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Grid-tied Converter with Intermediate Storage Chain for Multipurpose Applications

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Introduction

Development of all scales stand-alone and grid-connected renewable energy power systems, power storage systems, hybrid and purely electrical vehicles is closely related with such power electronics equipment as autonomous and grid-tied inverters, DC/DC converters, maximum power point trackers, battery chargers and other. Numbers of installations in the mentioned energy sectors are growing worldwide year by year. Rates of the solar and wind power development in Germany during the last time are shown correspondingly in Fig. 1 and Fig. 2.

According to the White Paper of EU, initially it was set a target for the EU to reach the installed cumulative capacity of solar power 3000 MWp till the year 2010 (for the comparison it can be noted that capacity of Ignalina Nuclear PP before the decommissioning was 1300 MW).

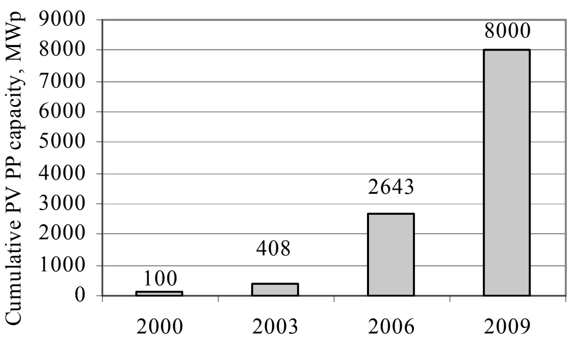

Fig. 1. Progress of installed cumulative solar power capacity in Germany during the period 2000-2009

However, in reality development of the solar power systems was much more rapid and in 2010 Germany alone this target was exceeded 3 times (www.jrc.ec.europa.eu).

Similar progress is achieved in the process of wind power development in the world, including Germany, which here is a leading country over a long time (Fig. 2).

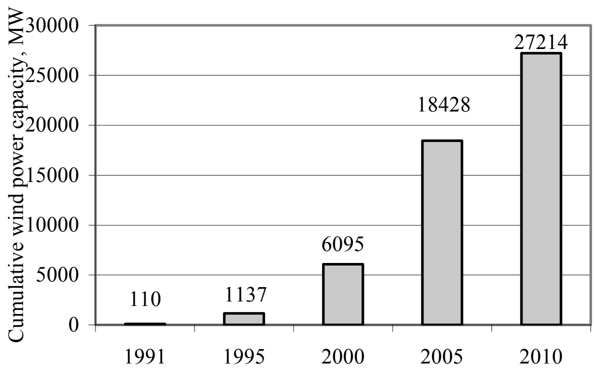

Fig. 2. Progress of installed cumulative wind power capacity in Germany during the period 1991-2010

Small renewable power systems and distributed power generation are becoming more and more important [1, 2, 3]. Rapid development of renewable power systems, power storage systems and electric vehicles enhanced role of the power electronics in sector of power engineering and raised accelerated development of the power electronics industry.

Object of research

Usually grid-tied inverters are specialized and designed for one purpose, e.g., for the solar power system, wind power system and so on. Scheme of the proposed grid-tied converter has universal application. The converter under research includes the grid-tied inverter and one or more (practically unlimited number) of DC/DC converters containing the intermediate DC power converting circuits with power storage elements. It can be used for any power source having either stable or unstable (varying) DC voltage in the input of the proposed converter independently on the origin of the DC power source, including the power sources based on renewables. Besides, this converter operating together with control system is able to perform maximum power point tracking function in the solar power system depending on solar irradiance or in the wind power system depending on the wind speed. The proposed converter is also suitable for operating with several wind turbines or several very different DC power sources of various types and different capacities [4]. It can be the wind turbine (WT), hydro turbine, PV array, fuel cells (FC), flow battery or any other DC power source, which can be connected to supply electric power into the grid over the same mutual inverter. In this case number of intermediate power storage inductances has to be equal to the number of the DC power sources. Meanwhile power storage capacitor or storage battery can be used one – mutual.

