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Mathematical control system of grid-tied multilevel voltage inverter

***Abstract**. The paper synthesizes the control law and computer model for grid-tied multilevel inverter of solar module that allows to hold the solar module operation within the point of maximum power output, which increases its efficiency. The improved models of the direct-axis and quadrature-axis components of inverter current regulator that allow the preservation of power, frequency and voltage balance in the power grid were suggested. The digital realization of control system could be used in smart grid technology of power distribution within electric loss minimization.*

***Streszczenie.** W artykule zostały sformułowane zasady sterowania oraz model komputerowy dla wielopoziomowego przekształtnika grid-tied modułu słonecznego, które pozwalają utrzymać działanie modułu słonecznego w punkcie maksymalnej mocy wyjściowej, co zwiększa jego efektywność. Zaproponowano udoskonalone modele jedno i czterokwadraturowych składowych regulatora prądu przekształtnika, które poprawiają zachowanie mocy, częstotliwości i napięcia w sieci energetycznej. Cyfrowa realizacja systemu sterowania może być użyta w technologii smart-grid dystrybucji energii z minimalnymi stratami. (**Matematyczny system sterowania wielopoziomowego przekształtnika napięcia grid-tied**).*

Keywords: multilevel voltage inverter, control, solar module.
Słowa kluczowe: wielopoziomowy przekształtnik napięcia, sterowanie, moduł słoneczny.

Introduction

The use of the renewable energy sources has dramatically increased recently making it easy to understand why solar farms are becoming more and more popular. As a result, the production of thin-film solar modules is also increasing [1, 2, 3]. To form the output voltage variable there have been used the grid-tied multilevel voltage inverters, applied as the adjusters, which were produced serially [4]. Papers [5, 6, 7] consider the models of multilevel voltage inverters used as the converting units for regulated asynchronous electric drives. The above models have been researched for the motoring conditions of the electric drives with the traditional vector control system in multilevel inverters. But these researches were lacking the performance analysis of inverters, operating in generating conditions of the electric drive, analysis of operation in parallel with the electrical grid which proves the necessity in researches aimed at synthesis of control system for multilevel inverters used in solar power stations.

The results of work [8] are oriented to the introduction of the inverter control system on the level of solar power station and coordination of balances between the active and reactive power, that is important for distributed electrical networks and is not used in practice for low voltage networks of 0.4 kV, aimed at consumers. The system therefore needs to be adjusted to the requirements of the consumers, i. e. the maintaining of the correspondent graphs of voltage and frequency, that is the electric energy quality parameters.

The objective of this paper is the synthesis of the control law for multilevel voltage inverter during the operation with the solar module as well as the device, designed for the realization of this law, which considers the parameters of the inverter, network, solar modules, allowing optimizing of the operation of the solar modules.

Equivalent electric circuit of solar battery

The value of voltage on the output of photovoltaic material of the solar module is constantly changing as a result of certain factors such as weather conditions, time of the day and panels temperature [9]. The state of the capacitor battery of solar cells also changes depending whether it is charged or discharged. An important factor from the point of view of inverter control system development is to ensure the operation of the solar module within the point of maximum power output. The algorithm for searching such as operation mode has to stipulate for searching this point in a wide voltage range to avoid getting into the local maximums, caused by the short-term changes in the environment (the shade on the panel due to a small cloud). The advantage of this algorithm is that the device will constantly be in search for operation with maximum efficiency. This algorithm, inherent in commercially produced single-level solar voltage inverters will be combined with the calculation of the derivative capacity of the solar module, made from the voltage on the inverter input, which equals zero and which gives a control system the value of the sought quasiextremum or extrema within the specified operating range of voltages.

Each solar module consists of the set of solar batteries, switched in series and/or parallel. A solar battery may be presented by an equivalent electrical circuit as shown in Figure 1 [10].

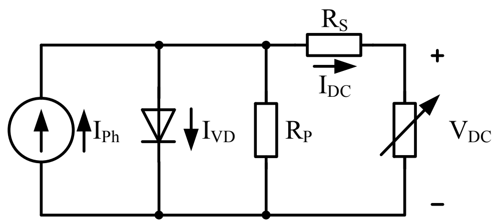

Fig.1. An equivalent electric circuit of solar battery

This elementary solar battery may be described by the following equation:

(1) $$I_{DC} = I_{Ph} - I_{VD} - \frac{V_{DC}+I_{DC}\cdot R_S}{R_p},$$

where I_{DC} and V_{DC} are output current and voltage of the solar battery, respectively; I_{Ph} is battery photon current; I_{VD} is diode current; R_S and R_P are series switched and shunt resistances, respectively.

