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Small Hydropower Plant with variable speed PM generator

***Abstract**. This paper presents a new concept of a Small Hydropower Plant (SHP) which is based on a permanent magnet generator (PM generator) with a propeller turbine integrated with the generator rotor. The PM generator can work at a variable speed and therefore energy produced by the PM generator has to be converted by means of a power electronic unit to fit to the three-phase power grid parameters. The paper describes elements of the energy conversion system and it also presents the results of numerical calculations of this system working.*

***Streszczenie.** W artykule zaprezentowano nową koncepcję Małej Elektrowni Wodnej (MEW) opartej o zintegrowany z turbiną śmigłową generator synchroniczny z magnesami trwałymi. Generator pracuje ze zmienną prędkością obrotową, dlatego energia przez niego wytwarzana musi być przekształcona za pomocą układu energoelektronicznego do parametrów zgodnych z wymaganiami sieci trójfazowej. W artykule opisano elementy systemu wytwarzania i przekształcania energii oraz przedstawiono przykładowe wyniki obliczeń numerycznych pracy tego systemu. (**Mała Elektrownia Wodna z generatorem z magnesami trwałymi pracującym ze zmienną prędkością obrotową**).*

Keywords: propeller turbine, PM generator, PWM rectifier, small hydro power plant.
Słowa kluczowe: turbina śmigłowa, generator z magnesami trwałymi, prostownik z modulacją szerokości impulsów, mała elektrownia wodna.

Introduction

Small Hydro Power Plants (SHP) are widely used across the world. Electrical generators for today's small hydro power plants are designed for a constant rotation speed, which is kept by a speed controller often consisting of mechanical equipment. Changes of energy provided by water depend on water flow, which is very unreliable for small rivers in mountainous areas. Therefore, full efficiency can be achieved for power technology with generators working at ~~a~~ variable speed. So, in this paper a new solution of a PM generator integrated with a propeller turbine working at a variable speed is discussed [1].

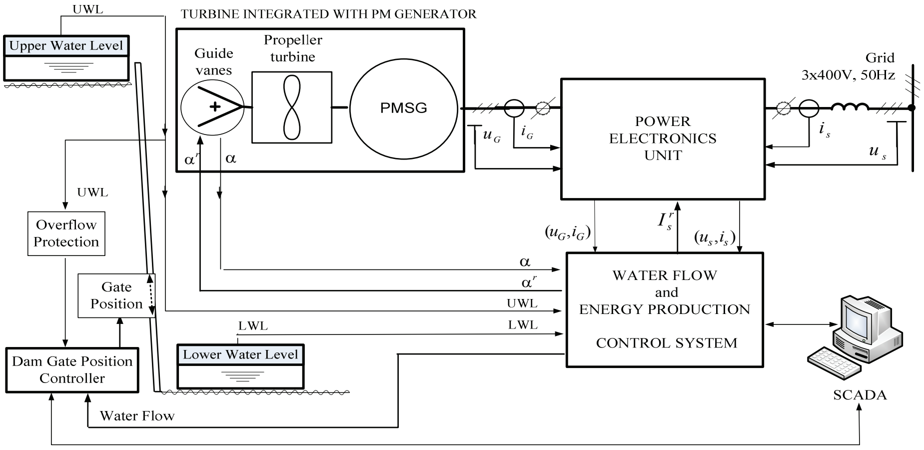

Fig.1. Energy conversion system of the Small Hydro Power Plant

It is assumed that the mechanical system for speed control via the change of the angle of turbine blades is removed. This leads to an essential simplification of mechanical systems but this in turn requires an application of a power electronic unit (PEU) in the energy conversion system (Fig.1). The rotation speed of the propeller turbine can be variable and for different values of the water flow it should be controlled by the PEU to ensure the highest possible efficiency [2]. Due to non-linear turbine characteristics it is necessary to formulate a suitable control algorithm for the whole system of energy conversion. Therefore, the PEU has to be applied not only to ensure the output frequency and voltages required by the power grid, but also to control the energy flow from the PM generator to the three-phase grid.

