Reactive power of nonlinear sign – changing loads

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***Abstract*— This paper presents a discussion about simulation modelling of reactive power and its control by a single – phase inverter in a photovoltaic system. Reactive power is one of the most important electrical magnitudes that requires proper control in a system. The simulation is done in MATLAB/ Simulink environment. The model consists of a single – phase photovoltaic inverter, a source representing the grid and control of said inverter. Currents and voltages are subjected to Clarke's and Park's transformations following p – q theory. As the model is operating with a single – phase inverter only the quadrature component is considered. This component is further passed to a proportional – resonant controller which is considered a suitable replacement to proportional – integral one as it can introduce infinite gain at fundamental frequency. Simulation results present satisfactory waveform of both voltage and current that are injected to the grid.**

Keywords*— *nonlinear loads, photovoltaic inverter, reactive power, single – phase

I. INTRODUCTION

Depletion of fossil fuels, which are used in classical methods of electrical energy production, current environmental conditions and the problems that they present, and other factors have pushed the attention of electrical energy production towards renewable energy sources (RES) on a global scale.

This paper presents a discussion about reactive power, its compensation by means of inverters in a photovoltaic (PV) system.

II. REACTIVE AND COMPENSATION NECESSITY

Reactive power has always been a significant factor in electric power system. More precisely it is a significant factor in the system's stability. Even though transmission of reactive power causes power losses, voltage losses, disruptions in stability, lower quality of energy, etc. it cannot be removed from the system as reactive power is the essence of rotating magnetic fields in electric machines. Thus, reactive energy must be regulated (compensated) and a balance of energy must be maintained. In the past generally only inductive type reactive energy, which can be treated as positive, was controlled, sanctioned and compensated. However, the vast spread of electronic components even in domestic applications has made capacitive reactive energy (negative) as important.

Reactive energy is traditionally considered only for sinusoidal regimes, i.e. circuits operating with sinusoidal voltages and sinusoidal currents. However, power electronics with non- linear V-A characteristic, electric arc furnaces, static sources of reactive power, non- linear loads, etc. introduce harmonics. This leads to non- sinusoidal regimes of operation. A power equilibrium in sinusoidal conditions can be characterized by the coefficient "cos φ", which is easily depicted by the triangle of powers. However, for non-sinusoidal conditions reactive power cannot be expressed in a trivial manner and there is a plethora of definitions. In case of non- sinusoidal current "cos φ" becomes undefined quantity. A power factor (PF) should be used.

Two theories have been widely utilized to function as cores in many non- sinusoidal quantities' definitions and expressions. Those are Budeanu's and Fryze's theories [1], [2]. In Budeanu's theory non- sinusoidal quantities are considered in the frequency domain. Fryze's theory considers them in the time domain.

According to Budeanu's theory reactive power can be expressed as (2) following active power's expression (1) to maintain similarity with sinusoidal power balance. From these considerations another power is present, namely distortion power (3) [1], [2].

$$P = \sum_1^n U_n I_n \cos\varphi_n \tag{1}$$

$$Q = \sum_1^n U_n I_n \sin\varphi_n \tag{2}$$

$$D = \sqrt{S^2 - (P^2 + Q^2)} \tag{3}$$

where P is active power, Q – reactive power, S – apparent power, D- distortion power, U_n and I_n are root mean square (RMS) values of voltage and current of n-th harmonic respectively.

Fig. 1 presents a visualization of triangle of powers in sinusoidal regimes (on the left- hand side) and the distortion power in non- sinusoidal regimes (on the right- hand side).

Fryze's theory on the other hand considers current (i) to be composed of two components – active component (i_a) and reactive component (i_r) [1], [2]. These components can be expressed by (4) and (5) respectively:

$$i_a(t) \cong \frac{P}{U^2} u(t) \tag{4}$$

$$i_r(t) = i(t) - i_a(t) \tag{5}$$

$$Q = UI_r \tag{6}$$

where P/U^2 has the meaning of conductance, u(t) is supply voltage, i(t) is supply current and capital U and I_r are RMS values of voltage and reactive current component respectively.

