Modelling and Control of a Grid-connected PV System for Smart Grid Integration

Hristiyan Kanchev[1)], Nikolay Hinov[1)], Dimitar Arnaudov[1)] and Rad Stanev[2)]
Technical University of Sofia, 8 Kliment Ohridski blvd., 1000 Sofia, Bulgaria
[1)] Department of Power Electronics, Faculty of Electronic Engineering and Technologies
[2)] Department of Power Engineering, Faculty of Electical Engineering
hkanchev@tu-sofia.bg

Abstract*: This paper presents the modelling and control of a grid-connected PV system in LabVIEW environment. The proposed control system provides interactivity with the grid: the control system features communication with the grid operator and thus it is able to operate either in maximum power point tracking (MPPT) or in limited power point tracking (LPPT). The second is useful in certain cases when there is considerable excess of renewable energy generation and low consumption – in such cases, although rarely, the grid operator can curtail certain PV or wind generators in order to preserve the system stability. With the feature of LPPT, PV generators can be dispatched to maintain a limited power output, controlled by the distribution system operator thus enabling interactivity with the grid.*

1. INTRODUCTION

This paper presents the modeling and control of a grid-connected photovoltaic system featuring dispatching by the grid operator - a control strategy that ensures a smooth power control, allowing either injection of the maximum available PV power to the grid or an active PV plant control. The system is modeled and tested in LabVIEW environment. The described control strategies allow grid-interactive features: power limitation of the system without the switching off whole strings of the PV array. This control method methods provides dispatching of the PV systems enabling their further integration in the Smart Grid.

In power systems with high percentage of PV generators massive overproduction can occur causing difficulties for distribution and transmission network operators. In those cases, although rarely, the dispatchers can limit the amount of generated PV power. PV systems are rather passive generators from the grid operator point of view, because the output power control is passive and discrete (it is realized by the PV array owner by disabling strings or switching off the inverter), in this way it is hard to provide smooth and accurate power limitation [1, 2]. Therefore it is interesting to enable Maximum Power Point Tracking (MPPT) and Limited Power Point Tracking (LPPT) by demand: operation of the system at a given constant power output below the maximum power point. Moreover, communication with the grid operator would allow switching between both control strategies automatically.

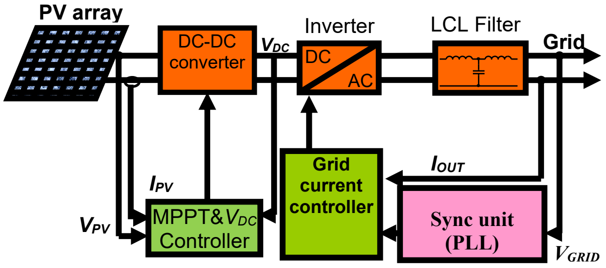

Fig.1. Structure of the studied system

2. PV ARRAY MODELING

Two main approaches of PV system modeling can be found in literature: One approach is the calculation of the PV system daily, monthly and yearly average yield at a given location, often for the goals of a feasibility study. In this approach the model searches to determinate the output power or the PV efficiency and the result is an estimation of the energy generated for a given period.

The second approach consists in modeling of the electrical variables of the panel - the PV cell is modeled by its equivalent circuit. In this study the second approach is chosen because the MPPT and LPPT controls generate a reference of an electrical variable – the inductor current of the boost converter. This approach allows modeling of the electrical variables of the PV system – the PV array current and voltage, DC boost converter output and input voltages and currents and those of the grid-connected inverter. As a result, the so created model can be used with real-time meteorological data for hardware in the loop implementations.

Two equivalent circuits of a PV cell are common in the literature – the equivalent circuit with one diode (fig. 2) and with two diodes (fig. 3) [3, 4]. Both equivalent circuits use a current source to model the photocurrent I_{ph}, a series and a shunt resistance (R_s and R_{sh}). A module is modeled by the number of cells in series and in parallel, then using to the number of strings and panels in string is modeled the entire PV array.