This paper presents a new concept for an experimental power station with the variable speed PM generator which is integrated with the propeller turbine (nominal data of the PM generator: $P_N = 30$ kW, $U_N = 500$ V, $I_N = 34{,}7$ A, $f = 50$ Hz, $n_N = 600$ rpm).

Turbine integrated with PM generator

The hydro-set is based on a tubular turbine construction where the working fluid changes pressure when it moves through the turbine, giving up its energy. Typical solutions utilize a shaft to transfer the torque from a turbine impeller to a synchronous or induction generator.

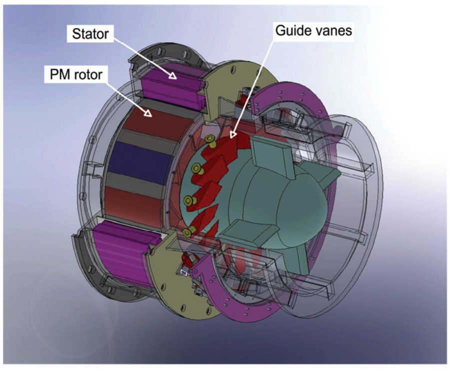

Fig.2. View of turbine integrated with PM generator

This new construction avoids the need of a shaft and a shaft guide system. The torque is transferred by a special external ring, being an integrated part of the turbine impeller. This system is simple, durable and reliable, therefore it does not require special service. Figure 2 shows a view of the complete hydro-set designed by CEDI [3]. Permanent magnets are mounted on the external surface of the external ring [4] and spaces between magnets are filled with non-magnetic epoxy resin (Fig.3). Both the internal stator surface and the external rotor surface are protected by waterproof tubes. Water which flows through the gap between the rotor and the stator additionally ensures generator self-cooling system of stator windings and permanent magnets. Guide vanes direct the water to the turbine vanes. The water flow acts on the runner blades (Fig.3), causing runner rotation. The guide vanes can be adjusted to allow efficient turbine operation for a wide range of water flow conditions and continuous energy production with the highest possible efficiency of the whole system.

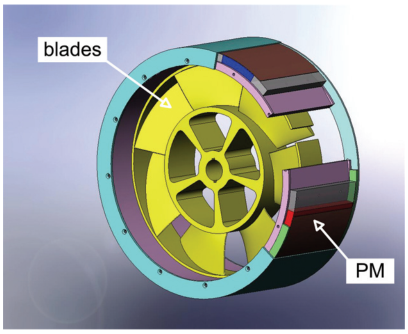

Fig.3. Location of permanent magnets on the rotor

Changes of the guide vanes angle α can be caused by hydrological conditions or by a certain decreasing of energy consumption in the three-phase grid. It requires a certain reduction of the energy production. This angle is equal to 90 degrees if the guide vanes are fully open and it equals zero when the hydro-set inlet is closed. In consequence the control system of the guide vanes should be an integral part of whole energy conversion system.

Figure 4 presents relations $P_m = f(\omega)$ between the PM generator power and the rotation speed of the hydro-set in case of constant head H (where H is a difference between upper and lower water levels) for some chosen angles of the guide vanes.

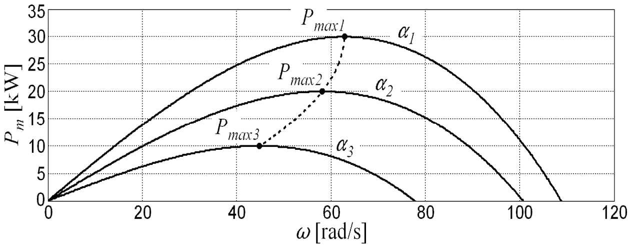

Fig.4. Relations between the PM generator power P_m and the rotation speed ω of the hydro-set for some chosen guide vanes angles α: $\alpha_1 = \alpha_{max} = 90^0$, $\alpha_1 > \alpha_2 > \alpha_3$ for constant head

