http://dx.doi.org/10.5755/j01.eee.19.1.3250 ELEKTRONIKA IR ELEKTROTECHNIKA, ISSN 1392-1215, VOL. 19, NO. 1, 2013

Research of the Reactive Power Control Possibilities in the Grid-tied PV Power Plant

C. Ramonas[1], V. Adomavicius[1]
[1]The Centre of Renewable Energy, Kaunas University of Technology,
Studentų str. 48-329, LT-51367 Kaunas, Lithuania, phone: +370 37 351181
ceslovas.ramonas@ktu.lt

Abstract—**Results of control possibilities research of the reactive power generated by grid-tied PV power plant are presented in this paper. The innovative grid-connected inverter with the intermediate power storage chain (DC/DC converter) is used for the PV power plant. The converter operates well when DC input voltage generated by the PV source changes in a wide range. Mathematical description for the circuit part between the inverter output and the grid is presented. Detailed researches of PV system were carried out by means of the mathematical simulation. The researches disclosed dependence of the system reactive power on the phase of sinusoidal modulation voltage of the inverter. It is defined that phase of the modulation voltage must be positive and can vary in the range 0÷20 degrees. Researches show that researched PV system can generate the capacitive reactive power for compensation of the inductive reactive power of the grid. Operation mode of the system when the reactive power is equal to zero can be achieved in this system. It is defined that electromagnetic distortion (THD) of the grid has maximal value at the point when the reactive power is equal to zero. Consequently, this feature must be evaluated at the design of the inverter filter.**

Index Terms—**Power converters, reactive power control, distributed power generation, solar energy.**

I. INTRODUCTION

The reactive power control in the electrical grid of power system or in the microgrids is a very important problem. Proper compensation of the reactive power in the mentioned above electrical grids allows minimizing of the electrical losses. Usually reactive power of the inductive character prevails in the electrical grids and various measures have to be taken in order to minimize this unwelcome power. Mostly batteries of capacitors or the synchronous compensators were used earlier in order to compensate the inductive power. Presently the function of reactive power control in the entire power system or in the particular microgrid also can be performed by means of various renewable power conversion systems, which include grid inverters [1], [2].

II. OBJECT OF RESEARCH

Small-scale renewable power systems with grid-tied converters those contain the intermediate DC power converting circuits with power storage elements have some positive peculiarities [3], [4]. It can be exploited in any power source having variable DC voltage in the input of the converter. 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 [3]. Besides, this converter operating together with control system is able to perform maximum power point tracking function in the solar or wind power system depending on the signals of corresponding sensors [4]. Such power systems also have possibilities to control the inverter‘s reactive power by adjusting phase of the modulation voltage in respect of grid voltage what was mentioned in the reference [3].

Results of reactive power control possibilities in the small-scale grid-tied PV power system are presented in this paper. Simplified electrical scheme of the researched system is shown in Fig. 1. The installed capacity of this system is 6 kWp. Single phase grid-tied bridge inverter with mutual power storage capacitor C_k is used for the power supply into the grid. This scheme of power conversion allows controlling reactive power of the PV system by changing phase of the modulation voltage of the inverter. As it is shown in Fig. 1, control system of the small power plant consists of two subsystems: the control section for the PV power source (units RCF, CRS, SCPF1 and current controller W_{cc1}) and the grid inverter‘s control section (units IMVF and IPF). Control system of the PV power source is operating in order to ensure the maximum available power production at any usable values of solar irradiance.

The control system of the PV power source is comprised on basis of previous works of authors [4]. Two variables are measured here: the irradiance E and the output current of the PV array I_s. The necessary load current of the PV array I_{rs} is calculated in the RCF unit by using the irradiance E and the reference signal of the load current U_{rs} in the CRS unit. The load current signal U_s is calculated by using the actual load current I_s. The error signal is passed to the current controller W_{cc}. Output signal of the controller is passed to the former of shorting transistor control pulses SCPF where control pulse of necessary width is formed for the transistor V_t. The PI controller is used in the control system and therefore static error of the load current regulation is equal to zero.

Modulation voltage former IMVF of the inverter forms the modulation voltage – the sinusoidal signal with the

Manuscript received March 19, 2012; accepted May 22, 2012.

magnitude depending on the modulating factor with the frequency adjusted by the signal U_f and with the phase adjusted by the signal U_{fi}. This signal is passed to the former of the inverter's transistor control pulses IPF where control pulses of necessary width are formed for the transistors $V_1 \div V_4$.

