Grid connected PV systems with single-phase inverter

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***Abstract* — This article analyses a photovoltaic (PV) system connected to the electrical grid, which uses Maximum Power Point Tracking (MPPT) control. The system is composed of a single-phase inverter, filter and low-frequency transformer connected to the grid. A detailed simulation model of whole system including the control algorithms is created. The used method for MPPT is perturb and observe. A simulation study has been realized using Matlab/Simulink software environment. The obtained theoretical results for the single-phase PV system are validated experimentally under the same operating conditions.**

Keywords— simulation and computer models, single-phase PV system, MPPT controller, experimental study

I. INTRODUCTION

Optimization of energy use and increase of energy efficiency are measures that would support sustainable development in the provision of the necessary energy. One of the most important tasks is to develop strategies and systems, providing power to an environmental foundation. From a prospect only renewable energy sources (RES) such as the Sun and the wind meet all the conditions that must be introduced for the energy supply of the future. Moreover, these energy sources are inexhaustible, while the development of fossil fuels can only continue for a limited period.

Various Maximum Power Point Tracking (MPPT) control methods can be found in the literature [1], [2]. Mainly these methods are the perturb and observe, incremental conductance, open circuit voltage, pilot cell and etc. Perturb and Observe method (P&O) is amongst the most widespread methods used in PV inverters. However, many authors show that the incremental conductance method (ICM) gives comparable results to the P&O, but it is not so commonly used. Incremental conductance method is based on the fact, that at the maximum power point the derivative of the PV panel power, as a function of the panel's voltage equals zero. The main advantage of incremental conductance method against the P&O control algorithm is that ICM is able to determine the direction in which to perform the perturbation and can correctly locate the MPP, instead of fluctuating around it. Open circuit voltage method is used mainly on single photovoltaic cells rather than on whole PV arrays. The low-power PV systems (under 8kW) are usually connected to the grid using single-phase inverters. In these systems the requirement for electrical insulations from the grid is strong and the solution is to use a transformer in the inverter structure [3]. The simplest solution is to use a single-phase transformer for grid frequency (50-60Hz) at the output of the inverter. Thus, full isolation is achieved and any DC component of the injected current is cancelled.

The aim of this work is to create mathematical and simulation models of all elements of a photovoltaic system with single- phase inverter connected to the electrical grid. The models are developed in the Matlab/Simscape software and the power of the system is controlled using a P&O algorithm. The developed models are verified using the existing experimental platform for study of PV systems in the Technical University of Sofia [4].

II. PRESENTATION OF THE STUDIED SYSTEM

The structure of the studied system is presented at Fig. 1. The PV array is connected to the grid via single-phase inverter, LC filter and a low-frequency transformer. The PV array consists of one string with 5 panels connected in series, with total power 1200W. The models of the system elements and a complete simulation model are presented thereinafter.

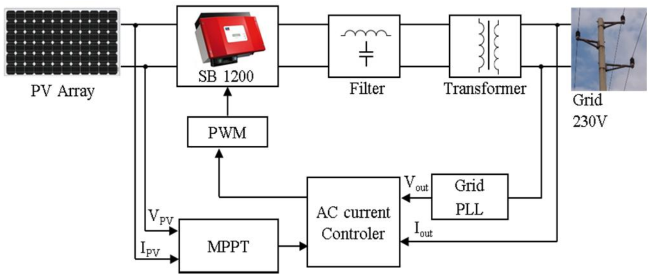

Fig. 1. The structure of the examined PV system with MPPT control.

III. MODELING OF THE PHOTOVOLTAIC STRING

The created PV cell and string model is derived from the equivalent circuit presented in Fig. 2. The circuit consist of a current source, diode and a series resistor [5], [6]. The current generated current by the cell is the photocurrent I_{pv}. The photocurrent is proportional to the solar radiation G_a.