Results of research of small scale grid-tied hybrid PV-WT power system with mutual inverter operation are presented in this paper. Simplified electrical scheme of the researched system is shown in Fig. 3. Total installed capacity of this system is 8.5 kW (PV system – 5 kW and WT – 3.5 kW). Single phase grid-tied bridge inverter with mutual power storage capacitor C_k is used for power supply into the grid. This scheme of power conversion allows controlling of PV and WT systems independently with different algorithms permitting their optimal exploitation. As it is shown in Fig. 3, control system of the small hybrid power plant consists of three subsystems: the PV section (units RCF, CRS, SCPF1 and current controller W_{cc1}); the WT section (units TSF, CRS, SCPF2 and current controller W_{cc2}) and the grid inverter‘s section IPF. PV and WT sections of control system are operating in order to ensure the maximum available power production at any values of solar irradiance and wind speed.

The control section of PV system is comprised on basis of previous works of authors [4]. Two variables are measured here: the irradiance E and output current of the PV array I_{s1}. The necessary load current of the PV array I_{rs1} is calculated by using the irradiance E in RCF unit and the reference signal of load current U_{rs1} in CRS unit. The load current signal U_{s1} is calculated using actual load current I_{s1}. The error signal is passed to the current controller W_{cc1}.

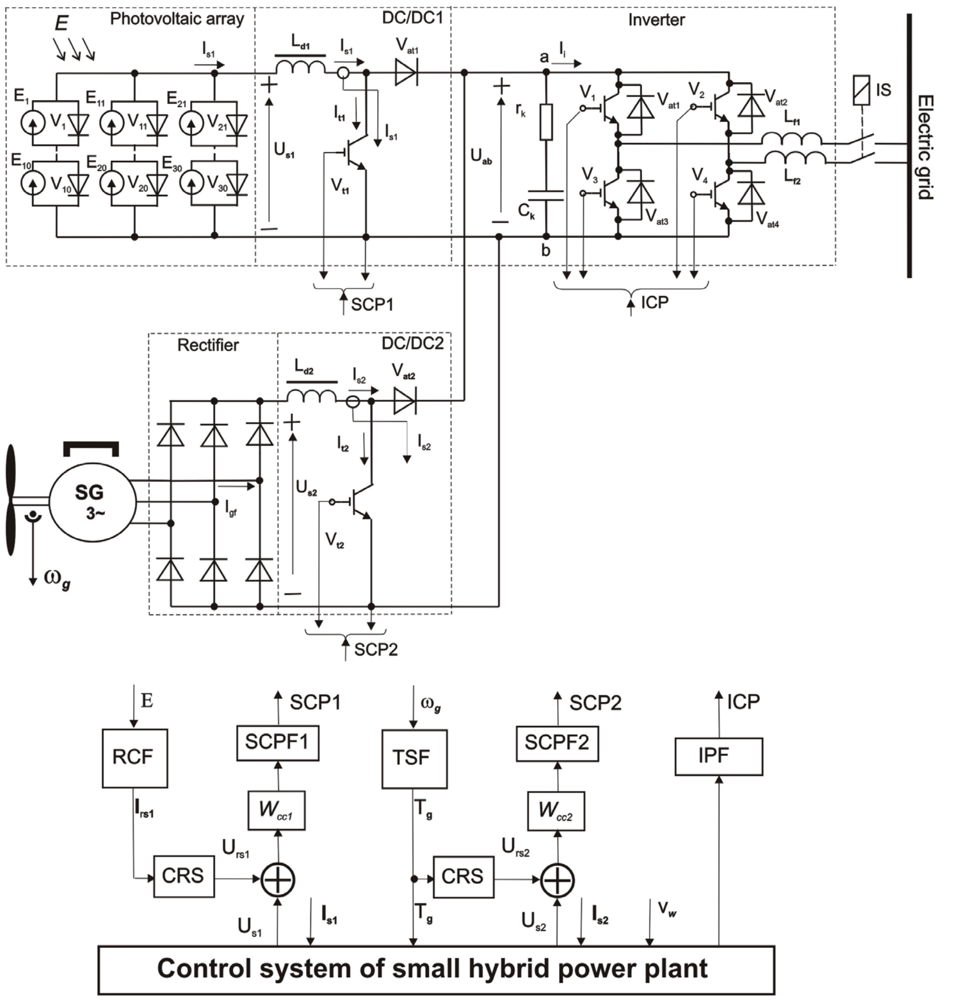

Fig. 3. Simplified electrical scheme of the innovative small scale grid-tied hybrid PV–WT power system with mutual converter

Output signal of the controller is passed to the former of shorting transistor‘s control pulses SCPF1 where control pulse of necessary width is formed for the transistor V_{t1}. The PI controller is used in the control system and therefore static error of the load current regulation is equal to zero.