In view of previous expression, the output voltage of the solar battery could be determined as follows:

(2) $$V_{DC} = (I_{Ph} - I_{VD} - I_{DC}) \cdot R_P - I_{DC} \cdot R_S.$$

Photon current and diode current depend on the illumination and temperature. For the set panel temperature T (Kelvin) and illumination level G (Wt / m^2), I_{Ph} and I_{VD} could be calculated as follows:

$$
\begin{cases}
I_{Ph|T,G} = \frac{G}{G_{ref}} I_{Ph|T,G_{ref}} = \\
= \frac{G}{G_{ref}} I_{SC|T_{ref},G_{ref}} \left[1 + \alpha\left(T - T_{ref}\right)\right], \\
I_{VD|T,G} = I_{0|T,G} \cdot \left[e^{\frac{q(V+I\cdot R_S)}{nkT}} - 1\right], \\
I_{0|T,G} = I_{0|T,G} \cdot \left(\frac{T}{T_{ref}}\right)^{\frac{3}{n}} \cdot e^{\left(\frac{-qE_g}{nk}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right)}, \\
I_{0|T_{ref},G} = \frac{I_{SC|T_{ref},G_{ref}}}{e^{\left(\frac{qV_{OC_{ref}}}{nkT_{ref}} - 1\right)}},
\end{cases} \tag{3}
$$

where T_{ref} and G_{ref} represent the difference in temperature (T_{ref} = 25°C = 298 K) and difference in illumination level (G_{ref} = 1000 Wt / m^2) under standard conditions; α is temperature coefficient; I_{SC} is short-circuit current of the solar battery; $I_{0|T,G}$ is reverse voltage-saturation current of the diode; n is coefficient of diode ideality; q =1.602exp(-19) C is the Coulomb constant, k = 1.38exp(-23) J/K is the Boltzmann constant, E_g is energy range between the valence band and band bottom of conductivity, E_g =1.12 eV (at 25°C), V_{OC} is the no-load voltage of the solar battery.

The resistance in series could be determined using the above parameters at normal temperature and illumination:

$$
R_S = -\frac{dV}{dt} I_{V_{OC_{ref}}} - \frac{nkT_{ref}}{I_{0|T_{ref},G} \cdot q \cdot e^{\frac{q\cdot V_{OC_{ref}}}{nkT_{ref}}}}, \tag{4}
$$

where $\frac{dV}{dt} I_{V_{OC_{ref}}}$ can be obtained from the manufacturer datasheet.

Graph of power relationships, which may be produced by a solar module to the grid inverter during the operation with the actual output voltage can be obtained by simulating the equation system (3) and their substitution in (2). The result of the simulation is shown in Figure 2.

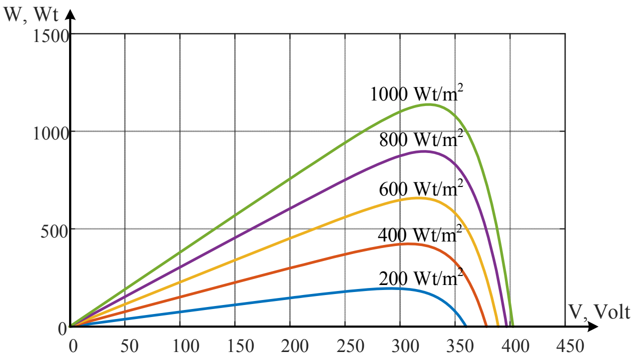

Fig.2. Graph of power relationships, which may be produced by a solar module to grid inverter during the operation with the actual output voltage

The power relationships, which may be produced by a solar module to the grid inverter during the operation with the actual output voltage, greatly depend on the temperature of the solar panel. To prove this, we used the solar battery model embedded in Matlab shown in Figure 3, set the temperature and illumination value arrays and generated the power-voltage curve for a solar battery. The understanding of the power-voltage curve is important for inverter designing. Ideally the solar battery always operate in peak operation with the consideration of the illumination level and panel temperature. Figure 4 shows the power relationships, which may be produced by a solar module to the grid inverter during the operation with the actual output voltage at difference values of temperature of the solar module.

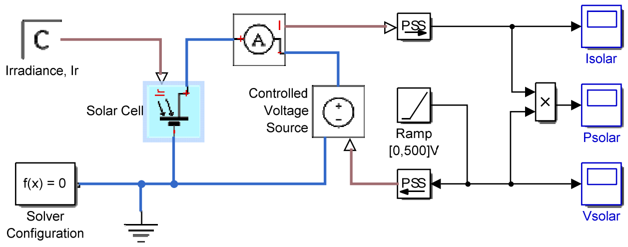

Fig.3. Block diagram of the model for solar cell power curve

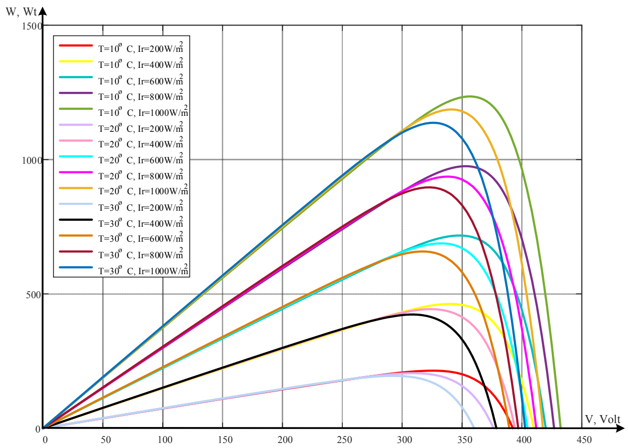

Fig.4. Graph of power relationships, which may be produced by a solar module to grid inverter during the operation with the actual output voltage at difference values of temperature of the solar module