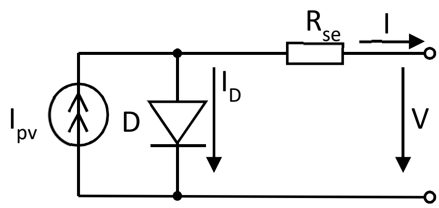

Fig. 2. Equivalent circuit of PV cells with a single diode and series resistance.

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When the cell is irradiated, the diode current I_d is subtracted from the current I_{pv}. The mathematical expression of PV cell current is [5], [8]:

$$I = I_{pv} - I_d \tag{1}$$

where: I_{pv} the photocurrent, I_d - the diode current,.

The following equation describes the diode current I_d:

$$I_d = I_0 \left(e^{\frac{q(V+IR_{se})}{AkT}} - 1 \right) \tag{2}$$

where: I_0 - saturation current, V - PV cell's terminal voltage, k - Boltzmann constant, q - electron charge, R_{se} – series resistance, T – cell temperature [K], A - ideality factor.

The saturation current I_0 is:

$$I_0 = D(T)^3 e^{\frac{-q\mathcal{E}_g}{AkT}} \tag{3}$$

where:

- D - diode diffusion factor;
- Ɛ is a material bandgap energy, specific for each material;

I_0 is also associated to the temperature. Determining it for conditions different than Standard Test Conditions (STC) is as follows:

$$I_0 = I_{ostc} \left(\frac{T}{Tstc}\right)^3 e\left[\left(\frac{q\mathcal{E}g}{kA}\right)\left(\frac{1}{Tstc} - \frac{1}{T}\right)\right] \tag{4}$$

where: I_{0stc} is the saturation current at STC according to (8), T_{stc} = 298K is temperature at STC.

Taking into account (1) and (2) the PV cell current is expressed as follows:

$$I = I_{ph} - I_0 \left(e^{\frac{q(V+IR_{se}}{CkT}} - 1 \right) \tag{5}$$

The module (array) shape factor C depends on the amount of sequentially connected cells in one module N_s, as well as the ideality factor A of the diode. The equation is following:

$$C = AN_s \tag{6}$$

The shape factor C is found by the expression:

$$C = \frac{v\left(\left(V_{mp,stc} + I_{mp,stc}R_{se}\right)\right)}{ln\left(1 - \frac{I_{mp,stc}}{I_{sc,stc}}\right)} \tag{7}$$

where: $V_{mp,stc}$ and $I_{mp,stc}$ are respectively the voltage and the current at the point of maximal power at standard test conditions.

The saturation current $I_{0,stc}$ is calculated as follows :

$$I_{0stc} = I_{sc,stc} exp\left(\frac{-vV_{oc,stc}}{C}\right) \tag{8}$$

The current I_{pv} could be calculated for different weather conditions as follows:

$$I_{0stc} = I_{sc,stc} exp\left(\frac{-vV_{oc,stc}}{C}\right) \tag{9}$$

where: G_{stc} =1000W/m^2 is the solar irradiation at STC; $I_{sc,stc}$ is the short-circuit current at STC and the coefficient k_i is the short-circuit current temperature coefficient.

IV. Modeling of the Single-Phase Inverter

The inverter used in the studied system is a single-phase connected to the electrical grid by LC filter and a low-frequency transformer. The inverter circuit is a full bridge with 4 MOSFET transistors [8], [9]. One of the reasons for using a transformer is the ability to increase the voltage from the inverter 2.7 times, thus providing the possibility to operate with a lower DC input voltage. Besides, the transformer provides an electrical isolation from the grid and cancels any DC component of the inverter output current. The structure of the developed detailed model of the inverter, which includes LC filter and transformer, is presented in Fig. 3.

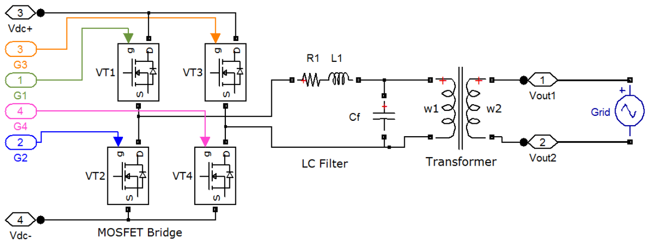


Fig. 3. Detailed model of single-phase inverter with LC filter and transformer in Matlab.