Instantaneous reactive power representation by space vectors proposed by Akagi [3] in the 80s of twentieth century has also been widely utilized.

Not only is Q defined ambiguously, but there is the question of how to calculate PF properly as well. There are also various methods to calculate PF. Some of these methods are as follows:

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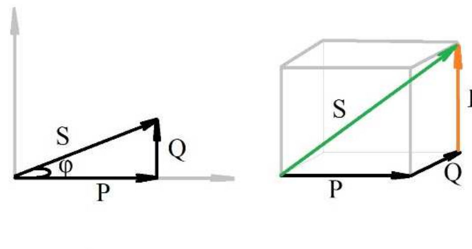

sinusoidal non- sinusoidal

Fig. 1. Representation of powers in sinusoidal and non-sinusoidal regimes.

From triangle of powers PF can be found as:

$$PF = \frac{P}{S}, Q = \sqrt{S^2 - P^2} \tag{7}$$

If definition of reactive power (2) is considered and then further with (7) a Fourier analysis is applied, then:

$$PF = atan\left(\frac{Q}{P}\right) \tag{8}$$

Whenever the method of quarter period delay is applied to (7), (8), then reactive power may be found as:

$$Q = \frac{1}{T}\int_0^T u(t)i\left(t + \frac{T}{4}\right)dt \tag{9}$$

III. CONTROL OF REACTIVE POWER BY PHOTOVOLTAIC SYSTEM

As many other countries have seen an urge and stimulation to implement RES in their power systems, RES have been implemented in Bulgaria also. Electricity generated from PV systems has been an appealing way of reducing electricity expenses even for domestic customers as many have installed rooftop PV systems. Here a problem arises. If a PV system is used for purposes of covering own needs, then it is being used only for change in real power consumption while reactive power remains unchanged. As billing measurement is typically done in point of common coupling (PCC), then the unchanged reactive power may result in a change of PF's value outside required borders [4]. Thus, to compensate reactive power without use of additional devices it is beneficial to use PV systems connected to the grid. Compensation is done by control of the PV's inverter and by injecting PV's power to the grid [5] - [9].

Since control of three - phase magnitudes is more complex, p - q theory, which is based on Clark's transformation on a stationary reference frame, is highly applicable [10] - [12]. This is described by (10) – (12):

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{12}$$

In order to simulate PV processes properly an accurate mathematical description and physical representation is required. Usually a PV cell is represented by an equivalent electrical circuit consisting of a current source, a series resistance based on cell's materials, a shunt resistance occurring due to leakage and one or two diodes [10], [13], [14].

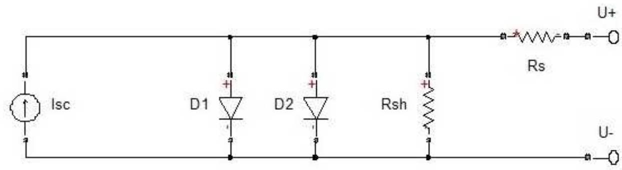

Fig. 2. Equivalent circuit of a PV cell

$$I = I_{sc} - I_0\left(e^{\frac{qV}{kT}} - 1\right), A \tag{13}$$

Where I_{SC} is short circuit photocurrent, I_0 is termed "dark current" which is the current whenever there is no irradiation.

Equation (13) describes an ideal behavior of a PV cell. In practice there is a ideality factor. Thus (13) can be transformed as shown in (14):

$$I = I_{sc} - I_0\left(e^{\frac{qV_d}{nkT}} - 1\right) - \frac{V_d}{R_{sh}}, A \tag{14}$$

where V_d is diode's voltage, n is ideality factor (between 1 and 2), R_{sh} is shunt resistance.

The second diode is included to describe the effects of recombination which is not considered in Shockley's equation for the model with one diode. The equivalent circuit with two diodes is shown on Fig. 2. Thus, by considering this equivalent circuit, setting ideality factors of both diodes as $n_1 = 1$ and $n_2 = 2$ respectively, having diode currents from Shockley's equations and with some simplifications we obtain (15) [14]:

$$I = I_{sc} - I_{d1} - I_{d2} - I_{sh}, A \tag{15}$$

where I_{d1} and I_{d2} are diode currents, I_{sh} is current obtained from V_d/ R_{sh}.