The WT‘s control section is comprised on basis of previous works of authors as well [5]. In this case three variable parameters are measured: the angular velocity of WT ω_g, the wind speed v_w and the load current of the WT‘s generator I_{s2}. The WT‘s control section operates in the same way as the control section of PV system.

Mathematical model of the researched system

MATLAB/SIMULINK model is created by using SymPowerSystems library. Overall model diagram of the researched small-scale hybrid solar-wind power system is presented in Fig. 4.

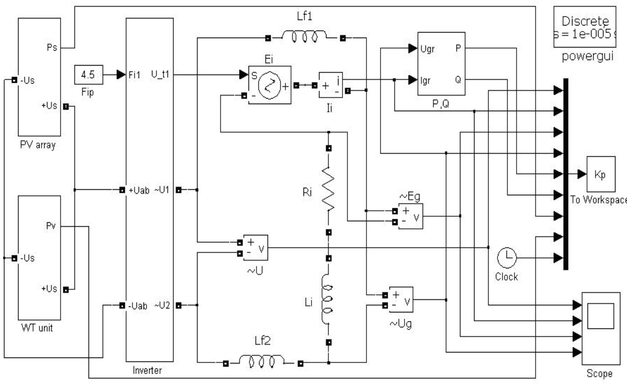

Fig. 4. Model diagram of the small hybrid power plant

This model consists of the following units: “PV array”, “WT unit”, the inverter, the grid voltage source “E$_i$”, the active resistance and inductance of the grid “Ir” and “L$_i$”, inductances of the filter “L$_{f1}$” and “L$_{f2}$”, measurement units for active and reactive power P, Q and the measurement units for voltage and current.

Model of the PV system is shown in Fig. 5. It consists of the following units: “PV”, controller of current „Controller“, converter of the current signal “U_is”, adjustable voltage source “Us”, choke “Ld, Rd”, shorting transistor “Vt1”, disjunctive diode “Vat” and measurement units for voltage and current.

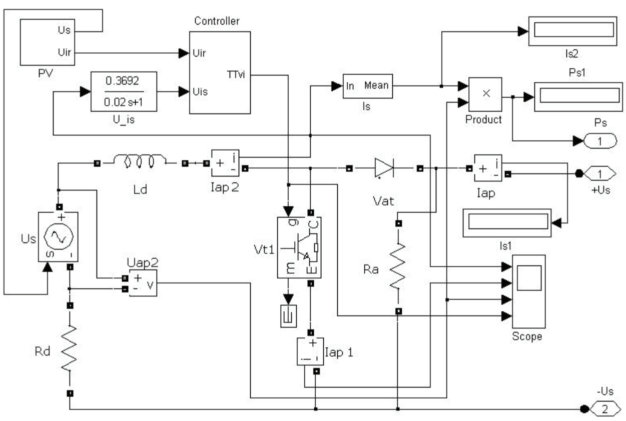

Fig. 5. Model diagram of the PV unit

Control voltage for the “Us” unit is calculated in the “PV” unit [4]. Therefore its output voltage is always equal to the voltage of PV array optimal operation point (MPP). DC/DC converter is operating according to the pulse-width modulation (PWM) principle. Signal of the direct current measured by the device “Iap2” is passed via current signal converter to the current controller (“Controller”). Current controller forms control signal depending on the error of current signal. The control signal is passed to the control scheme of shorting transistor “Vt1”, which is integrated into the unit of “Controller”. This scheme forms control pulses, which width changes in order to reduce current signal error. Unit “Is” calculates medium value of the PV array‘s current, which is indicated by the device “Is2”. Device “Ps1” shows the medium power of the PV array.

Model of the WT system is shown in Fig. 6. It consists of the following units: the wind turbine “WT1”, the current controller “Controller”, the converter of current signal “U_is”, the synchronous generator with permanent magnets “PMSG”, the rectifier of PMSG current “Rectifier”, the choke “Ld, Rd”, the shorting transistor “Vt2”, the disjunctive diode “Vat” and the measurement units for voltage and current.