The PM generator should be specially designed for the sake of turbine dimensions. Its design should ensure water protection, proper parameters of this generator, especially its internal reactance X_d and electromotive force EMF. The mathematical model of the PM generator which assuming the base-harmonic of MMF and magnetic linearity is following:

$$\left(\begin{bmatrix} L_{\sigma s} & M_{\sigma s} & M_{\sigma s} \\ M_{\sigma s} & L_{\sigma s} & M_{\sigma s} \\ M_{\sigma s} & M_{\sigma s} & L_{\sigma s} \end{bmatrix} + \begin{bmatrix} L_s & M_s & M_s \\ M_s & L_s & M_s \\ M_s & M_s & L_s \end{bmatrix}\right) \frac{d}{dt}\begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} - \tag{1}$$

$$- p\omega\,\psi_m \begin{bmatrix} sin(p\omega t) \\ sin(p\omega t - {}^{2\pi}\!/_{3}) \\ sin(p\omega t - {}^{4\pi}\!/_{3}) \end{bmatrix} = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} - \begin{bmatrix} R_s & & \\ & R_s & \\ & & R_s \end{bmatrix}\begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix}$$

The results of field computation and design formulas allowed to approximate PM flux leakage of windings and inductances for experimental PM generator:

L_s = 1,41 mH, $M_s \approx -0{,}5\ L_s = -0{,}69$ mH,
$L_{\sigma s}$ = 0,99 mH, $M_{\sigma s} = -0{,}32$ mH,
Ψ_m = 1,36 Wb, R_s = 0,99 Ω
L_d = 3,42 mH, X_d = 1,07 Ω.

Water flow and energy production control system

The fundamental purpose of the proposed control strategy is to transfer maximum possible amount of energy, produced by the hydro-set, to the power grid. The Energy Production Controller and Turbine Water Flow Controller (Fig.5) ensure correct operation of the whole energy conversion system during changes of working conditions.

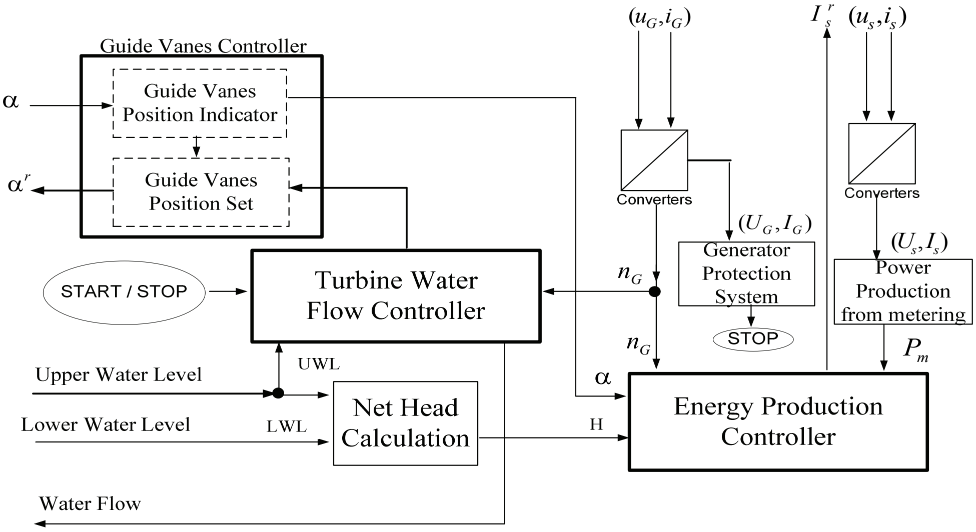

Fig.5. Water flow and power production control system

The amount of energy, which can be produced, depends on hydrological conditions. The Turbine Water Flow Controller decides about the water stream flowing through the turbine by setting proper angle α of guide vanes on the basis upper water level UWL which should be constant.