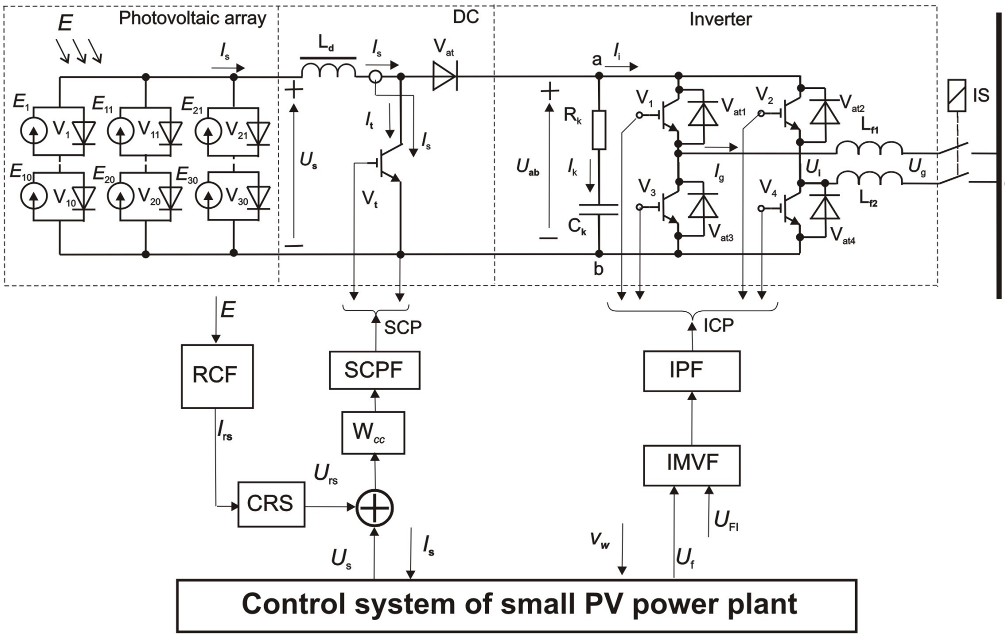

Fig. 1. Simplified electrical scheme of the small-scale grid-tied PV power system.

III. MATHEMATICAL DESCRIPTION OF THE RESEARCHED SYSTEM

Mathematical description of the PV array and DC/DC converter is the same as it was developed in the previous works of authors [3], [4]. Well known in power electronics theory mathematical description was used for the inverter. Output voltage of the inverter u_i is non-sinusoidal. Therefore the filter (resistance R_f and inductance L_f) is used in order to get the voltage in the output of the converter u_g closer to the sinus shape. The equivalent scheme of the circuit part between the inverter output and the electric grid for the fundamental frequency is presented in Fig. 2.

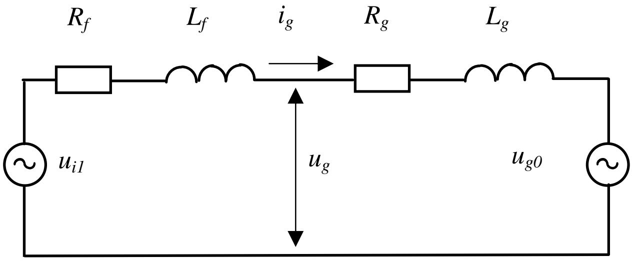

Fig. 2. The equivalent scheme of the circuit part between the inverter output and the grid for the fundamental frequency.

Inverter voltage u_i can be expressed by Fourier series

$$u_i(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos(n\omega t) + b_n \sin(n\omega t), \qquad (1)$$

where n represents the rank of the harmonics (n=1 corresponds to the fundamental component).

Voltage of the fundamental frequency is described as follows

$$u_{i1}(t) = U_{i1m} \sin(\omega t + \varphi_{i1}). \qquad (2)$$

The magnitude U_{i1m} and phase φ_{i1} of the fundamental component are calculated by the following equations:

$$U_{i1m} = \sqrt{a_1^2 + b_1^2}, \qquad (3)$$

$$\varphi_{i1} = \arctan\left(\frac{a_1}{b_1}\right), \qquad (4)$$

$$a_1 = \frac{2}{T} + \int_{t-T}^{T} u_i(t) \cos \omega t dt, \qquad (5)$$

$$b_1 = \frac{2}{T} + \int_{t-T}^{T} u_i(t) \sin \omega t dt, \qquad (6)$$

where $T=1/f_1$, f_1 – the fundamental frequency.