The inverter model is detailed because it also takes into account transistor switching with a modulation frequency of 20kHz. It is used to simulate short periods of time and determine the exact waveforms of voltages and currents in the circuit of the entire system.

The values of the inverter elements used in the simulations are as follows:

- Input filter capacitor for V_{dc} 5000µF;
- LC filter L_l= 0,002H, R_l=0,02Ω, C_f=5µF;
- Transformer: inductance and active resistance of the magnetizing branch L_m = 0,95H, R_m= 9400Ω. Primary and secondary leakage inductance winding L_{s1}=0,0005H, L_{s2}=0,002H; Active winding resistances R_{w1}=0,27Ω and R_{w2}=0,55Ω.

The block diagram of the created simulation model of the PV system with single-phase inverter and a transformer, developed in the Matlab/Simscape environment is shown in Fig. 4.

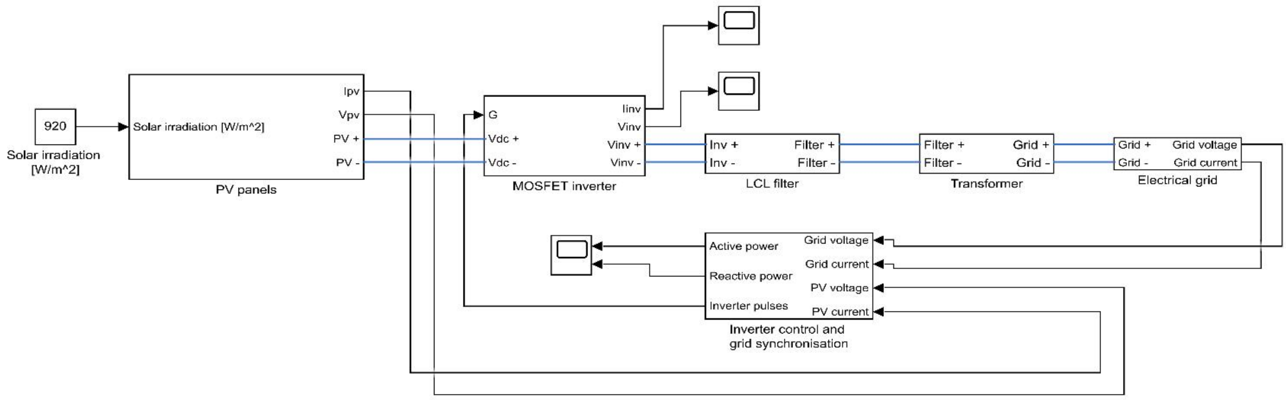


Fig. 4. Block diagram of the studied system in Matlab/Simscape.

V. Method for Maximum Power Point Traking

In this article is used Perturb and Observe method for MPPT. In the P&O method a slight deviation from the current operating point is induced and the change in the power is observed. If the deviation increases the power, this is the correct direction of change of the operating point and the deviation continues in the same direction. If the power decreases with deviation, the operating point must move in the other direction. If the power goes down in both directions, the current operating point coincides with the maximum.

The P&O method does not find the MPP exactly, but fluctuates around it, and the algorithm must change the sign of the perturbation after each measurement.

P&O method uses the following dependencies for maximum power point traking:

$$\begin{array}{l} \left.\begin{array}{l}+\Delta P\\ +\Delta V\end{array}\right\rangle + \Rightarrow \quad \Delta V\uparrow \quad \Delta I\downarrow \\ \left.\begin{array}{l}-\Delta P\\ -\Delta V\end{array}\right\rangle + \Rightarrow \quad \Delta V\uparrow \quad \Delta I\downarrow \\ \left.\begin{array}{l}+\Delta P\\ -\Delta V\end{array}\right\rangle - \Rightarrow \quad \Delta V\downarrow \quad \Delta I\uparrow \\ \left.\begin{array}{l}-\Delta P\\ +\Delta V\end{array}\right\rangle - \Rightarrow \quad \Delta V\downarrow \quad \Delta I\uparrow \end{array} \tag{10}$$