The non-linear characteristics of the hydro-set (turbine integrated with PM generator) should be stored in a memory of the Energy Production Controller and implemented in the control algorithm. The energy which can be transferred to the three-phase grid is calculated on the basis of the turbine characteristic $P_m = f(\omega)$ (Fig.4) for the current position of the guide vanes and then, the controller determines the reference current I_s^r for PEU. Changes of net head additionally modify the maximum value of power on characteristic $P_m = f(\omega)$ according to following formula:

$$P_{max} \approx (\omega)^3 (H)^{3/2} \tag{2}$$

It is necessary to underline that the guide vanes angle α changes much slower with respect to electric quantities. So, this angle can be treated as a constant value in the PEU control system.

Power electronic unit (PEU)

The RMS voltage and the frequency of the PM generator can change about -60% ÷ +30% with respect to the nominal values. It means that the hydro-set operates at a variable speed. In the proposed energy conversion system energy produced by the generator is converted into direct current energy (DC link), and then it is transferred to power grid (3x400 V, 50 Hz) via voltage source inverter [5]. In practice, two schemes of energy conversion are used, especially with reference to wind turbine.

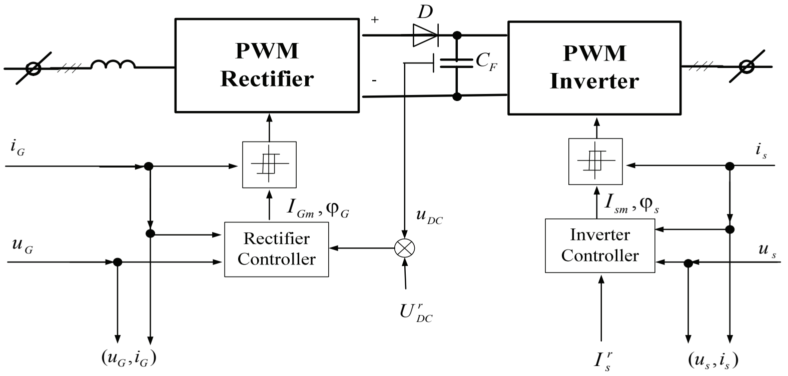

Fig.6. Power electronic unit with the PWM rectifier

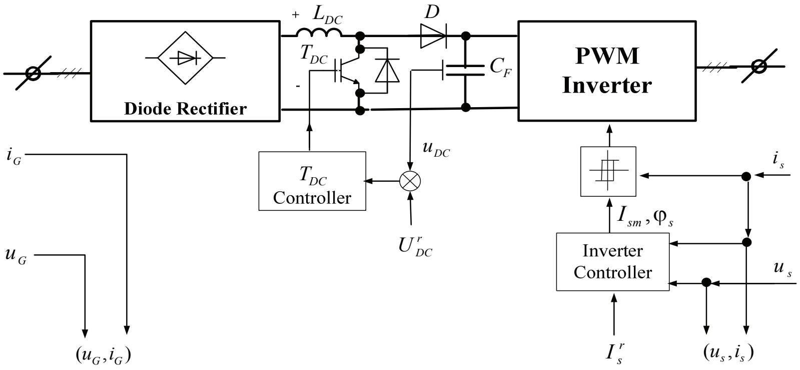

Fig.7. Power electronic unit with the diode rectifier and the DC-DC boost converter

In the first one (Fig.6) a PWM rectifier is applied. In this case the PM generator currents have almost sinusoidal shapes. The second one (Fig.7) is based on a diode rectifier and a DC-DC boost converter which can increase voltage in the DC link. In both cases, the voltage source inverter is coupled with the power grid using a transformer or induction chokes. The second method of energy conversion is not recommended because the diode rectifier can cause significant distortion of the generator currents with respect to sinusoidal shapes. As a result of this distortion the generator torque contains an alternating component with relatively high amplitude [6]. It is a certain disadvantage because the presence of this alternating component of the generator torque can badly influence durability and reliability of the hydro-set.