The research of the inverter shows that angle φ_{i1} is equal approximately to the phase angle of the modulation voltage of inverter φ_m. The grid current for fundamental frequency is expressed as follows

$$i_g(t) = \frac{u_{i1}(t) - u_{g0}(t)}{Z} = \frac{u_d(t)}{Z} = \frac{U_{dm} \sin(\omega t + \varphi_d)}{Z} = I_{gm} \sin(\omega t + \varphi_{gi}), \qquad (7)$$

where u_d – the voltage drop in the circuit resistance, U_{dm} – the magnitude of voltage drop, φ_d – the phase of voltage drop, Z – the impedance of the analyzed circuit, φ_z – the angle of the impedance, I_{gm} – the magnitude of the grid current, $\varphi_{gi}=\varphi_d-\varphi_z$ – the phase of the grid current:

$$u_{g0}(t) = U_{g0m} \sin \omega t, \qquad (8)$$

$$U_{dm} = \sqrt{(U_{i1m} \cos \varphi_{i1} - U_{gom})^2 + (U_{i1m} \sin \varphi_{i1})^2}, \qquad (9)$$

$$\varphi_d = \arctan \frac{U_{i1m} \sin \varphi_{i1}}{U_{i1m} \cos \varphi_{i1} - U_{g0m}}, \tag{10}$$

$$Z = \sqrt{\left(R_f + R_g\right)^2 + \left(x_f + x_g\right)^2}, \tag{11}$$

$$\varphi_z = \arctan\left(\frac{x_f + x_g}{R_f + R_g}\right). \tag{12}$$

The voltage drop in the grid impedance for fundamental frequency is defined as follows

$$u_{dg}(t) = I_{gm} z_g \sin(\omega t + \varphi_{gi}) = \\ = I_{gm} Z_{gm} \sin(\omega t + \varphi_{dg}) = U_{dgm} \sin(\omega t + \varphi_{dg}), \tag{13}$$

where z_g – the grid impedance, $Z_{gm} = \sqrt{R_g^2 + x_g^2}$ – the magnitude of the grid impedance, $\varphi_{dg} = \varphi_{gi} + \varphi_{zg}$ – the phase of the voltage drop in the grid impedance, $\varphi_{zg} = \arctan(x_g / R_g)$ – the phase angle generated by the grid impedance.

The voltage of the grid for fundamental frequency is expressed as follows

$$u_g(t) = u_{g0}(t) + u_{dg}(t) = U_{gm} \sin(\omega t + \varphi_{gu}), \tag{14}$$

where

$$U_{gm} = \sqrt{\left(U_{g0m} + U_{dgm} \cos \varphi_{dg}\right)^2 + \left(U_{dgm} \sin \varphi_{dg}\right)^2}, \tag{15}$$

$$\varphi_{gu} = \arctan\left(\frac{\sin \varphi_{dg}}{U_{g0m}/U_{dgm} + \cos \varphi_{dg}}\right). \tag{16}$$

Analysis of equation (16) shows that the phase angle between the grid voltage and the no load grid voltage is small. The active and reactive powers are expressed as follows:

$$P = \frac{1}{2} U_{gm} I_{gm} \cos \varphi_{gi}, \tag{17}$$

$$Q = \frac{1}{2} U_{gm} I_{gm} \sin \varphi_{gi}. \tag{18}$$

IV. MATHEMATICAL MODEL OF THE RESEARCHED SYSTEM

Method of digital simulation is used for research of the system. MATLAB/SIMULINK model is based on the SymPowerSystems library. Overall model diagram of the researched solar power system is presented in Fig.3.

This model consists of the following units: PV array, the inverter, the grid voltage source u_{g0}, the active resistance and inductance of the grid Rg and Lg, the inductances of the filter Lf1 and Lf2, the measurement units for the active and reactive power P, Q and the measurement units for main parameters of system M-unit.