IV. MODELLING

Modelling and simulation is performed in MATLAB/ Simulink environment. The model consists of a PV module, a single – phase inverter, an AC source describing the grid, and control of inverter. The layout of the model is shown on Fig. 3. The LCL filter which is between the single – phase inverter and the grid is used to smooth out the current's waveform. For simplicity of the model PV module feeding the inverter is considered as a DC voltage source and a buck – boost converter is not present on the DC side.

Control of inverter is done following the p – q theory and applying pulse – width modulation (PWM). Clarke's transformation is implemented according to (10) and shown on Fig. 4. Furthermore alpha – beta voltages are subjected to Park's transformation for easier and more convenient control. This is displayed on Fig. 5. From Park's transformation only the quadrature axis' component is of interest for a single – phase and it is controlled via a proportional – integral (PI) control approach as the desired reference is zero. The integrator block at the right hand side is used to compose ωt which is used in forming of d – q vectors. Following (1) and (2) ωt is also subjected to sine and cosine functions which are further used in current control.

Inverter's current, termed Iinv, is controlled by a proportional – resonant (PR) controller. A PR controller is considered as a suitable replacement to PI as it is said that can introduce an infinite gain at fundamental frequency [15]. This is shown on Fig. 6. Current's desired amplitude can be set by the gain block at the left hand side of the subsystem. Since inverter's voltage vector is collinear with grid's voltage vector whenever power is injected into the grid, they are summed and form the considered reference voltage (Vref). The gain block 1/Udc at the end acts as a limit.

Obtained reference voltage Vref is used in single - phase PWM. The carrier signal is modelled as a triangular with amplitude between -1 and 1 and with 20 kHz frequency. Creation of gate pulses by PWM is shown on Fig. 7. The gate pulses for lower side switches (T4 and T2) are complementary to respective upper side switch. This is accomplished by NOT logical operators.

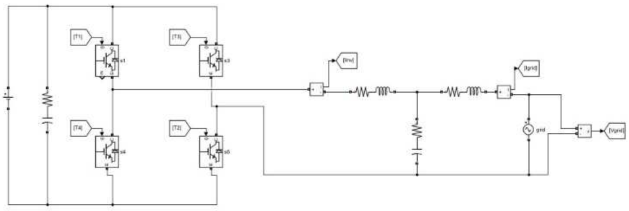

Fig. 3. Model of single – phase PV inverter connected to grid

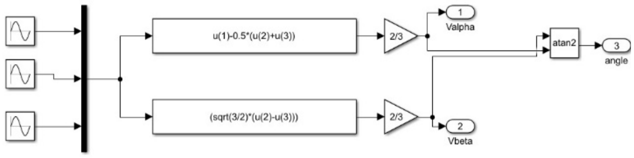

Fig. 4. Implementation of Clarke's transformation

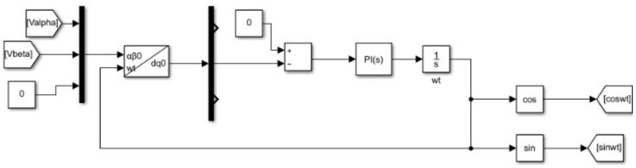

Fig. 5. Implementation of Park's transformation and formation of ωt.

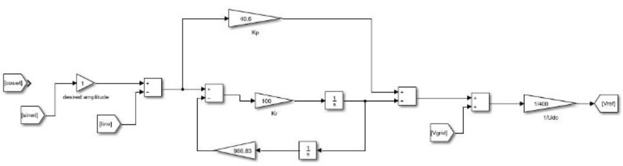

Fig. 6. Control of inverter's current and sum of collinear voltage vectors.