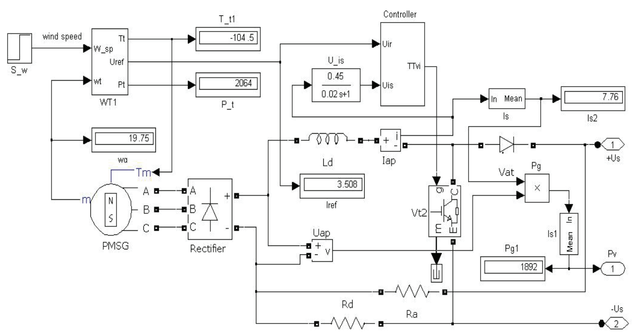

Fig. 6. Model diagram of the WT unit

Permanent magnet synchronous generator (PMSG) capacity of 3.5 kW is rotated by the wind turbine of horizontal axis. Mathematical description of the WT is based on its power curve, which is given in the wind turbine’s technical documentation. Polynomial of the fifth order is used for the approximation of the power curve on purpose to have a sufficient adequacy of the mathematical description. Thus, the power curve of horizontal wind turbine mathematically can be described by (1)

$$P_t = -0{,}0149 \cdot v_w^5 + 1{,}0791 \cdot v_w^4 - 27{,}8347 \cdot v_w^3 + \\ + 288{,}9708 \cdot v_w^2 - 720{,}8552 \cdot v_w + 157{,}4845. \qquad (1)$$

Model of the generator‘s current controller is analogous to the current controller of PV system. DC/DC converter of the WT‘s subsystem operates in the same way as described above. Reference signal U_{rs2} for the WT current regulator is calculated by using these formulas:

$$T_m = \frac{P_t}{\omega_g}, \qquad (2)$$

$$k_m = \frac{T_N}{I_{dN}}, \qquad (3)$$

$$U_{rs2} = \frac{k_{ug}.T_m}{k_m}, \qquad (4)$$

here k_{ug} – coefficient of the converter for current reference signal conversion into the voltage signal; k_m – coefficient of the generator torque; ω_g – angular velocity of the generator; T_N – rated capacity of the generator; I_{dN} – rated rectified current of the generator.

Dependence of generator‘s angular velocity on the WT‘s capacity is found using its technical documentation (Fig. 7).

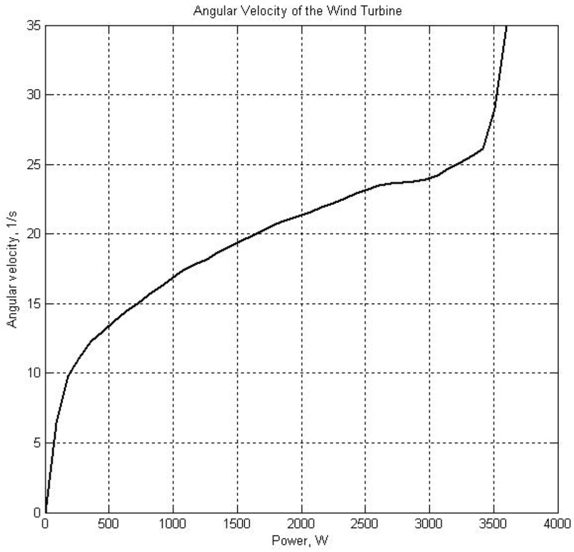

Fig. 7. Dependence of generator‘s angular velocity on the WT‘s capacity

Model of the wind turbine itself WT1 is presented in Fig 8. Unit “Pt1” here calculates the power developed by the wind turbine P_t depending on the wind speed “W_sp” (according to equation 1). Torque of the wind turbine T_m is calculated through the division of the power P_t by the angular velocity of the wind turbine‘s generator ω_g (according to (2)).

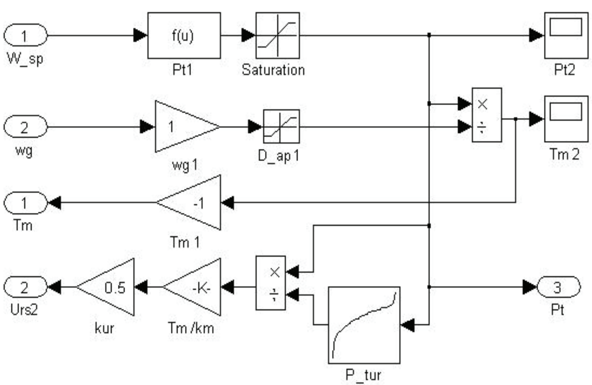

Fig. 8. Wind turbine‘s mathematical model *WT1*

The lower branch of this mathematical model is used for calculation of the current reference signal “Urs2” according formulas (2÷4). Maximum value of the reference signal depends on the control scheme of DC/DC converter. In our case it can not exceed 5 V at maximum value of the current.