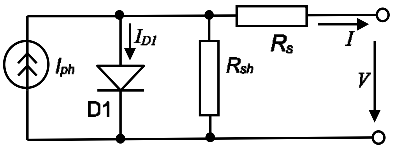

Fig. 2. One diode photovoltaic cell equivalent circuit

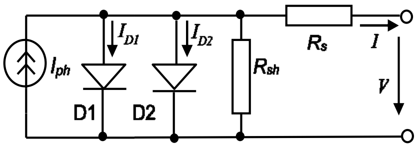

Fig. 3. Two diode photovoltaic cell equivalent circuit

The photovoltaic model implemented in this study is based on the one diode model [3 - 5]. This model is preferred and widely used, because of the reduced number of parameters that have to be taken into account. The cell temperature calculation is based on the ambient temperature and the solar irradiation. In this way the model input variables are the ambient temperature (T_a) and the global irradiation at the PV array surface (G_a). The model is implemented as a virtual instrument in the LabVIEW environment (fig. 4). The studied PV array is composed of 2 strings with 3 modules each with a total peak power of 330W. Modeling a given PV array is done starting from the module rated parameters: module maximum power, short circuit current, open circuit voltage and the number of cells connected in series and in parallel are taken from its datasheet and static simulations are performed with constant values of T_a *and* G_a. There are three constants (*C1, C2 and C3)* in the model whose values are adjusted in order to fit the I-V curves given in the module datasheet for several values of G_a and T_a. The constant *C1* models the cell short-circuit current dependence on the solar irradiation, *C2* – the influence of G_a and T_a on the cell temperature. The constant *C3* determines the influence of the solar irradiation on the cell open circuit voltage. The resulting I-V curves for one module are presented in fig. 5.

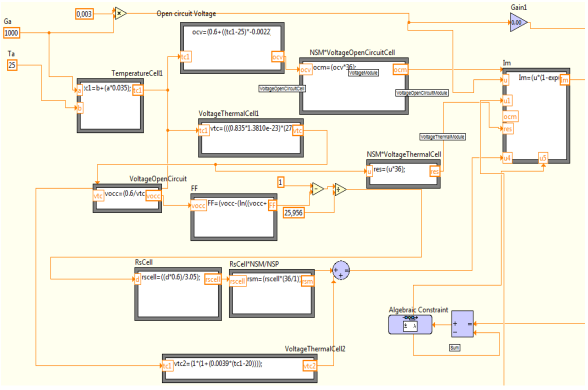

Fig. 4. PV cell virtual instrument implementation in LabVIEW

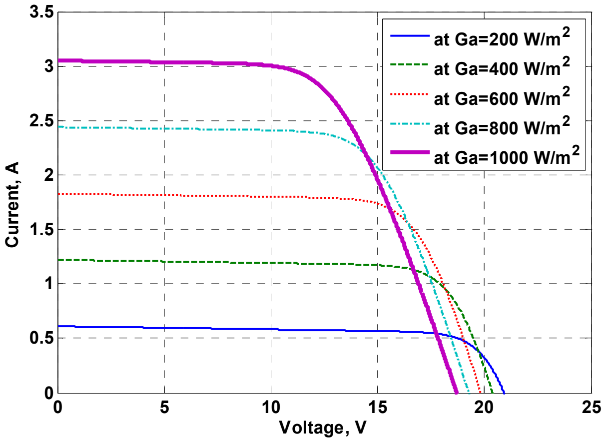

Fig. 5. *P=f(V)* curves for various ambient temperatures

3. MAXIMUM POWER POINT TRACKING OF A PV ARRAY

The I-V characteristic of a PV array under constant irradiance (fig.4) has a unique point, called maximum power point (MPP) at which the array reaches the maximum power for given conditions. This point changes when variations in the solar irradiance or ambient temperature occur. If the PV array is directly connected to a load or a battery, the PV array's operating point will be different from the MPP in most cases. A solution to this problem is the introduction of a DC-DC converter between the PV array and the inverter (or the load), so that the PV array operating voltage and current are independent from the load and are can be maintained at the MPP by an appropriate control algorithm. The location of the MPP is not known a priori, due to the fact that this point moves in function of the solar irradiance and cell temperature, as illustrated in fig. 5.

There is a number of studies on the implementation of a fuzzy logic controller to track the MPP of photovoltaic arrays, however it is difficult to find a model of the whole conversion chain: PV array, DC-DC converter with fuzzy logic-based MPPT and inverter. In this paper we propose a fuzzy logic-based MPPT that controls the current drawn from the PV array through a boost DC-DC converter.