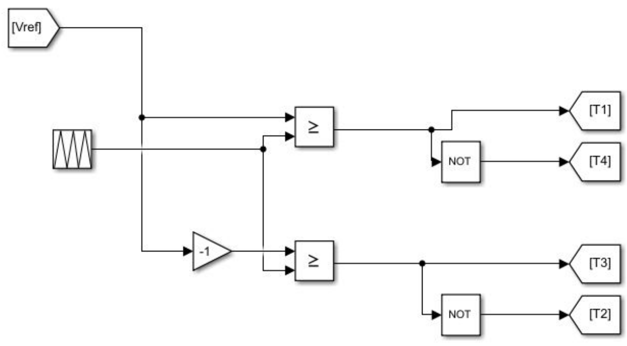

Fig. 7. Implemented PWM for single – phase inverter.

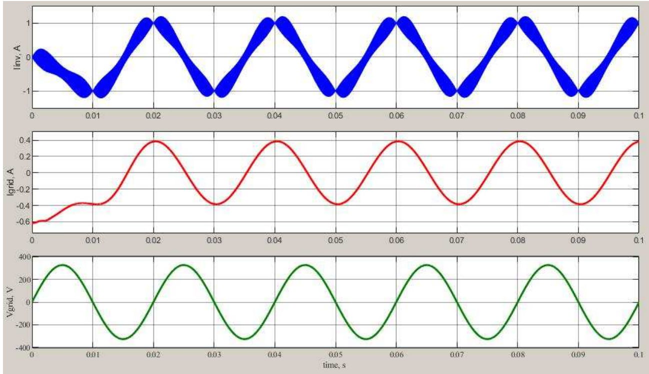

Fig. 8. Simulation results for Iinv with 1 A amplitude.

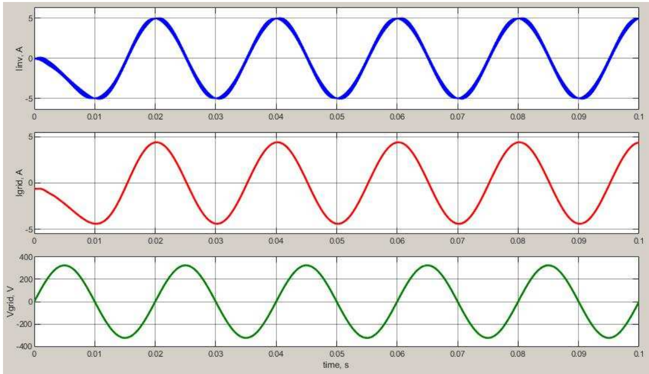

Fig. 9. Simulation results for Iinv with 5 A amplitude

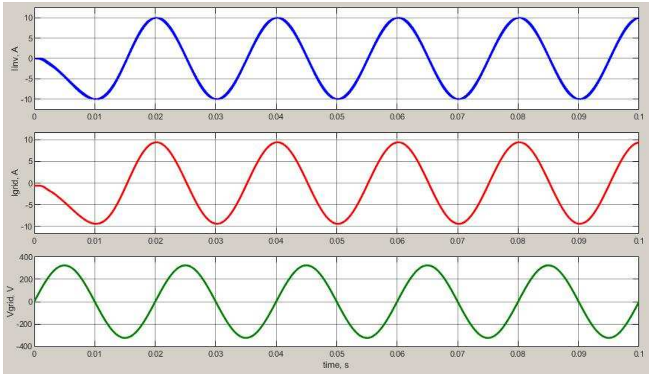

Fig. 10. Simulation results for Iinv with 10 A amplitude

Simulation results with amplitudes of Iinv of 1A, 5A and 10A are shown on Fig. 8 through Fig. 10. On these figures three plots are displayed. The first plot shows the relation of inverter's current Iinv to time. The second plot shows the relation between grid's current Igrid to time. Lastly, on the third plot is shown the relation of grid's voltage Vgrid to time.

CONCLUSIONS

This paper presents a simulation model of a single – phase PV inverter connected to the grid. The purpose is to control the flow and boundaries of reactive power.

From simulation results there is a phase difference of 90 electrical degrees between Ugrid and the currents on the other two plots, from which it can be considered that reactive power is being injected into the modelled grid. Furthermore the waveform of Igrid is significantly smoother than the waveform of Iinv which is due to the LCL filter. It can be also observed that the control of Iinv by the implemented PR controller is more satisfactory with higher values of set amplitude.

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