Circuit of three level grid inverter with internal circuits for regulation of currents I_d and I_q

The inverter vector control systems use the adjustment of the three-phase current of inverter system to the orthogonal d-q-coordinate system. Thus, the output voltage on the inverter output will be set in proportion to the direct-axis component of current I_d, and the output capacity will be ensured by the corresponding value of the quadrature-axis component of the current I_q. During the coordination of the multilevel inverter operation with grid for monitoring the point of quasiextremum current-voltage characteristics of the solar module, the direct-axis component of current as well as the quadrature-axis component of the current of multilevel inverter will provide voltage and capacity which from the input side of the inverter will be taken from the solar module, and from the output of inverter will be transferred out to the network. The work [11] states that the lower order harmonics strongly affect the inverter operation, and it makes sense to install the L-filter between the output of the voltage inverter and the grid. Considering the above and the structure of the control system, which is presented in [12], the structure of the internal circuit of the control system of multilevel inverter and its power contour will be as shown in Figure 5.

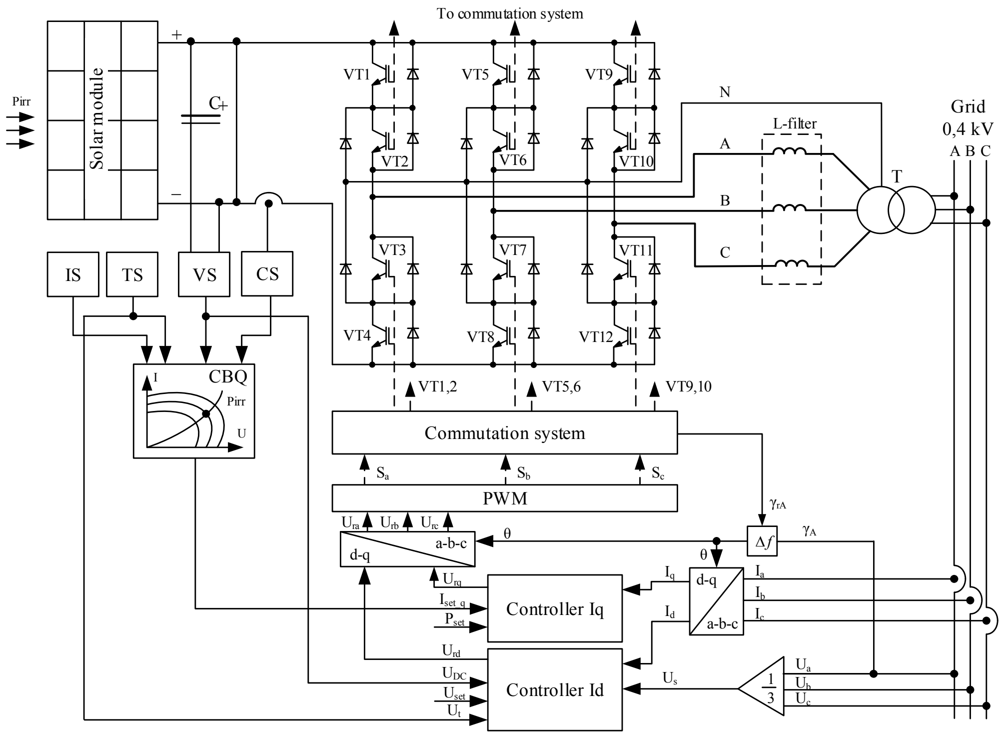

Fig.5. Chain diagram of three level grid inverter with internal circuits for regulation of currents I_d and I_q: IS – illumination sensor; TS – temperature sensor, VS – voltage sensor, CS – current sensor

Calculation block of quasiextremum (CBQ) calculates the coordinates within the point of maximum power output and generates the assignment signal after the current $I_{q.set}$ for regulator of quadrature-axis component Iq of inverter current. Sensor of the output solar module voltage generates the assignment signal after the voltage U_{DC} for the regulator of the direct-axis component I_d of the inverter current.

Feedbacks of these regulators could be implemented by transferring the three-phase system of currents Ia, Ib and Ic to the orthogonal system I_d and I_q. This transformation is made in accordance with the angle of the electromagnetic load of inverter θ.