Several Maximum Power Point Tracking (MPPT) control strategies exist [1, 2]: perturb and observe; open circuit voltage; pilot cell; incremental conductance; parasitic capacitance etc. Although by now the Perturb and Observe method is the most common in PV inverters available on the market. However, researches demonstrate that results obtained from the incremental conductance method are similar to the P&O, so it is difficult to say which one performs better [5, 6].

When using P&O method, the PV array current (or voltage) is perturbed by a small increment (ΔI or ΔV) and the resulting change in power (ΔP) is measured. If ΔP is positive, the next perturbation is also in this direction (with same algebraic sign). If ΔP is negative, the system's operating point has moved away from the MPP, thus the sign of the perturbation will be changed in order to step back, towards the MPP (see fig.1 and fig.2).

Despite of its advantages, however this method has certain limitations:

- It becomes difficult for the MPPT algorithm to find the location of the MPP at low solar irradiances because the MPP curve flattens out or in case of partial shading when the resultant I-V curve has two local maximums.

- The P&O algorithm doesn't locate the MPP, but oscillates around it, changing the sign of the perturbation after each measurement.

And finally, it is known that most of the P&O implementations can have random behavior under rapidly changing solar irradiance [1 - 3].

Other popular MPPT methods are:

Open circuit voltage, which uses the ratio of the array's MPP voltage to its open-circuit voltage.

Short-circuit current method. Uses short-circuit current instead of open-circuit voltage.

Pilot cell method. Here the open circuit voltage or short-circuit current method is used, but on a single PV cell rather than on the whole array.

Incremental conductance method is based on the fact, that at the MPP the derivative of the power, as a function of the voltage is zero (fig.1 and fig. 2) [1]. The main advantage of this method against the P&O method is that it can decide in which direction to perturb and can locate the MPP exactly, instead of oscillating around it.

The parasitic capacitance method is similar to the incremental conductance but the effect of the cell's parasitic junction capacitance is taken into account [2].

4. IMPLEMENTATION OF PERTURB AND OBSERVE STRATEGY BY A FUZZY LOGIC CONTROLLER

The fuzzy logic is a form of many-valuated logic. It deals with reasoning that is rather approximate than fixed and exact. In contrast with traditional logic, it can have varying values. Fuzzy logic variables can have a truth value that ranges in degree between 0 and 1 (completely false and completely true). This makes it far more flexible than binary logic, where sets have two-valued logic: true or false.

A basic application of fuzzy logic might characterize sub ranges of a continuous variable. For example a temperature measurement can have several separate membership functions defining particular temperature ranges: PB - Positive big, PM - Positive

Middle, PS - Positive Small, ZE - Zero, NS - Negative Small, NM - Negative Middle and NB - Negative Big .

In this research fuzzy logic is used to search for the MPP of a PV array under changing solar irradiance and temperature. A fuzzy logic-based MPPT is robust and with simple design [6-7]. This method does not require exact knowledge of the PV-array, in other words, the same MPPT controller could be used in different PV arrays. The main stages in the operation of a fuzzy logic controller (FLC) are fuzzification, rule-based inference and defuzzification (fig. 6).

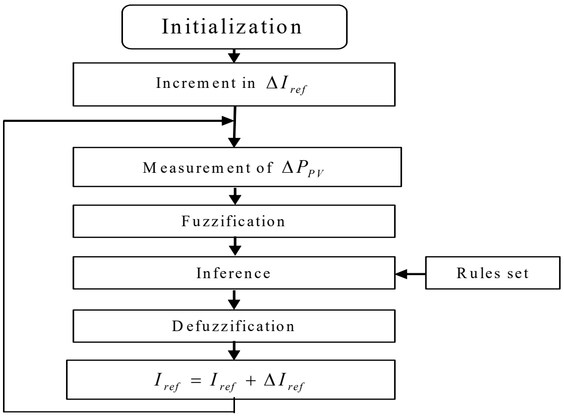

Fig. 6. Flowchart of the FLC

In the studied system, input variables of the fuzzy logic controller are the change in array's power ΔP_{pv} and change in the array current ΔI_{pv}. The output of the FLC is the magnitude of ΔI_{ref} (the change in the boost converter current reference). This reference is the command variable for controlling the current drawn from the PV array.

