Modelling and simulation of a stand-alone photovoltaic system

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Abstract: - This paper presents a number of models for modelling and simulation of a stand-alone photovoltaic (PV) system. The work has been supported by the no.126/2006 Excellence Grant „*Research concerning the achievement of an intelligent railways vehicle for a safe comfortable and efficient passengers transport*". The main activities in this work purpose to establish a library a simple mathematical models for each individual component of a stand-alone PV system, namely solar cells, battery, controller, inverter and load. The implementation is done using Matlab/Simulink, a simulation program that provides a graphical interface for building models as modular block diagrams.
Key-Words: - modelling, simulation, solar cells, photovoltaic system, PV generator

1 Introduction

In the last years the application of renewable energy sources in electricity supply systems rapidly increase. The limited resources and high cost of conventional energy sources (oil, gas, coal), as well as the continued environmental pollution are some of the main reasons for their widespread introduction in electrical power systems.

The paper investigates on the modelling of a stand-alone PV system. Starting from the analysis of the equivalent model of the system components and from the description of the control strategies, a complete simulation model of the system and of the control strategies was realized in the Matlab-Simulink environment. Each physical component is modelled as a separate component subroutine and Simulink block for a modular system simulation program. All of the developed models are based on physical and chemical principles, as well as empirical parameters. The models have been designed to be as general as possible and all the blocks take both design parameters, (such as number of cells in series and/or parallel) and specific component characteristics obtained from manufacturers or from experiments (such us current-voltage curve) into account.

2 Component models for stand alone PV system

The main purpose of this section is to describe the models for the elements of a stand-alone PV system: PV generator, battery, controller, inverter and load. The modelling of the PV system is based on modular blocks, as illustrated in figure 1. The modular structure facilitates the modelling of the other system structures and replacing of elements, for instance a DC load instead of an AC load.
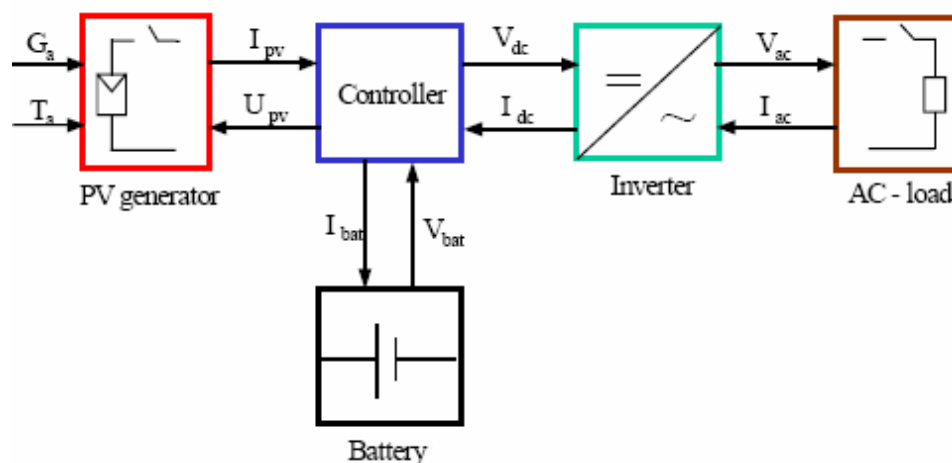

Fig. 4: Block diagram for the stand-alone PV system

2.1 PV Generator model

A PV generator is the whole assembly of solar cells, connections, protective parts, supports etc. In the present modelling, the focus is only on cell/module/array.

2.1.1 PV cell model

During darkness, the solar cell is not an active device; it works as a diode, i.e. a p-n junction. It produces neither a current nor a voltage. However, if it is connected to an external supply (large voltage) it generates a current I_D, called diode current or dark current.

A solar cell is usually represented by an electrical equivalent one-diode model [4], as shown in figure 2..