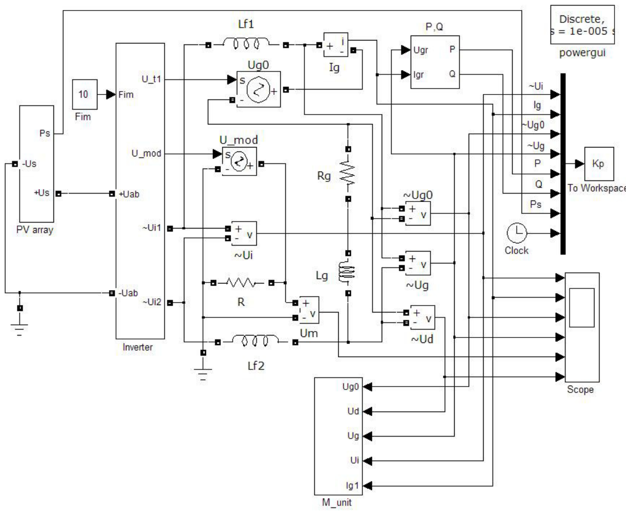

Fig. 3. Model diagram of the small PV power plant.

Model of the modulation voltage unit of inverter is shown in Fig. 4. It consists of the following units: the adder (1), the unit of the sine function calculation (2) and the unit of the modulation index (3).

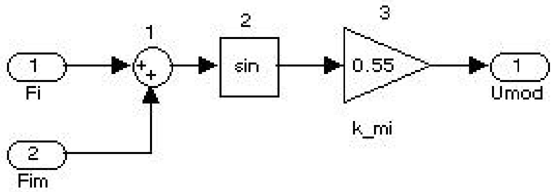

Fig. 4. Model diagram of the modulation voltage unit.

Modulation voltage unit calculates the sinusoidal signal of the modulation voltage as follows

$$u_{\text{mod}} = U_{\text{mod}} \cdot k_{mi} \sin(\omega t + \varphi_m), \tag{19}$$

where $U_{\text{mod}}=1$ – the amplitude of modulation voltage; $k_{mi}=0{,}55$ – the modulation index; $\omega t = Fi$ – the instantaneous angle of the grid voltage; $\varphi_m = Fim$ – the phase of modulation voltage.

V. RESULTS OF THE RESEARCH

The main target of research was analysis of active and reactive power dependences on the modulation voltage of the inverter. Total harmonic distortion (THD) was also considered as one of the essential parameters of grid inverters [5], [6]. The main results of the research are presented in Fig. 5 and Fig. 6. Fig. 5 illustrates operation of the grid-tied PV system dependently on the time for the case when the modulation voltage phase is equal 10 degrees (Fim=10 deg.). Fig. 5 shows that the inverted current in this instance leads the grid voltage by some phase angle. It means that reactive power has capacitive character. Besides, the second and fourth curves show that some electromagnetic disturbances exist in the system. THD coefficient is used to evaluate the distortion rate of the grid voltage and current.

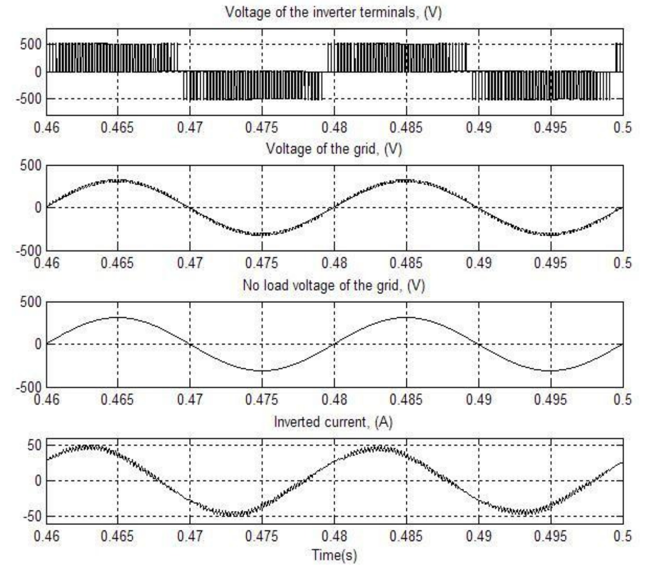

Fig. 5. Curves of the small power plant parameters versus time (Phase of inverter modulation voltage F_{im}=10 deg).