PEU control strategy

The main task of the PEU control strategy is to decrease the THD factor of the current flowing to the three-phase grid. The transistors of the voltage source inverter are controlled according to the given sinusoidal current signals using hysteresis controllers. The amplitude I_{sm} of these signals is determined by the power value which can be transferred to the three-phase grid and by the actual RMS voltage of the power grid. It is assumed that the phase shift between the given current signals and appropriate phase voltages of the three-phase grid is almost equal to zero (unity power factor). The transistors of the PWM rectifier are controlled similarly as in the PWM inverter. The amplitude I_{Gm} of the given current signals should have a value which permits to keep voltage in the DC link on the assumed level (about 800 V). These current signals are synchronized with the output voltages of the PM generator. In general, phase shifts between voltages and currents of both converters are equal to zero, although, these shifts can be changed. If the RMS voltage of the three-phase grid achieves the maximum value (for example as a result of lower consumption in the power grid) then the amplitude of the given current signals of the PWM inverter decreases. It determines a certain change of the guide vanes angle α. In this case, according to the characteristics $P_m = f(\omega)$ (Fig.4), the energy produced by the hydro-set is reduced.

Numerical calculations were made for the selected working cases, which differ due to changeable hydrological conditions or due to voltage changes in the three-phase power grid. Changes of hydrological conditions influence the rotational speed of the hydro-set. Therefore, in numerical calculations it is necessary to take into account the relation between the generator torque and its rotational speed. On the basis of the characteristics $P_m = f(\omega)$ (Fig.4) this relation can be written as follows:

$$(3) \qquad T_m(\omega) = T_{max}\left[1-\left(\frac{\omega}{\omega_{max}}\right)^2\right]$$

where both T_{max} and ω_{max} depend on the guide vanes angle α.

The chosen waveforms in the energy conversion system with the PWM rectifier in a steady state for certain working conditions are shown in Figure 8. It was assumed that the guide vanes angle α is lesser than α_{max} and it was equal to 30°. In this case the generator output power decreased to 9 kW. According to the characteristic $P_m = f(\omega)$, at the optimal working point, the generator rotates at 432 rpm and its voltages and currents have frequency about 36 Hz. Due to the application of the hysteresis controllers the generator and the PWM inverter currents contain certain higher harmonics, but the THD factor of these currents is lesser than 6 percent. It is worth to underline that frequencies of the transistor switching in the PWM rectifier and converter are not constant and they depend on the assumed hysteresis width. In the presented case these frequencies change between 2 kHz and 3 kHz.

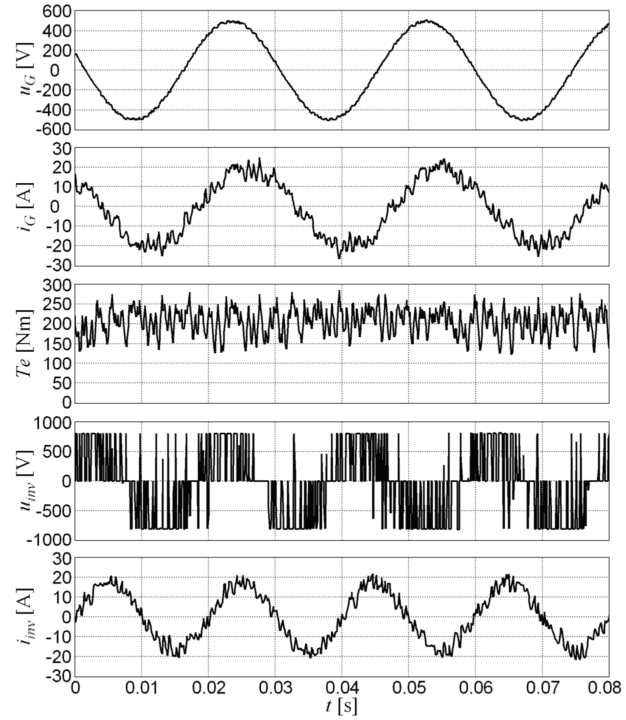

Fig.8. Waveforms in the energy conversion system with the PWM rectifier in steady state for $\alpha = 30°$: u_G, i_G, T_e – voltage, current and torque of the PM generator, u_{inv}, i_{inv} – voltage and current of the PWM voltage source inverter

Figure 9 presents chosen waveforms when the guide vanes angle α is being changed from 90 to about 45 degrees. In order to show this energy conversion system working it was assumed that the hydro-set moment of inertia is 15 times lesser than the real value.