The model contains a current source I_{ph}, one diode and a series resistance R_S, which represents the resistance inside each cell and in the connection between the cells. The net current is the difference between the photocurrent I_{ph} and the normal diode current I_D:

$$I = I_{ph} - I_D = I_{ph} - I_0\left(\exp\frac{e(V + IR_s)}{mkT_c} - 1\right) \qquad (1)$$

where m is idealising factor, k is Boltzmann's gas constant, T_c the absolute temperature of the cell, electronic charge and V is the voltage imposed across the cell. I_0 is the dark saturation current and it is strongly depending on temperature, [3].
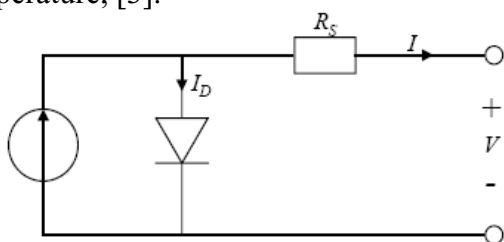

Fig. 2: Model for a single solar cell.

2.1.2 PV Module model

Cells are normally grouped into "modules", which are encapsulated with various materials to protect the cells and the electrical connectors from the environment. The manufacturers supply PV cells in modules, consisting of N_{PM} parallel branches, each with N_{SM} solar cells in series. In order to have a clear specification of which element (cell or module) the parameters in the mathematical model are regarding, the following notation is used from now on: the parameters with superscript "M" are referring to the PV module, while the parameters with superscript "C" are referring to the solar cell. Thus, the applied

voltage at the module's terminals is denoted by V^M, while the total generated current by the module is denoted by I^M.

A model for the PV module is obtained by replacing each cell, by the equivalent diagram from figure 2.

The PV module's current I^M under arbitrary operating conditions can thus be described as, [2]:

$$I^M = I_{SC}^M\left[1 - \exp\left(\frac{V^M - V_{OC}^M + R_s^M \cdot I^M}{N_s^M \cdot V_t^C}\right)\right] \qquad (2)$$

The expression of the PV module's current I^M is an implicit function, being dependent on:

- the short circuit current of the module, which is $I_{SC}^M = N_p^M \cdot V_{OC}^C$;
- the open circuit voltage of the module, which is $V_{OC}^M = N_s^M \cdot V_{OC}^C$;
- the equivalent serial resistance of the module, which is $R_s^M = \dfrac{N_s^M}{N_p^C} \cdot R_s^C$;
- the thermal voltage in the semiconductor of a single solar cell, which is $V_t^C = \dfrac{mkT^C}{e}$

The short circuit current of a solar cell I_{SC}^C is computed based on its linear dependency on the irradiation G_a:

$$I_{SC}^C = C_1 \cdot G_a \qquad (3)$$

The working temperature of the cells T^C depends exclusively on the irradiation G_a and on the ambient temperature T_a, according to the empirical linear relation:

$$T^C = T_a + C_2 \cdot G_a \qquad (4)$$

where the constant C_2 is computed as:

$$C_2 = \frac{T_{ref}^C - T_{a,ref}}{G_{a,ref}}$$

The open circuit voltage of the cell depends exclusively on the temperature of the solar cells [1]:

$$V_{OC}^C = V_{OC,0}^C + C_3\left(T^C - T_0^C\right)$$

where the constant C_3 is usually considered to be:
$$C_3 = -2,3\,mV\,/\,C$$

2.1.3 PV Array model

The modules in a PV system are typically connected in arrays.

The applied voltage at the array's terminals is denoted by V^A, while the total current of the array is

denoted by $I^A = \sum_{i=1}^{Mp} Ii$. If it is assumed that the modules are identical and the ambient irradiation is the same on all the modules [2], then the array's current is: $I^A = M_p \cdot I^M$

2.2 Battery model

The battery is necessary in such a system because of the fluctuating nature of the output delivered by the PV arrays. Thus, during the hours of sunshine, the PV system is directly feeding the load, the excess electrical energy being stored in the battery. During the night, or during a period of low solar irradiation, energy is supplied to the load from the battery.

