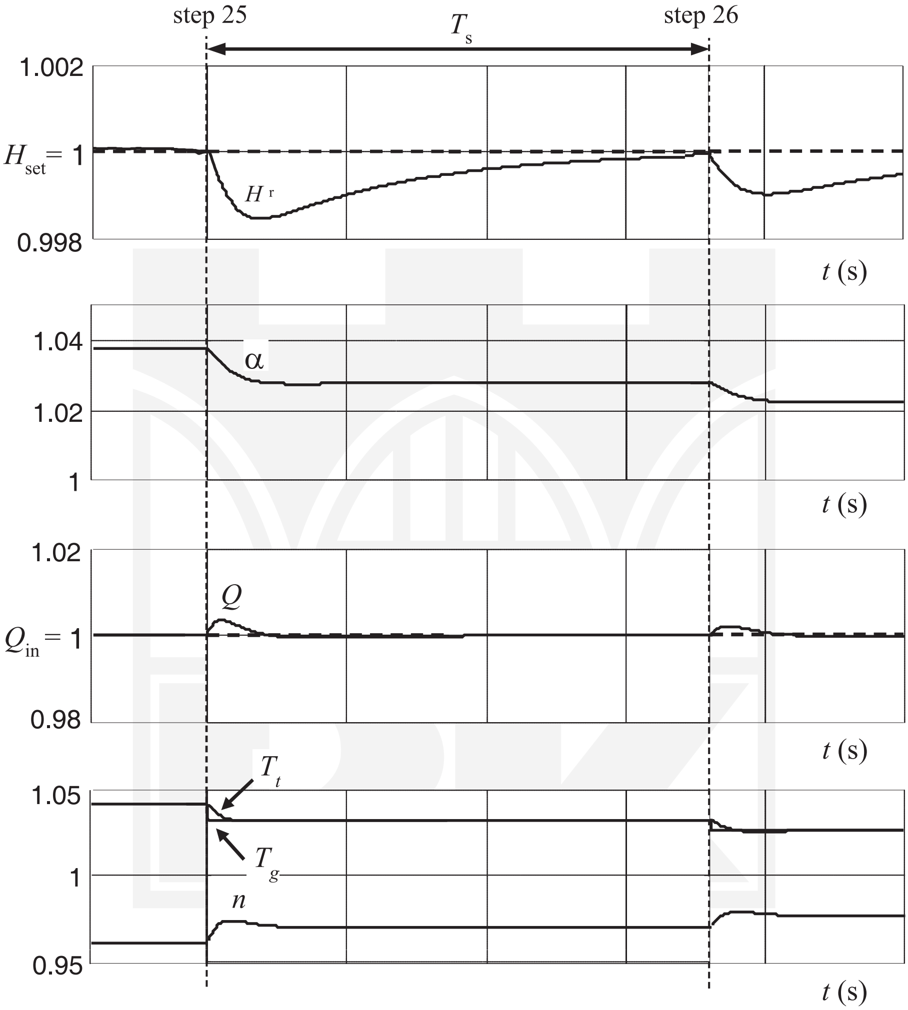


Fig. 6. Time domain system state variables during the example inter-optimizing period ($T_s = 660$ s) tuned by PI regulator

The optimizing method fulfils the main criterion of the control algorithm by obtaining the maximum efficiency of the whole system in the given hydrological conditions. This feature can be seen in Fig. 5c) and in the efficiency characteristic presented below (Fig. 7). The maximal efficiency is achieved after several algorithm steps. The continuous seeking process also provides optimal operation parameters after changes in the water flow value. This figure proves that the control algorithm maintains the constant water flow condition.

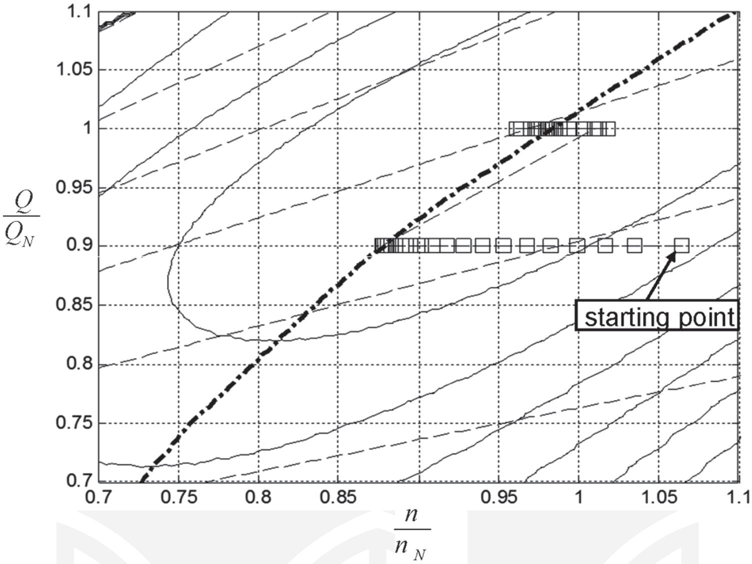


Fig. 7. Steady state algorithm steps (square markers) on the water flow – rotational speed plane (total efficiency isolines – solid line, guide angle lines – dashed line, maximal efficiency line – dash-dot line)

5. Summary

The changeable hydrological conditions and variable turbine parameters due to the ageing process as well as river pollution require adaptive control of 'run-of-the-river' plants. This paper presents the dedicated procedure based on the gradient method which tunes the generator armature current in order to obtain the highest possible efficiency. 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 a 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 also the global extreme.

The controller uses also the standard PI regulator which provides the desired upper water level. The introduced conditions defining the activation of the gradient procedure allow the quality function to be simplified. Due to this, water flow measurements (which are expensive and may be inaccurate) are not needed. This control algorithm can be easily implemented in the PLC controller with no installation of extra sensors.

The presented simulation results confirm the algorithm effectiveness and an application possibility on the real system.

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