Revised and more accurate estimation of PMSG mathematical model is used in this paper. Well known in theory of electric machines mathematical description using the system of coordinates linked with the rotating inductor is used here. It is considered that constant magnetic field of inductor creates a sinusoidal flux in the stator of generator. The following mathematical expressions deduced for the *d-q* system of coordinates are used here:

$$\begin{cases} \dfrac{di_d}{dt} = \dfrac{1}{L_d}u_d - \dfrac{R_s}{L_d}i_d + \dfrac{L_q}{L_d}p\omega_g i_q, \\ \dfrac{di_q}{dt} = \dfrac{1}{L_q}u_q - \dfrac{R_s}{L_q}i_q - \dfrac{L_d}{L_q}p\omega_g i_d - \dfrac{\lambda p \omega_g}{L_q}, \\ T_e = \dfrac{3}{2}p[\lambda i_q + \left(L_d - L_q\right)i_d i_q], \end{cases} \qquad (5)$$

here u_q, u_d – q and d axis voltages; i_q, i_d – q and d axis currents; L_q, L_d – q and d axis inductances; R_s – resistance of the stator windings; ω_g – angular velocity of the rotor; λ – amplitude of the flux induced by the permanent magnets of the rotor in the stator phases; p – number of pole pairs; T_e – electromagnetic torque.

Mechanical system of the model can be described as follows:

$$\begin{cases} \dfrac{d\omega_g}{dt} = \dfrac{1}{J_\Sigma}\left(T_e - F\omega_r - T_m\right), \\ \dfrac{d\theta}{dt} = \omega_g, \end{cases} \qquad (6)$$

here J_Σ – combined inertia of rotor and load; F – combined viscous friction of rotor and load; θ – rotor angular position; T_m – shaft mechanical torque.

The amplitude of the flux λ induced by the permanent magnets of the rotor in the stator phases can be calculated as follows [6]

$$\lambda = \frac{\sqrt{(2/3)} \cdot U_{gl}}{p\omega_N}, \qquad (7)$$

here U_{gl} – no load line-to-line rms voltage of the generator while it is driven trough the shaft at a rated angular velocity; ω_N – rated angular velocity of the generator.

Scheme of inverter model is presented in Fig. 9. Power circuit consists of the single phase bridge inverter based on the IGBT power transistors with disjunctive diodes “V1÷V4” and power storage capacitor “Ck”. Resistor *Rk* has the value of the active resistance of storage circuit.

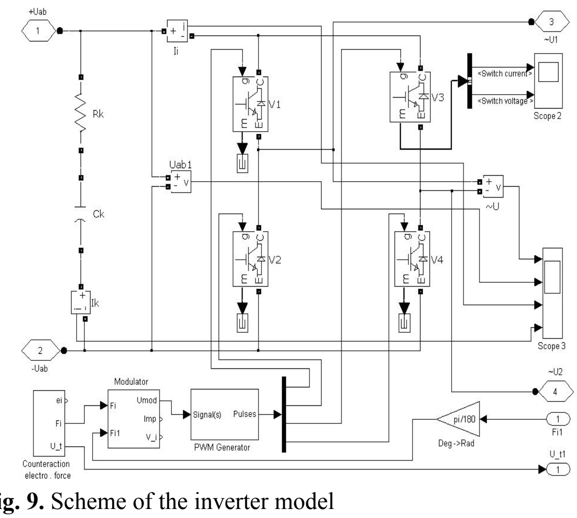

Fig. 9. Scheme of the inverter model

Units “Ii“ and “Ik“ measures correspondingly the currents of inverted and storage circuits. Units “Uab1” and “~U” are correspondingly the rectified voltages of inverter terminals and the output voltage of inverter. The part of inverter control system is corresponded by units “Counteraction electro force“, “Modulator“ and “PWM Generator“, which are described in previous papers of authors [4]. Input “Fi1” of unit “Modulator“ is used for the variations of modulation voltage phase what is applied for the control of reactive power flows taking place between the inverter and electric grid.

Results of the research

The main target of research was analysing of operation quality of small-scale hybrid power system with mutual inverter. Mathematic model of grid-tied solar-wind power system was elaborated for this purpose. The main results of simulation are presented below in Fig. 10 ÷ Fig. 12. Fig. 10 illustrates operation of the grid inverter dependently on variations of solar irradiance and wind speed, which often take place in natural conditions. We assumed a jump down of solar irradiance *E* at the time 3 s, Respond of the researched system is decrease of the inverter‘s output voltage, the inverted current, the inverted active power and, especially, the inverted reactive power.