In general, the battery models view the battery as a voltage source E in series with an internal resistance R_0, as shown in figure 3.
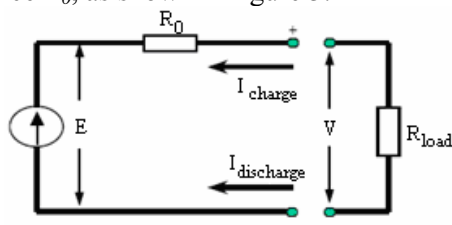

Fig. 3: Schematic diagram of the battery.

The terminal voltage V is given by [2]:

$$V = E - R_0 \cdot I \tag{5}$$

As the internal voltage E is assumed to be a function only of the state of charge (SOC), the instantaneous steps in current affects the terminal voltage V_{bat} through the term $R_0 \cdot I_{bat}$. Thus, the internal resistance can be estimated by:

$$R_0 = \frac{\Delta V_{bat}}{\Delta I_{bat}} \tag{6}$$

where ΔV_{bat} and ΔI_{bat} are the steps in terminal voltage and battery current, respectively.

2.3 Controller model

All power systems must include a control strategy that describes the interactions between its components. The use of battery as a storage form implies thus the presence of a charge controller.

The charge controller is used to manage the energy flow to PV system, batteries and loads by collecting information on the battery voltage and knowing the maximum and minimum values acceptable for the battery voltage. There are two main operating modes for the controller:

- normal operating condition, when the battery voltage fluctuates between maximum and minimum voltages.
- overcharge or over-discharge condition, which occur when the battery volt-age reaches some critical values.

To protect the battery against an excessive charge, the PV arrays are disconnected from the system, when the terminal voltage increases above a certain threshold V_{max_off} and when the current required by the load is less than the current delivered by the PV arrays. PV arrays are connected again when the terminal voltage decreases below a certain value V_{max_on}. This can be done by using a switch with a hysteresis cycle, as shown in figure 4.
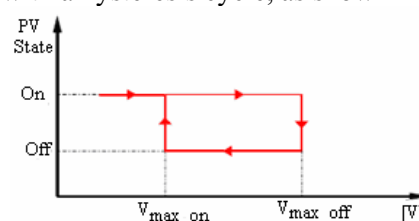

Fig. 4: Operating principle of an overcharge protector.

To protect the battery against excessive discharge, the load is disconnected when the terminal voltage falls below a certain threshold V_{min_off} and when the current required by the load is bigger than the current delivered by the PV arrays. The load is reconnected to the system when the terminal voltage is above a certain value V_{min_on}, using a switch with a hysteresis cycle, as shown in figure 5.
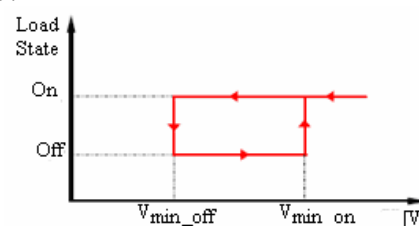

Fig. 5: Operating principle of a discharge protector.

The steps in the modelling of the controller process are summarised in Table 3.

Table 3: Summary of the controller process.

	Constrait	Comand
1	If $V > V_{max\_off}$ and $I_{load} < I_{pv}$	Disconect PV arrays from the system
2	If comand 1 is done and $V < V_{max\_on}$	Reconnect PV arrays to the system
3	If $V < V_{min\_off}$ and $I_{load} > I_{pv}$	Disconnect the load from the system
4	If comand 3 is done and $V > V_{min\_on}$	Reconnect the load to the system

2.4 Inverter model

As known, the PV arrays produce DC power and therefore when the stand-alone PV system contains an AC load, as it is the case for the system, a DC/AC conversion is required.