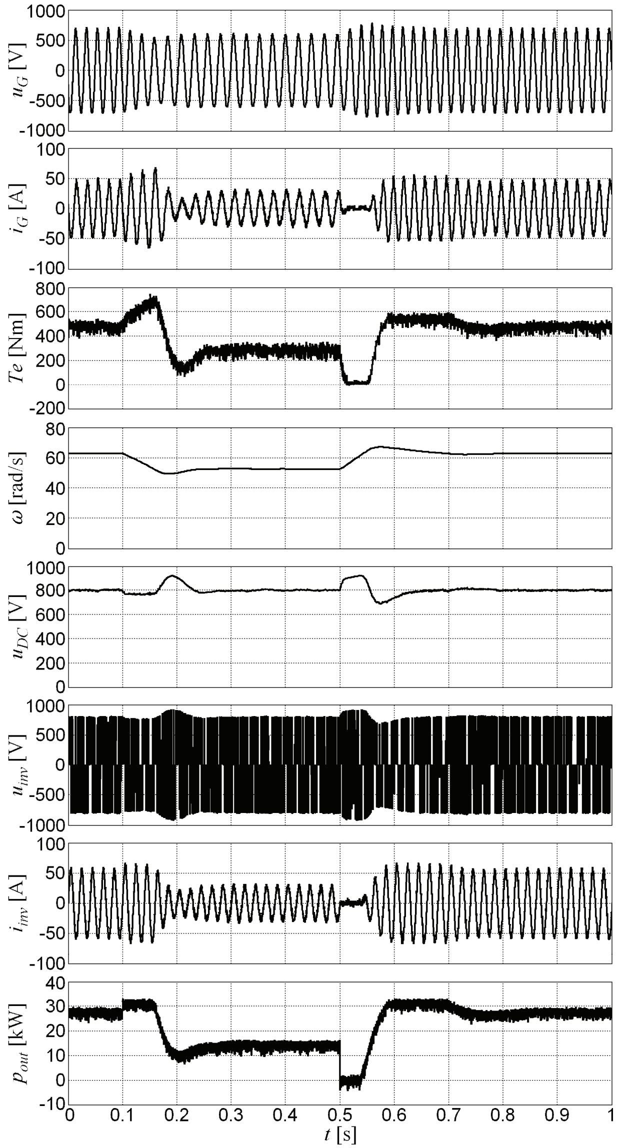

Fig.9. Waveforms in the energy conversion system with the PWM rectifier during the change of the guide vanes angle α: ω – generator rotation speed, u_{DC} –voltage in the DC link, P_{out} –power given to the three-phase grid

The maximum energy amount produced by the PM generator decreases if the guide vanes angle α is lesser than 90 degrees according to the characteristics $P_m = f(\omega)$ (Fig.4). A short increasing of the power given to the three-phase grid (short increasing of currents) causes that the generator achieves the new rotation speed value quickly. In the steady state in new working conditions (the guide vanes angle α is lesser than 90 degrees) the current amplitudes are lesser than previously. If the guide vanes are full open again (α is equal to 90 degrees) then a short limiting of power given to the three-phase grid causes that the generator rotation speed increases quickly. It is necessary to stress that waveform shapes depend on controller settings in the energy conversion system.