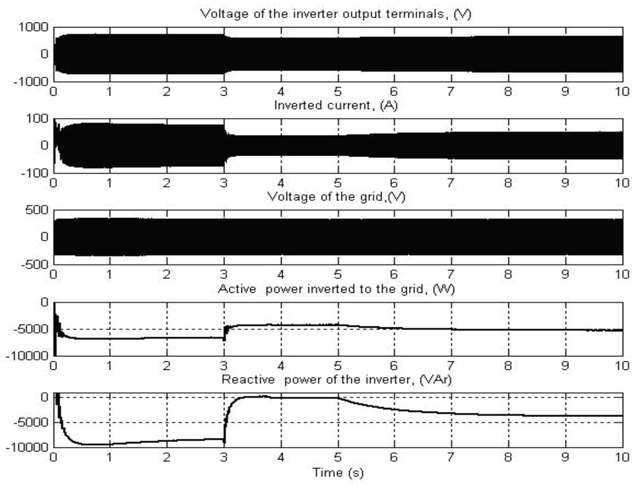

Fig. 10. Curves of the small hybrid power plant parameters versus time at the jumps of solar irradiance and wind velocity v_w (*E* jump from 1000 to 600 W/m^2, at $t = 3$ s and v_w jump from 7 to 12 m/s, at $t = 5$ s)

We assumed a jump up of the wind speed at the time 5 s. Respond of the system in this case is following: all mentioned above variables start to increase slowly. Slow processes stipulate huge torque of inertia of WT.

Fig. 11 shows details of the inverter operation after the jump of solar irradiance at the time 3 s. Reactive power in this case decreases significantly and even changes its sign, what is also can be noticed in Fig. 10. It confirms that natural variations of solar or wind energy intensity have considerable impact to the operation of inverter, especially to the inverter‘s reactive power. Preliminary researches disclosed possibility of the inverter‘s reactive power control by adjusting phase of the modulation voltage *Fip* (Fig. 10 ÷ Fig. 12 were determined at the value of parameter *Fip* = 6,5 el. deg.). Operation of the inverter have to be controlled on purpose to reduce its reactive power or, if it would be expedient, to generate capacitive power for compensation of inductive power of the system. Control of inverter‘s reactive power is not researched well enough by now and it will be the task for further work.

As it can be determined from Fig. 11, the inverted current is sinusoidal, however it has some pulsations. Magnitude of the pulsations depends on the inductance of filter connected to the output of inverter. Magnitude of the pulsations can be reduced by increasing inductance of the filter. Grid voltage also has some pulsations (Fig. 11). Thus, the grid is polluted by the higher harmonics.

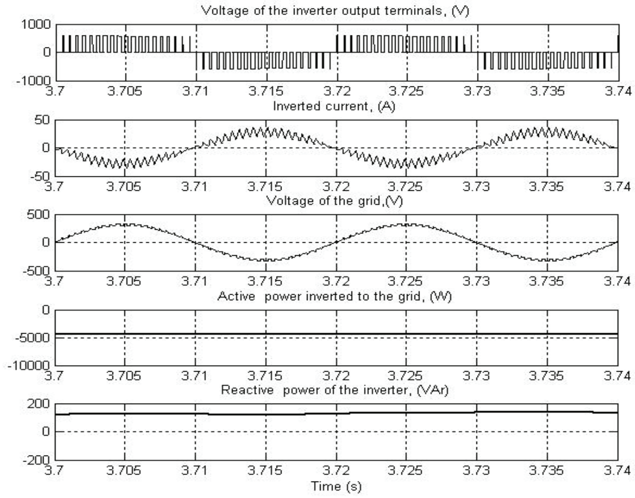

Fig. 11. Curves of the small hybrid power plant parameters versus time at the jumps of solar irradiance (*E* jump from 1000 to 600 W/m^2, at $t = 3$ s)