The inverter is characterised by a power dependent efficiency η. The role of the inverter is to keep on the AC side the voltage constant at the rated voltage 220V and to convert the input power P_{in} into the output power P_{out} with the best possible efficiency. The efficiency of the inverter is thus modelled as:

$$\eta = \frac{P_{out}}{Pi_n} = \frac{V_{ac} \cdot I_{ac} \cdot \cos\varphi}{V_{dc} \cdot I_{dc}} \Rightarrow I_{dc} = \frac{V_{ac} \cdot I_{ac} \cdot \cos\varphi}{\eta \cdot V_{dc}} \quad (7)$$

where I_{dc} is the current required by the inverter from the DC side (for example, from the controller) in order to be able to keep the rated voltage on the AC side (for example on the load). V_{dc} is the input voltage for the inverter delivered by the DC side, for example by the controller.

2.3 Load model

The load existing in a PV stand-alone system can be of many types, both DC (television, lighting) and AC (electrical motors, heaters, etc.).

The PV stand-alone system contains an AC load, which is an electrical heater. This heater is actually a simple resistance controlled by a thermostat. Thus, the load can be modelled as:

$$I_{ac} = \frac{V_{ac}}{R_h} \quad (8)$$

where I_{ac}, V_{ac} are the AC-current and voltage of the load, respectively. R_h is the resistance of heater, which can be determined by the rated power P_{h_nom} and rated voltage V_{h_nom} of the heater, as follows:

$$R_h = \frac{(V_{h\_nom})^2}{P_{h\_nom}} \quad (9)$$

3 Implementation in Simulink of models for stand-alone PV system

This section presents how the mathematical models of the components of a stand-alone PV system, described in paragraph 2, are implemented in Matlab/Simulink.

Simulink is a simulation program, which provides a graphical interface for building models as blocks diagrams.

For practical use, the Simulink model blocks for each component of the stand-alone PV system can be gathered in a library. The library can contain model blocks for a PV module, a battery, a load, an inverter and a controller.

The Simulink model for stand-alone PV system is illustrated in figure 6.
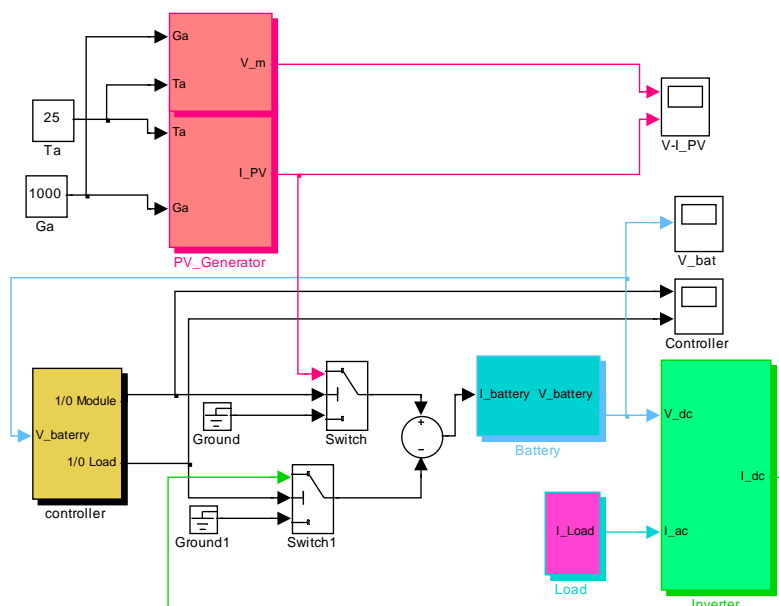

Fig. 6: Stand-alone PV system structure in Simulink.

The total system has thus as inputs the irradiation and the ambient temperature. These are used in the PV module together with the voltage from the controller to generate the PV current.