Angle of the electromagnetic load of the inverter could be calculated by a system in time interval as the frequency difference of the voltage in the grid and the inverter:

$$\theta = \int_0^{\pi} \Delta f dt. \tag{5}$$

The frequency difference could be determined in time interval at the appropriate interval as the interval time from the moment of issuing the command by the switching system to switch the VT1 key up to the moment of passing of the voltage curve (phase A) in the positive direction (signal γ) through 0.

Converting block of a three-phase current system "a-b-c" to the orthogonal "d-q could be described by the system of equations:

$$\begin{cases} I_d = \frac{2}{3} \cdot \begin{pmatrix} i_a \cdot cos\theta + \\ +i_b \cdot cos\left(\theta - \frac{2\pi}{3}\right) + \\ +i_c \cdot cos\left(\theta + \frac{2\pi}{3}\right) \end{pmatrix}, \\ I_q = \frac{2}{3} \cdot \begin{pmatrix} i_a \cdot sin\theta + \\ +i_b \cdot sin\left(\theta - \frac{2\pi}{3}\right) + \\ +i_c \cdot sin\left(\theta + \frac{2\pi}{3}\right) \end{pmatrix} \end{cases} \tag{6}$$

According to [13, 14] it is possible to obtain the following system of equations in synchronous "d-q" coordinate system:

$$\begin{cases} I_e^d \cdot r_2 + \frac{d\psi_e^d}{dt} + j\Omega_e \psi_e^d = 0, \\ I_e^q \cdot r_2 + \frac{d\psi_e^q}{dt} + j\Omega_e \psi_e^q = 0, \\ \frac{L_m \cdot r_2}{L_2} I = \frac{d\psi_e}{dt} + \left(\frac{r_2}{L_2} + j\Omega_e\right)\psi_2, \\ I = \frac{\psi_e}{L_m}(1 + T_e p + jT_e \Omega_e), \end{cases} \tag{7}$$

where I_e^d and I_e^d are equivalent values of the direct-axis and the quadrature-axis components of currents, respectively; r_2 is resistance of secondary winding of the transducer; ψ_e^d and ψ_e^d are equivalent values of flux linkage on direct and quadrature axes, respectively; Ω_e is equivalent frequency; ψ_e is equivalent value of flux linkage of transducer; L_m *is* mutual induction of primary and secondary windings; T_e *is* electromagnetic time constant of the transducer short circuit resistance; ($T_e = L_к / R_к$); I is output current of the inverter (geometric sum of direct and quadrature axes current components).

Control law for multilevel voltage inverter during the operation with solar module

The direct-axis component of current can be written as:

$$I_d = \frac{\psi_e}{L_m}(1 + T_e s) = \frac{w_e \Phi_e}{L_m}(1 + T_e s), \tag{8}$$

where Φ_e is equivalent magnetic flux in transducer core, s is Laplace operator.

Formula (8) may be rewritten as follows:

$$I_d = \frac{W_e \cdot \frac{E}{4{,}44 W_e f \sqrt{2}}}{L_m}(1 + T_e s) \approx \frac{U}{4{,}44 L_m f \sqrt{2}}(1 + T_e s). \tag{9}$$

As it is seen from dependence (8), the direct-axis component of current I_d regulates the magnetic flux of transducer, and according to (9) – electric line voltage.

In AC networks the frequency heavily depends on the balance of active power. Therefore, as a regulated frequency criterion it is possible to choose the indirect regulation of active power. Active power may be converted into another type of energy, therefore the control law for multilevel voltage inverter should not only include a value of power that is produced (or consumed) to the grid, but the power that comes from the sun to the solar module.

In fact, the active power, which is given away to the network through the transducer will have its mechanical equivalent that may be expressed through the appropriate equivalent angular speed and torque:

$$P_e = M_e \cdot \Omega_e. \tag{10}$$

Angular speed Ω_e determined as:

$$\Omega_e = \frac{2\pi f}{p_e}, \tag{11}$$

where f is the frequency of electric line voltage and the inverter after synchronization, p_e is equivalent number of pole pairs of magnetic field.

Equivalent torque according to [12] equals:

$$M_e = \frac{3}{2} p_e \frac{L_m}{L_2} \psi_e I_q. \tag{12}$$

The quadrature-axis component of the current could be written as follows:

$$I_q = \frac{\psi_e}{L_m} T_e \Omega_e. \tag{13}$$

Multiplying the left and right side of (12) by Ω_e one can write:

$$M_e \cdot \Omega_e = \frac{3}{2} p_e \frac{L_m}{L_2} \psi_e I_q \Omega_e. \tag{14}$$

Taking into consideration (5), one can obtain:

$$P_e = \frac{3}{2} p_e \frac{L_m}{L_2} \psi_e I_q \frac{2\pi f}{p_e},$$

$$P_e = 3\pi f \frac{L_m}{L_2} \psi_e I_q.$$

Expression for the quadrature-axis component of current I_q is as follows:

$$I_q = \frac{P_e L_2}{3\pi f L_m \psi_e}. \tag{15}$$

Thus, as it could be seen from (15) the quadrature-axis component sets an appropriate balance of active power from output of the solar module and the power, which is taken off by the grid.