The flow chart of the proposed FLC is presented in fig.6 and the fuzzy logic rules are presented in table 1. The variables are fuzzificated using linguistic values. The proposed algorithm is a variation of the P&O method. It perturbs the PV array current reference with a small value ΔI_{ref}, observing the change in PV array's power ΔP_{PV}. If a positive perturbation is applied in I_{ref} and the variation is positive ($\Delta P_{PV}>0$), the FLC will continue increasing I_{ref} until ΔP_{PV} becomes close to zero. At the other hand, if an increment in I_{ref} results in a decrease in PV power, then the FLC will "step back" the PV array current reference until the derivative of the array power is zero, thus the MPP is reached.

Table 1. FLC rules set.

Rule	If ΔP_{PV}	and ΔI_{PV}	Then ΔI_{ref}
1	PB	P	PB
2	PM	P	PM
3	PS	P	PS
4	ZE	P	PS
5	NS	P	NS
6	NM	P	NM
7	NB	P	NB
8	PB	ZE	PB
9	PM	ZE	PM
10	PS	ZE	PS
11	ZE	ZE	ZE
12	NS	ZE	NS
13	NM	ZE	NM
14	NB	ZE	NB
15	PB	N	NB
16	PM	N	NM
17	PS	N	NS
18	ZE	N	NS
19	NS	N	PS
20	NM	N	PM
21	NB	N	PB

5. LIMITED POWER POINT TRACKING (LPPT) CONTROL BY FUZZY LOGIC CONTROLLER

This control system determines the current reference value of the boost converter. Thus the photovoltaic array operation point can be maintained at a given position, imposed by the system operator. Control of the absolute value of the power drawn from the PV array is realized by fuzzy logic based controller (FLC), whose block diagram is presented on fig.7. The dispatcher sends a limited power reference that should be respected by the PV plant.

The power reference P_{LPP} is subtracted from the PV array measured power and then the difference is expressed as a percentage of the PV array measured power (0÷100%). This is the input variable of the fuzzy logic controller. The output of the FLC is the magnitude of the change of boost converter current reference ΔI_{ref}. This reference is the command for controlling the current drawn from the PV array. The variables are fuzzificated using linguistic values: PB - Positive Big, PM - Positive Middle, PS - Positive Small, ZE - Zero, NS - Negative Small, NM - Negative Middle and NB - Negative Big.

The proposed algorithm changes the PV array current reference with a certain value ΔI_{ref} in function of the difference between the PV array actual output power and the limited power reference P_{LPP}. If the difference is positive, the PV array power is greater than the demanded limited power. In this case the FLC decreases the PV current reference ($\Delta I_{ref}<0$), in order to obtain less output power from the PV array. On the other hand, if the difference is negative the PV array output power is smaller than the demanded limited power. In this case, the PV array current reference will be increased ($\Delta I_{ref}>0$), to obtain exactly the demanded limited power output from our PV array. The rules of the proposed fuzzy logic LPP controller are presented in table 2.

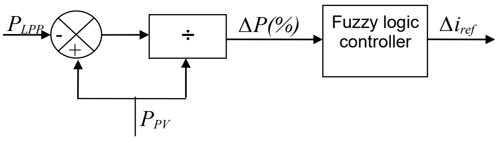

Fig.7. Block diagram of the LPP control with fuzzy logic

The limited power point tracking controller operates in MPPT mode if the operator does not impose a power limitation or if there is a lack of primary potential (solar irradiation).

Table 2. FLC for LPPT control rules set.

Rule no.	If ΔP	Then ΔI_{ref}
1	PB	NB
2	PM	NM
3	PS	NS
4	ZE	ZE
5	NS	PS
6	NM	PM
7	NB	NB

5. MODELING OF THE DC BOOST CONVERTER AND THE GRID-CONNECTED INVERTER

The boost converter is modeled with the equations, obtained by the Kirchhoff's laws application and the switching function:

$$\begin{cases} \frac{di_L}{dt} = \frac{1}{L_b}\left[V_{b,i} - (1-d)V_{dc}\right] \\ \frac{dV_{dc}}{dt} = \frac{1}{C_b}\left[(1-d)i_L - i_{inv}\right] \end{cases} \quad (1)$$

where i_L is the boost input current, L_b is the inductance, $V_{b,i}$ is the boost converter input voltage, d is the switch state, V_{dc} is the boost output voltage, C_b is the boost capacitor and i_{inv} is the boost converter output current (equal to the input current of the inverter). The boost converter model uses the input voltage and the output current as input variables and the input current and the output voltage are calculated.