Using perturb and observe algorithm, the photovoltaic current (or voltage) is changed by a slight increment (ΔI or ΔV) and the obtained change in power (ΔP) is measured. If the power (P) and the voltage (V) are positive, V increase and I decrease (see equation 10), it's the same when P and V are negative. If P is positive and V is negative V decrease and I increase, it's the same in last inequality. The implemented model of the Perturb & Observe MPTT algorithm in Simulink is shown in Fig. 5.

VI. Simulation Result

Several simulations were performed with the created models. Here are shown the most important results from the simulations and experiments.

On the Fig.6 is shown the operation of a system under abrupt change in solar radiation in both directions – down and up.

The graph shows that current and power follow well the change in solar radiation. Even with sudden changes in radiation, the system manages to work them out but with some delay. The delay is due to the MPPT algorithm, which has limited voltage change rate. Nevertheless, the performance of the developed algorithm is good enough for real weather conditions where the change of the solar radiation in one second almost never happens.

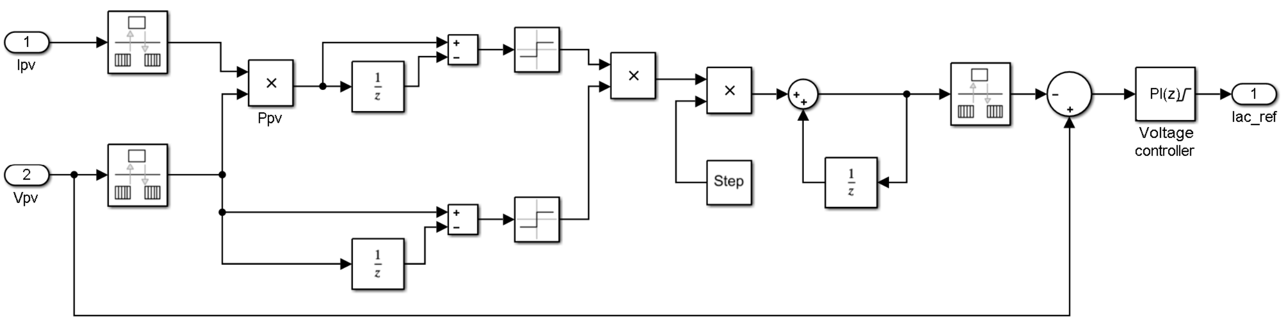


Fig. 5. Perturb&Observe MPPT algorithm implementation in Simulink.

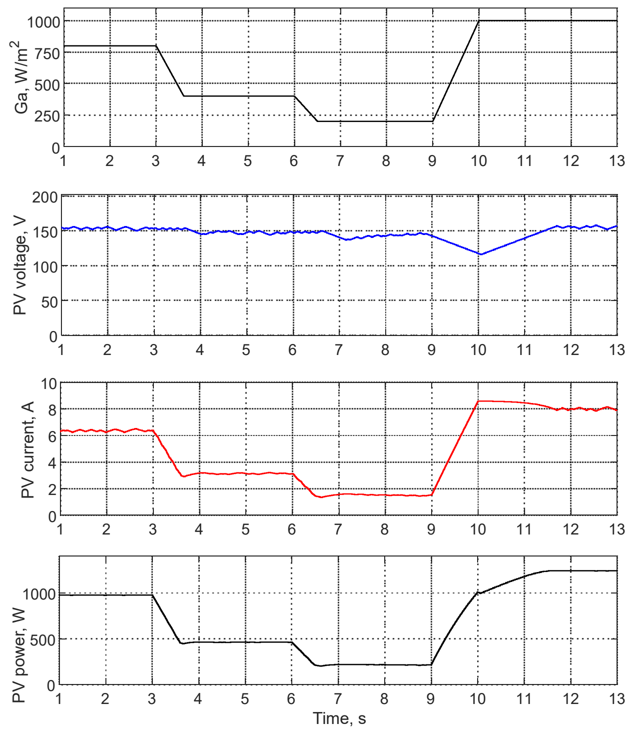
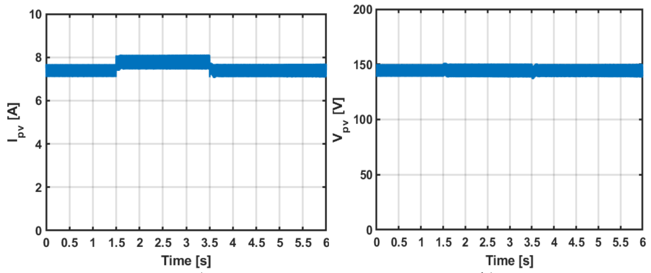