The voltage of the three-phase grid can change significantly faster than the guide vanes angle. Very often an increase of the grid voltage occurs when a high-power load is turned off (power consumption in the three-phase grid is lesser than usually). Figure 10 presents the chosen waveforms for this working case. If the grid voltage achieves a given maximum admissible value then the amplitude of the PWM inverter current has to be reduced. Consequently, the current amplitude of the PM generator has to be decreased. At the same time the guide vanes angle α should be suitably adjusted, due to the significant decrease of the energy transferred to the grid, otherwise the generator speed can rise significantly.

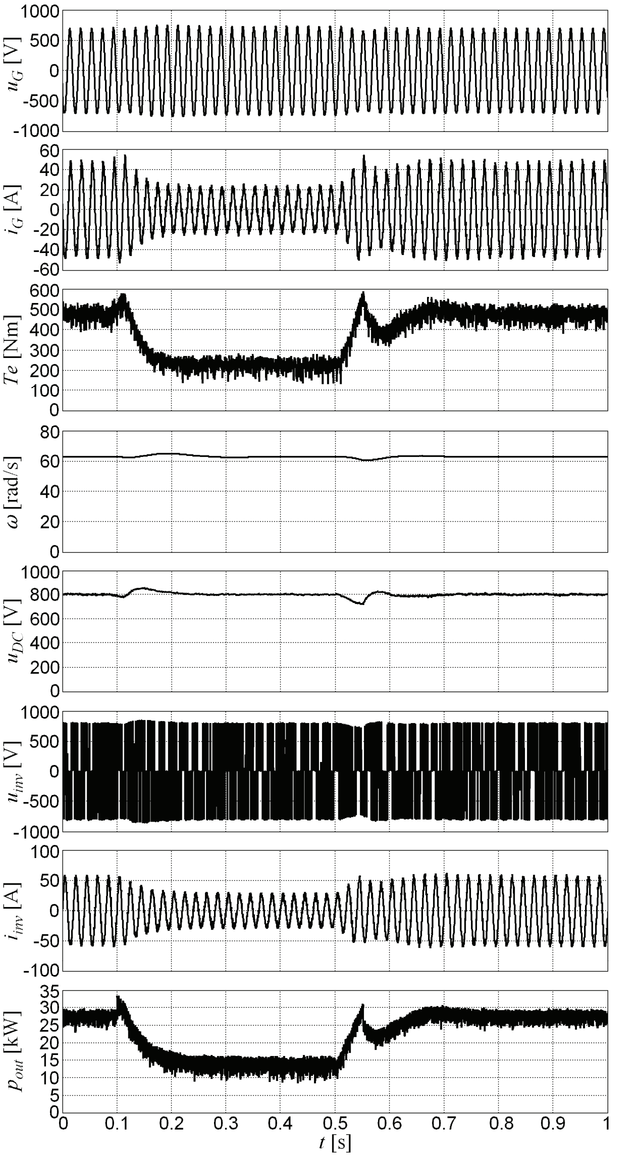

Fig.10. Waveforms in the energy conversion system with the PWM rectifier during changes of power consumption in the three-phase grid

It was earlier remarked that energy produced by the PM generator can be converted in the power electronic system with the diode rectifier and the DC-DC boost converter. Figure 11 presents chosen waveforms in this energy conversion system for the same guide vanes angle α as in Figure 8. The generator current has non-sinusoidal shape. It is the reason that the generator torque includes an alternating component, which has significantly higher value in respect to the energy conversion system with the PWM rectifier. It can significantly lower durability and reliability of the hydro-set.