According to [15] the control law for grid-tied multilevel inverter of solar module that allows to hold the solar module operation within the point of maximum power output without considering of temperature of solar module equals:

$$\begin{cases} I_{set\_q} = k_P \cdot k_{g\_irr} \cdot P_{irr} + k_P \cdot P_{set} + \\ \quad + k_u \cdot U_{DC} - k_{sl} \cdot I_{DC}, \\ U_{rq} = k_{pq} \cdot \begin{pmatrix} k_{g\_rq} \cdot (I_{set\_q} - I_q) + \\ + \frac{1}{T_{iq}} \cdot \int_0^t \begin{matrix} (I_{set\_q} - I_q)dt + \\ + T_{dq} \cdot \frac{d(I_{set\_q} - I_q)}{dt} \end{matrix} \end{pmatrix}, \\ I_{set_d} = k_{pd} \cdot \begin{pmatrix} U_{set} \cdot U_{DC} \cdot k_{g\_DC} - \\ - U_s \cdot k_{g\_s} \end{pmatrix}, \\ U_{rd} = k_{pd} \cdot \begin{pmatrix} k_{g\_rd} \cdot (I_{set\_d} - I_d) + \\ + \frac{1}{T_{id}} \cdot \int_0^t \begin{matrix} (I_{set\_d} - I_d)dt + \\ + T_{dd} \frac{d(I_{set\_d} - I_d)}{dt} \end{matrix} \end{pmatrix}. \end{cases} \tag{16}$$

where k_{pd} and k_{pq} are gain coefficients of sub-regulators of direct-axis and quadrature-axis components of the inverter current, respectively; T_{id} and T_{iq} are time constants of regulators integration, respectively; T_{dd} and T_{dq} are time constants of regulators differentiation, respectively; U_{rd} and U_{rq} are regulator's outputs signals of direct-axis and quadrature-axis components of inverter current, respectively; k_P is coefficient with the dimension of conductivity to bring capacity to the respective current value; k_{g_irr} is weight coefficient of gaining in value of capacity that enters the light sensor; P_{set} is set value of active power; k_u is coefficient with dimension of conductivity for bringing the voltage value in assignment channel of regulator to the appropriate value of the current at the measuring input of the controller; U_{DC} is voltage on the output of the voltage sensor of solar module; k_{sl} is slope coefficient of adjusting characteristic; I_{DC} is the value of current that comes to CBQ output from the current sensor; k_{g_rq} is gain coefficient of P-component of output voltage U_{rq}; k_{b_c} is signal bringing coefficient voltage to current; U_{set} is set value of voltage on load; k_{g_DC} is voltage gain coefficient on output of voltage sensor; U_s is measured value of grid voltage; k_{g_s} is gain coefficient of value of grid voltage; k_{g_rd} is gain coefficient of P-component of output voltage U_{rd};.

In view of the above, for ensuring the regime of holding the solar module within the point of maximum capacity, the automatic voltage regulators (direct-axis component of the inverter current I_d) and capacity (quadrature-axis component of the inverter current I_q) will operate according to the sub-law of control and could be described by the equation:

$$\begin{cases} I_{set\_q} = k_P \cdot k_{g\_irr} \cdot P_{irr} + k_P \cdot P_{set} + \\ \quad + k_u \cdot U_{DC} - k_{sl} \cdot I_{DC}, \\ U_{rq} = k_{pq} \cdot \begin{pmatrix} k_{g\_rq} \cdot (I_{set\_q} - I_q) + \\ + \frac{1}{T_{iq}} \cdot \int_0^t \begin{matrix} (I_{set\_q} - I_q)dt + \\ + T_{dq} \cdot \frac{d(I_{set\_q} - I_q)}{dt} \end{matrix} \end{pmatrix}, \\ I_{set_d} = k_{pd} \cdot \begin{pmatrix} U_{set} \cdot U_{DC} \cdot k_{g_{DC}} - \\ - U_s \cdot k_{g\_s} + k_t \cdot \left(\frac{T}{T_{ref}}\right)^2 \end{pmatrix}, \\ U_{rd} = k_{pd} \cdot \begin{pmatrix} k_{g_{rd}} \cdot (I_{set\_d} - I_d) + \\ + \frac{1}{T_{id}} \cdot \int_0^t \begin{matrix} (I_{set\_d} - I_d)dt + \\ + T_{dd} \frac{d(I_{set\_d} - I_d)}{dt} \end{matrix} \end{pmatrix}. \end{cases} \tag{17}$$

where T is temperature of the solar battery.