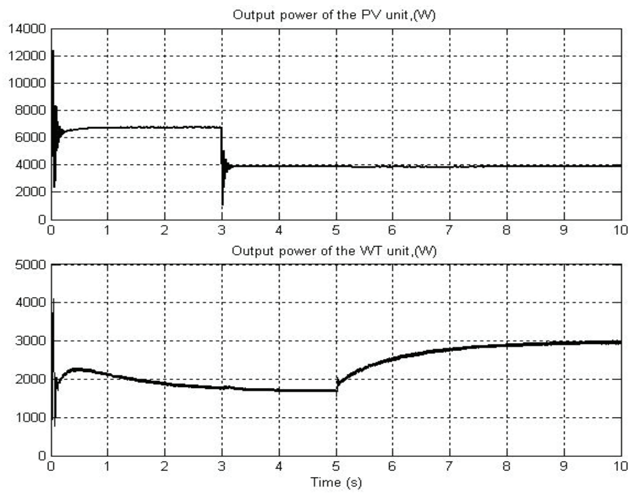

Fig. 12. Output power curves of the PV array and WT unit versus time at the jumps of solar irradiance *E* and wind velocity v_w (*E* jump from 1000 to 600 W/m^2, at $t = 3$ s and v_w jump from 7 to 12 m/s, at $t = 5$ s)

Pollution of grid by the upper harmonics is restricted by standard, which determines THD – the permitted total harmonic distortion [7]. Presently permissible THD have not to exceed 8 % value in regard of grid‘s rated voltage.

As it is evident from Fig. 12, impact of the wind and solar subsystems of the researched hybrid power system is vanishingly low and may be reasonably neglected.

Conclusions

1. Development of the RES-based power systems enhanced role of power electronics in this sector and raised accelerated development of power electronics industry.
2. Variations of solar irradiance and wind speed have significant impact to operation of the researched hybrid power plant, especially to the reactive power.
3. Preliminary researches disclosed possibility of the inverter‘s reactive power control by adjusting phase of the modulation voltage in respect of grid voltage.
4. Wind and solar subsystems of the researched hybrid power system have not harmful impact to each other.
5. Quality of the power inverted from the hybrid system can be enhanced by the increase of filter‘s inductance.

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Rapidly developing renewable power systems enhanced role of the power electronics in sector of power engineering and raised accelerated development of power electronics’ industry. Results of research presented in this paper are related with small-scale hybrid solar-wind power system. The system has innovative grid-connected converter for multipurpose applications. The main peculiarity of the conversion system is the intermediate power storage chain (DC/DC converter) integrated with the grid inverter. Research of the hybrid system operation was carried out by means of the mathematical simulation. The researches disclosed that variations of solar irradiance and wind speed have significant impact to operation of the researched hybrid power plant, especially to the inverter’s reactive power. Preliminary researches also confirmed possibility of the inverter‘s reactive power control by adjusting phase of the modulation voltage in respect of grid voltage. Wind and solar subsystems of the researched hybrid power system were found not having harmful impact to each other. Ill. 12, bibl. 8 (in English; abstracts in English and Lithuanian).

Č. Ramonas, V. Adomavičius. Daugiatikslis tinklo keitiklis su tarpine energijos kaupimo grandimi // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 7(113). – P. 15–20.

Sparti atsinaujinančiųjų energijos išteklių sistemų plėtra labai sustiprino galios elektronikos vaidmenį energetikoje ir paspartino galios elektronikos pramonės plėtrą. Šiame straipsnyje pateikti nedidelės galios hibridinės saulės ir vėjo elektrinės tyrimo rezultatai. Tiriamojoje sistemoje panaudotas į elektros tinklą integruojamas naujoviškas daugiatikslis galios keitiklis. Pagrindinė šios energijos konversijos sistemos ypatybė yra tarpinė energijos kaupimo grandis (NS/NS keitiklis), integruota su tinklo inverteriu. Nagrinėjamos hibridinės sistemos veikimo tyrimai buvo atlikti matematinio modeliavimo būdu. Tyrimai atskleidė didelį saulės apšvitos ir vėjo greičio pokyčių poveikį ištirtos mažosios hibridinės elektrinės darbui, ypač jos inverterio reaktyviajai galiai. Preliminarūs tyrimai taip pat patvirtino galimybę reguliuoti inverterio reaktyviąją galią keičiant moduliavimo įtampos fazę tinklo įtampos atžvilgiu. Taip pat buvo nustatyta, kad hibridinės elektrinės vėjo ir saulės energijos posistemiai beveik neturi nepageidaujamos įtakos vienas kito darbui. Il. 12, bibl. 8 (anglų kalba; santraukos anglų ir lietuvių k.).