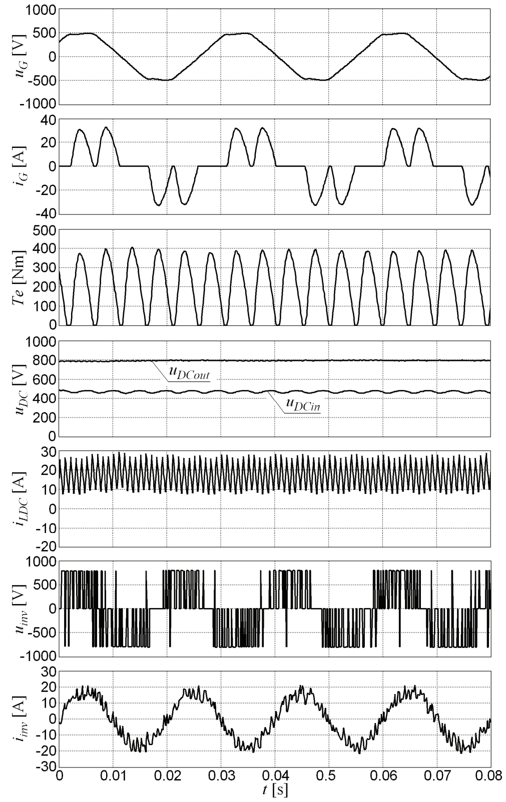

Fig.11. Waveforms in the energy conversion system with the diode rectifier in steady state: u_{DCin}, u_{DCout} – input and output voltage in the DC link respectively, i_{LDC} – current of choke L_{DC}

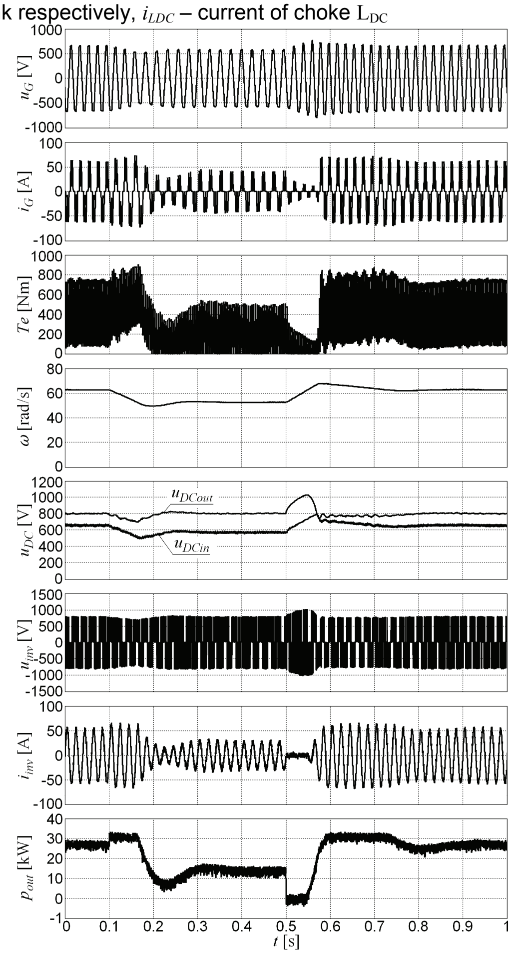

Fig.12. Waveforms in the energy conversion system with the diode rectifier during the change of the guide vanes angle α

During changes of working conditions the energy conversion system with the diode rectifier operates similarly to the system with PWM rectifier. Figure 12 presents chosen waveforms in the energy conversion system with the diode rectifier and the DC-DC boost converter when the guide vanes angle α is being changed from 90 to about 45 degrees. Similar waveforms in the system with PWM rectifier for the same working conditions are shown in Figure 9. The output voltage of the diode rectifier is increased to the assumed input value of the PWM inverter. It is necessary to stress once again that the generator torque contains a significant alternating component.

Conclusions

The described hydro-set has some advantages in comparison to classical hydro-generators with Kaplan turbines. The mechanical part of that hydro-set is essentially simplified because a shaft does not exist, a transmission gear is not necessary and a blades position control system is eliminated. All these facts have significant influence on investment costs and reliability of the whole Small Hydro Power plant.

Unlike energy conversion systems in windmill plants the control algorithm presented in this paper is relatively simple. The generator and PWM inverter currents are directly shaped by means of hysteresis controllers. Thank to this, the THD factor of these currents is satisfactorily low. The proposed control algorithm ensures correct operation of the whole energy conversion system in different working conditions.

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