Block of reverse transformation of orthogonal system of the calculated optimum values of currents I_{rd} and I_{rq} to the three-phase voltage system for controlling over the shoulders of inverter bridge U_{ra}-U_{rb}-U_{rc} works according to system of equations:

$$\begin{cases} U_{ra} = I_{rd} \cdot sin\theta + I_{rq} \cdot cos\theta, \\ U_{rb} = \frac{1}{2} \begin{pmatrix} (\sqrt{3} \cdot sin\theta - cos\theta) I_{rq} - \\ (sin\theta + \sqrt{3} \cdot cos\theta) I_{rd} \end{pmatrix}, \\ U_{rc} = -U_{ra} - U_{rb}. \end{cases} \tag{18}$$

It is necessary to carry out the researches of the models of regulators of the direct-axis and quadrature-axis components of inverter current with further stability testing. With the objective to determine the optimal parameters of the inverter current components we compose a computer model (Figure 4), which is built in accordance with the synthesized law.

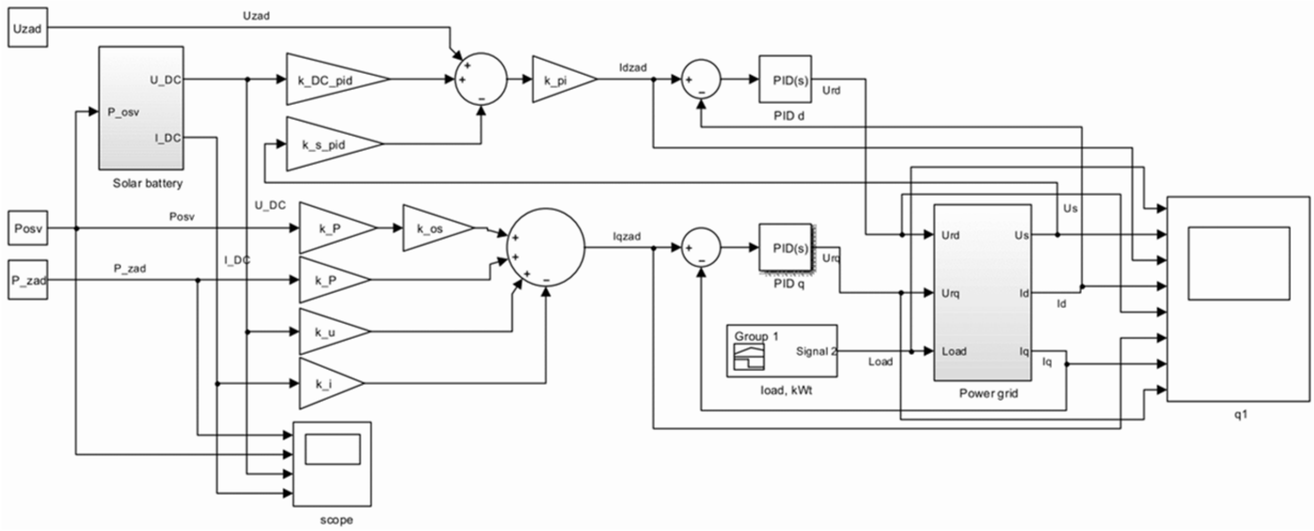

Fig.6. The computer model to test the adequacy of control of *d* and *q* current components of power inverter: Uzad – set grid voltage value; P_osv – power value that is perceived by lighting; P_zad – set voltage value of solar module; PID d – PID controller of the longitudinal component of the current of inverter; PID q – PID controller of the transverse component of the current of inverter; load – load preset schedule; Power grid – network model

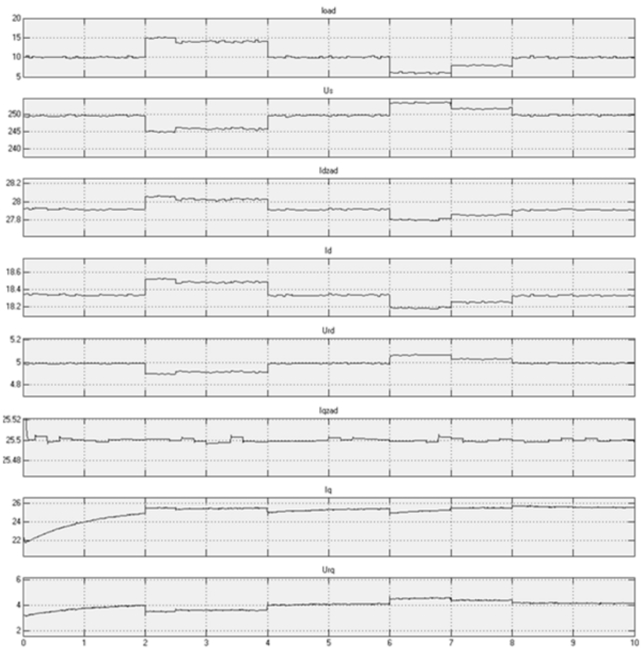

Fig.7. Simulation results for PID controllers of longitudinal and transverse components of the current inverter