The modeled single-phase inverter is full-bridge transistor voltage source converter. It is modeled by the switching function (γ = -1 or 1 depending on the inverter branches state) and thus the inverter output voltage is:

$$V_{1n} = \gamma . V_{dc} \quad (2)$$

6. SIMULATION RESULTS

The model of the described system is implemented and simulated in LabVIEW environment. Simulations were performed with the solar irradiation (Ga) and ambient temperature (Ta) profiles presented in fig.8 along with the power generated by the PV array P_{PV}.

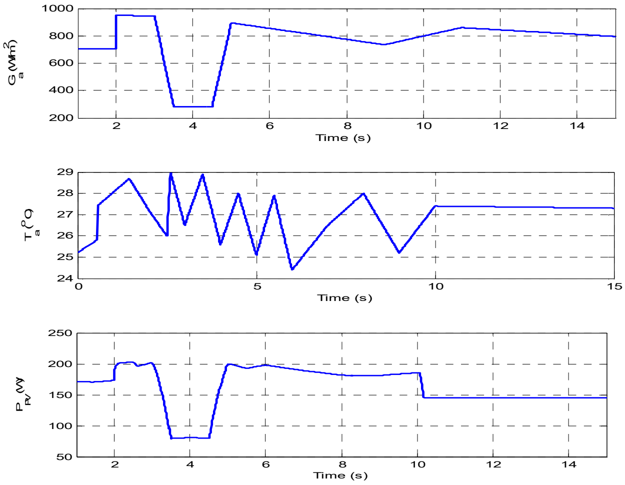

Fig. 8. Simulation results

The simulated variations of the ambient temperature and solar irradiation are artificial and illustrate system stability and proper operation of the fuzzy logic controller. The control system operates in MPPT and after 10 seconds a limited power reference $P_{LPP}=150W$ is imposed. The PV power is then limited to 150 W and, as demonstrated in fig. 8 the system follows this reference accurately.

7. CONCLUSION

This paper presents the modelling and control of a grid-connected PV system in LabVIEW environment. The proposed control system provides interactivity with the grid: the control system features communication with the grid operator and thus it is able to operate either in maximum power point tracking (MPPT) or in limited power point tracking (LPPT). The MPPT and LPPT control is implemented through a fuzzy logic controller. Simulation results demonstrate proper operation of the system even by profound changes in the ambient temperature and solar irradiation - fluctuations with several degrees Celsius or several hundreds of W/m^2 in a few seconds.

ACKNOWLEDGEMENT

This research is realized in the framework of the project 'GIFEMN', Bulgarian National Scientific Fund and Agence Universitaire de la Francophonie.

REFERENCES

[1] Farhat M. and L. Sbita, “Advanced fuzzy MPPT control algorithm for photovoltaic systems”, Science Academy Transactions on Renewable energy Systems Engineering and Technology, vol. 1, no.1, pp. 29-36, 2011

[2] Takun P., S. Kaitwanidvilai and C. Jettanasen, “Maximum power point tracking using fuzzy logic control for photovoltaic systems”, proceedings of the International Multiconference of Engineers and Computer Scientists (IMECS'11), 16-18 March, Hong Kong, China, 2011

[3] Ishaque K., Z. Salam, H. Taheri, “Simple, fast and accurate two-diode model for photovoltaic modules”, Solar Energy Materials and Solar Cells, vol. 95, pp. 586-594, 2011

[4] Hansen, A., Sorensen P. et al. Models for stand-alone PV system, Riso National Laboratory report (Riso-R-1219(EN)/SEC-R-12), 2000.

[5] Tian H., F. Mancilla-David F., et al., “A cell-to-module-to-array detailed model for photovoltaic panels”, Solar Energy, vol. 86, pp. 2695-2706, 2012.

[6] Lazarov, V., Z. Zarkov, et al., “Grid-connected PV system with MPPT control“, Proceedings of the Technical University – Sofia, vol. 63/2013, book 1, pp. 357-366, ISSN 1311-0829, 2013

[7] Lazarov, V., Z. Zarkov et al., “Grid-connected photovoltaic systems with limited output power control”, Proceedings of the Technical University – Sofia, vol. 63/2013, book 2, pp. 331-340, ISSN 1311-0829, 2013.