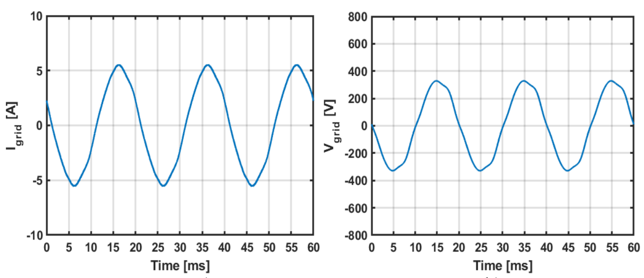
Fig.6 Simulation results under variable solar radiation.

The output current and voltage from the simulated photovoltaic array are shown on Fig.7. Fig. 8 shows the current and voltage of the grid.



a) b)

Fig.7. The output current from photovoltaic array a) output voltage from photovoltaic array b).



a) b)

Fig.8. The current injected in the grid a), voltage of the grid b).

From the simulated graphs, it can be seen that current is not an ideal sinusoidal wave due to voltage distortion. The sumulated result are very similar to the experimental that confirms the correct approach of modeling of the system.

VII. Experimantal Results

The validity of the created models has been proven with data from an experimental photovoltaic array, situated in the location of the Technical University of Sofia [9]. Fig. 9 shows experimentally obtained voltage and current of the PV array at the DC input of the inverter. Fig. 10 shows experimental output inverter current and voltage of the grid.

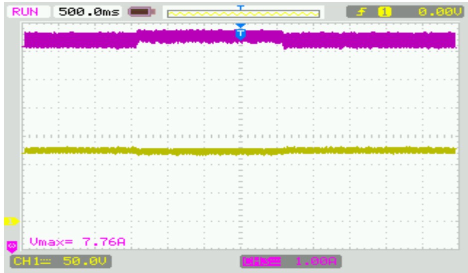


Fig.9. The experimantal voltage (yellow CH1) and current (purple CH2), from photovoltaic array at the input of the inverter.

Fig.10. The experimantal voltage of the grid (yellow CH1) and current injected in the grid (purple CH2).

It has been done harmonic analysis of experimental curve of current and voltage. Fig. 11 shows the grid voltage harmonic content.

In order to study the impact of the grid voltage distortions on the current harmonic content a simulation has been carried out. In the simulation was used grid voltage with same harmonic composition as a measured one. In the Simulink model, the grid was represented as a voltage source with the voltage of the form:

$$V_g(t) = \sum_{i=1}^{n} V_{im} \sin(i\omega t + \varphi_i) \qquad (11)$$

where i is the number of the corresponding harmonic component, V_{im} – the amplitude of i-th harmonic, φ_i – the phase of the i-th harmonic.

Harmonic analysis of simulated waveforms of current and voltage have been done.