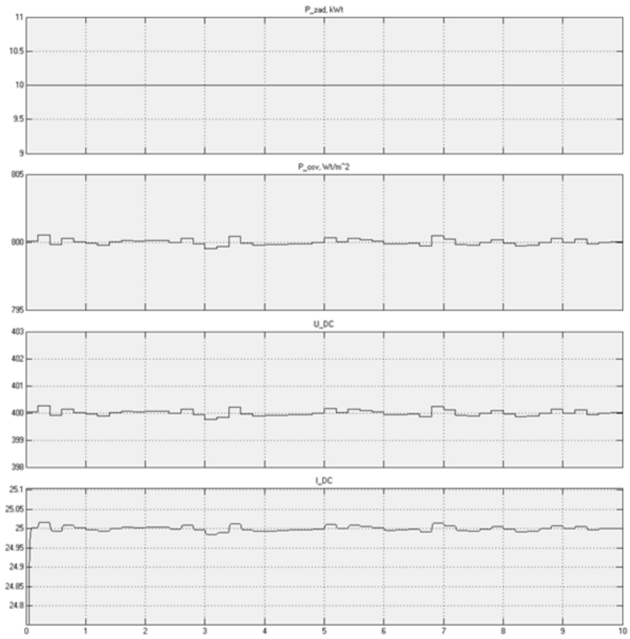

Fig.8. The set and the actual value of light level, the output current and voltage of the solar battery

Computer modelling of law for multilevel voltage inverter during the operation with solar module

The considered control law (16) needs clarification coefficients settings that meet the criteria for stability of control system.

Let us investigate the models of controllers of direct and quadrature currents components of the power inverter and check them for stability. Also, in order to establish the optimal parameters of current components of power inverter let us construct computer model as shown in Figure 6.

Results of modeling are shown in Figure 7.

The trends of setpoint and the actual value of lightness level, the output current and voltage of the solar cell are shown in Figure 8.

During the simulation the optimal settings of system controllers have been identified as shown in Fig.9 and their values are shown in Table 1.

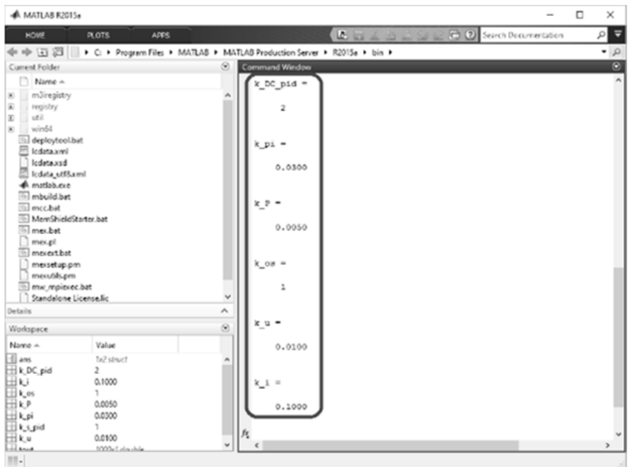

Fig.9. Optimal settings of system controllers

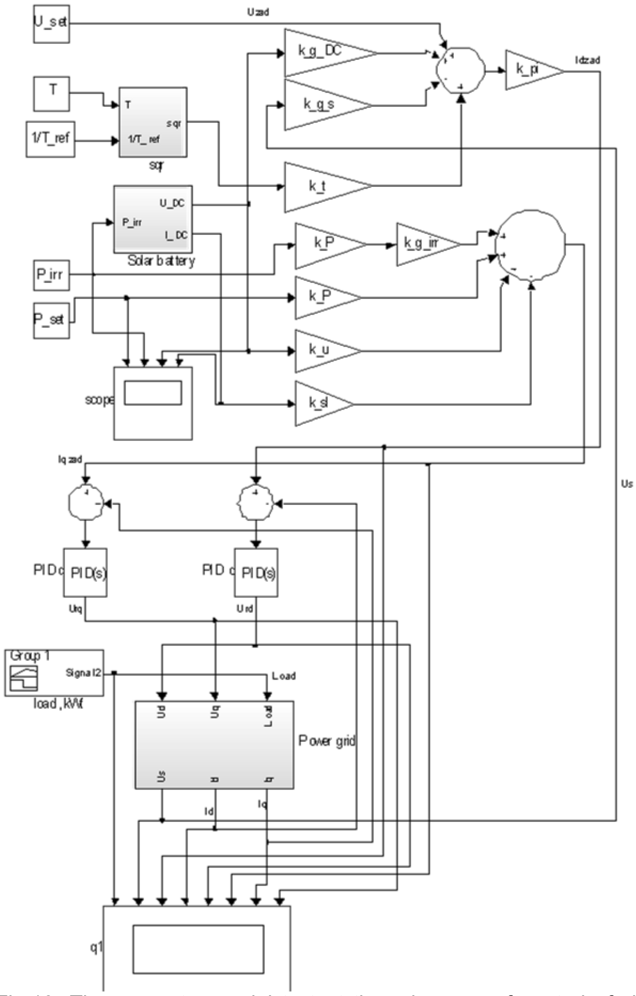

Fig.10. The computer model to test the adequacy of control of *d* and *q* current components of power inverter: sqr - square value ratio of temperature solar cell to the temperature difference between solar battery and environment