Fig. 6 shows the changes in the grid circuit main parameters after the change of the modulation voltage phase. It shows that grid current has minimum value when its phase is crossing the phase axes. The reactive power changes the sign and is crossing the phase axes at the same point. The THD coefficient has maximum value at the same point. Variations of the active power are small. The peculiarities noted above confirm that phase of the modulation voltage have considerable impact to the grid current, THD and to the inverter‘s reactive power. Character of the reactive power changes in the wide range: from the inductive to the capacitive. Phase of the modulation voltage can be changed within limits of 0÷20 degrees. Researches disclosed the possibility of the inverter‘s reactive power control by adjusting the phase of the modulation voltage.

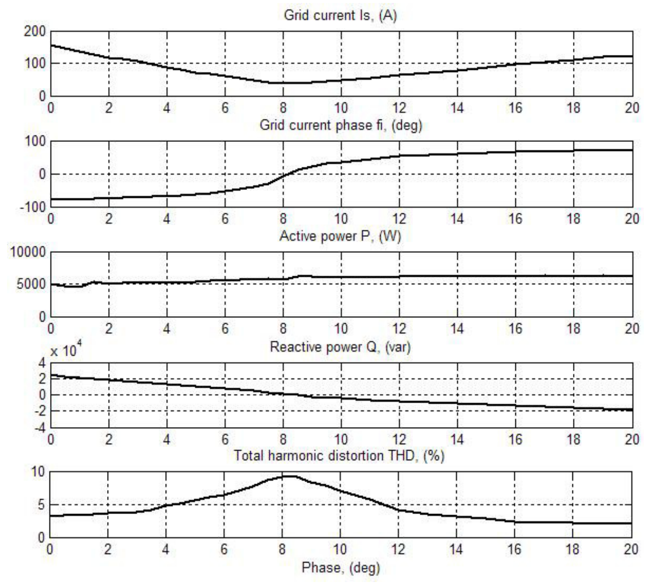

Fig. 6. Curves of the small PV power plant parameters versus phase of the inverter modulation voltage.

Control of the inverter allows reduction of its reactive power or, if it would be expedient, to generate capacitive power for compensation of the system inductive power.

VI. CONCLUSIONS

– The phase of modulation voltage has impact to the inverter‘s reactive power. It is noted that modulation voltage can be changed within limits of 0÷20 degrees.

– Researches disclosed possibility of the inverter‘s reactive power control by adjusting phase of the modulation voltage in respect of grid voltage. It is possible to compensate inductive power of the grid.

– It is defined that total harmonic distortion (THD) coefficient has maximum value at the point when reactive power curve is crossing the phase axes.

– The researched reactive power control system can be applied in the microgrids.

REFERENCES

[1] A. Cagnano, E. De Tuglie, M. Liserre, R A. Mastromauro, „Online Optimal Reactive Power Control Strategy of PV Inverters“, *IEEE Transactions on Industrial Electronics,* vol. 58, no. 10, pp. 4549–4558, 2011. [Online]. Available: http://dx.doi.org/10.1109/TIE.2011.2116757

[2] P. Balciūnas, P. Norkevicius, „Energy Conversion Processes Research of Inverter – Three Phase Dual System Converter“, *Elektronika ir Elektrotechnika (Electronics and Electrical Engineering*), no. 4, pp. pp. 9–14, 2012.

[3] Č. Ramonas, V. Adomavičius, „Grid-tied converter with intermediate storage chain for multipurpose applications“, *Elektronika ir Elektrotechnika (Electronics and Electrical Engineering),* no. 7, pp. pp. 15–20, 2011.

[4] Č. Ramonas, V. Adomavičius, “Research of EMD in small scale grid-tied PV system”, in *Proc. of the XX International Conference on Electromagnetic Disturbances (EMD 2010),* 2010, pp. 159–164.

[5] B. R. Lin, T. Y. Yang, “Implementation of active power filter with asymmetrical inverter legs for harmonic and reactive power compensation”, *Electric Power Systems Research,* Elsevier, vol. 73, 2005, pp. 227–237. [Online]. Available: http://dx.doi.org/10.1016/j.epsr.2004.08.007

[6] P. Görbe, A. Magyar, K. M. Hangos, “THD Reduction with Grid Synchronized Inverter’s Power Injection of Renewable Sources. International Symposium on Power Electronics”, in *Proc. of the Electrical Drives and Motion* (*SPEEDAM 2010)*, pp. 1381–1386.