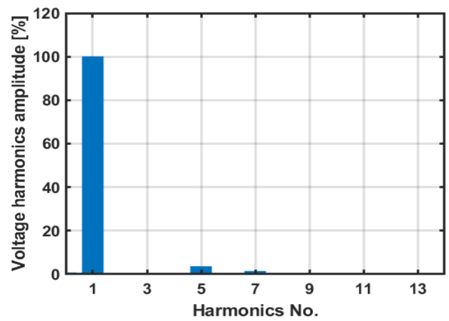
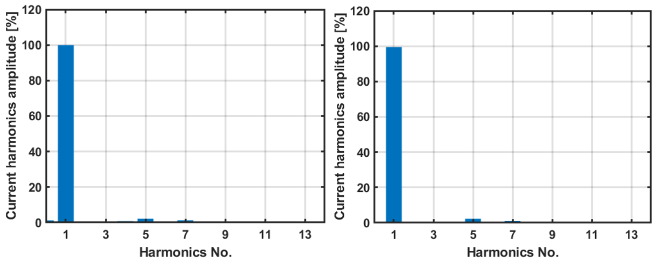


Fig.11. Experimental voltage harmonics content.

Fig. 12 shows the experimental and simulated current harmonics content.



a) experiment b) simulation

Fig.12. Experimental current harmonics amplitude a), simulated current harmonics amplitude b).

From these results it may be concluded that the output current waveform depends not only of the inverter voltage but also of the distortions of the grid voltage. In order to keep the current THD as low as possible it is necessary to apply special measures for compensation of the grid voltage distortions like more complicated current controller.

VIII. Conclusion

The paper proposes grid connected PV system with a single phase inverter and perturb and observe algorithm for MPPT. A model of the system has been developed in Matlab/Simscape. It has been done harmonic analysis of the current and voltage. Simulation results for the single-phase system were compared to experimental tests on a real PV array with the same parameters, which show good similarity. It is shown by simulations that the inverter output current is distorted due to the non-sinusoidal grid voltage in the point of connection. Additional measures may be necessary if the inverter current does not meet the local Grid code requirements for harmonic contents.

Acknowledgment

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References

[1] A. Mohapatra, B. Nayak and C. Saiprakash, "Adaptive Perturb & Observe MPPT for PV System with Experimental Validation," 2019 IEEE International Conference on Sustainable Energy Technologies and Systems (ICSETS), Bhubaneswar, India, 2019, pp. 257-261

[2] M. A. Elgendy, B. Zahawi and D. J. Atkinson, "Evaluation of perturb and observe MPPT algorithm implementation techniques," 6th IET International Conference on Power Electronics, Machines and Drives (PEMD 2012), Bristol, 2012, pp. 1-6

[3] V. Lazarov, Z. Zarkov, H. Kanchev, "Grid-connected single-phase inverter for renewable energy sources," Proceedings of the Technical University – Sofia, vol. 59, book 2, 2009, pp. 122-130

[4] Z. Zarkov, L. Stoyanov, H. Kanchev, V. Milenov, V. Lazarov, "Study of photovoltaic systems' performances with different module types," Materials Science Forum, Vol. 856, 2016, pp. 279-284

[5] W. De Soto, S.A.Klein and W.A.Beckman, "Improvement and validation of a model for photovoltaic array performance," Solar Energy, Volume 81, Issue 1, January 2007, pp. 150-154.

[6] M. G. Villalva, J. R. Gazoli and E. R. Filho, "Modeling and circuit-based simulation of photovoltaic arrays," 2009 Brazilian Power Electronics Conference, Bonito-Mato Grosso do Sul, 2009, pp. 1244-1254

[7] R.Chenni, M.Makhlouf, T.Kerbache and A.Bouzid, "A detailed modeling method for photovoltaic cells," Energy, Vol. 32, Issue 9, September 2007, pp. 1724-1730.

[8] S. A. Mahmoud, M. M. Alsari, E. I. Reda and R. M. Alhammadi, "MATLAB modeling and simulation of photovoltaic modules," 2012 IEEE 55th International Midwest Symposium on Circuits and Systems (MWSCAS), Boise, 2012, pp. 786-789.

[9] J. Wang, B. Ji, T. Wu and J. Chen, "Modeling and analysis of a single phase inverter system with PWM switch model," IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society, Dallas, TX, 2014, pp. 5115-5119.