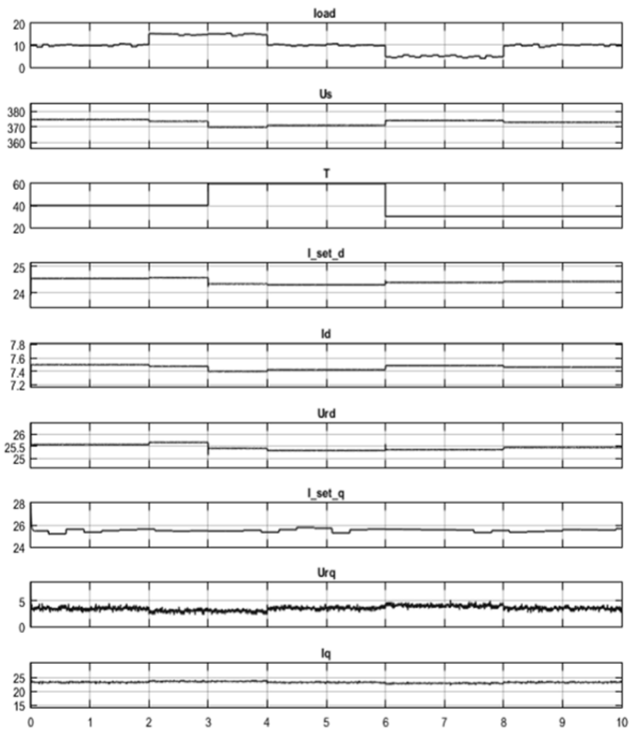

Fig.11. Simulation results for PID controllers of longitudinal and transverse components of the current inverter according to (17)

Table 1. Optimal settings of system controllers

Coefficient	k_{g_DC}	k_{g_s}	k_{g_i}	k_P	k_u	k_{g_irr}	k_{sl}
Value	2	1	0.03	2	0.01	0.1	0.1

Considered control law (17) needs clarification coefficient settings that meet the criteria for stability of control system. So, the constructed computer model of inverter control system according to (17) is shown in Fig.10. Results of modeling are shown in Fig.11.

The trends of setpoint and the actual value of lightness level, the output current and voltage of the solar cell for system with considering of temperature of solar module are shown in Figure 12.

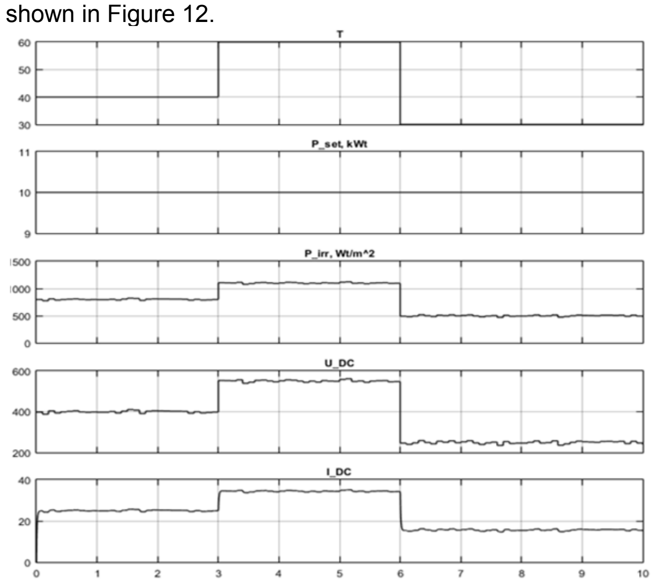

Fig.12. Temperature, the set and the actual value of light level, the output current and voltage of the solar battery

During the simulation of system which operates according (17) the optimal settings of system controllers and their values have been identified as shown in Table 2.

Table 2. Optimal settings of system controllers

Coefficient	k_{g_DC}	k_{g_s}	k_{g_i}	k_P	k_u	k_{g_irr}	k_{sl}
Value	2	1	0.03	2	0.01	0.1	0.2

Conclusions

The control law for multilevel grid-tied inverter of solar power station and improved structure for its implementation, which combines tasks of keeping the operation mode of the solar module at the point of maximum power output allowing to increase the efficiency of the solar module has been synthesized. This law takes into account the influence of the temperature on the solar module. The computer model including the synthesized control law for network multilevel inverter of solar module has been developed.

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