The basic blocks of the library can be used to build more specific structures.

Another powerful feature of the Simulink, called masking, is that it can simplify the use of the model by replacing many dialog boxes in a subsystem with a single dialog box. Instead of requiring the user of the model to open each block and enter parameter values, those parameter values can be entered on the mask dialog block and passed to the blocks in the masked subsystem.

Figure 7 shown the mask dialog block for the PV module looks like. The user has just to change the values of the parameters for different types of PV modules, which eventually are used in the stand-alone PV system.
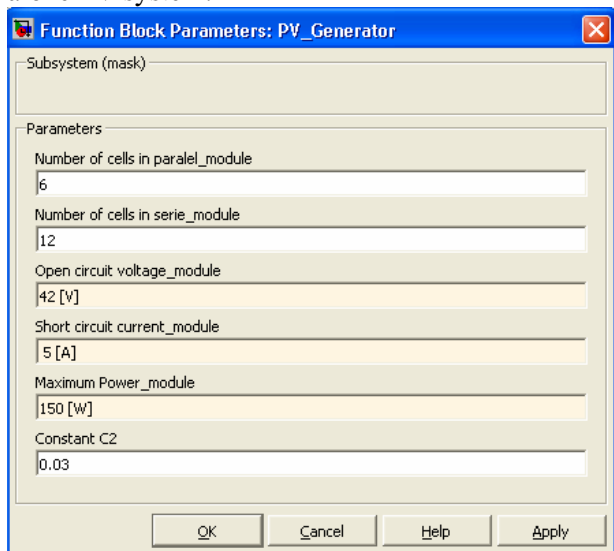

Fig. 7: Mask parameters for PV Generator block

The internal "hidden" structure of the block "PV Generator" from figure 6 is shown in figure 8. It represents the "detailed" Simulink implementation of the mathematical model of the PV module, describe in paragraph 2.1.
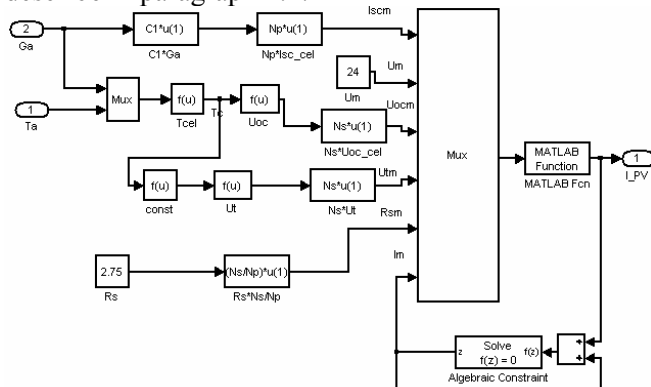

Fig. 8: PV module structure.

The implicit function of the current I^M, for the PV module, as it was described in paragraph 2.1.can be solved easily by the "algebraic constraint" block, from Simulink (Version 7.0.1).

The controller achieves information from the battery, PV module and inverter. Based on these inputs and on the control dispatch summarised in Table 1, the controller transmits control signals back to the inverter, PV-module and battery. The DC voltage from the controller is thus applied to the inverter together with the AC current, which is required by the load. In order to be able to keep the rated voltage on the AC side to V_{ac}=220V, the inverter requires further a specific value for DC current from the controller.

4 Simulation results

The most relevant parts of the series with particular events, from each of the set data of inputs, are chosen and analysed for understanding and modelling of the stand-alone PV system.

Figure 9 shows the simulation results, when the initial set data of inputs are: solar radiation Ga=500W/m^2, ambient temperature T$_a$=15°C, the load is connected and the PV current is directly used in the charging of the battery, but the I$_{PV}$<I$_{Load}$ and the battery voltage decreasing until V$_{min\_off}$=11.5V. In this time, the load is disconnected, and the battery voltage increasing until V$_{min\_on}$=12V, when the load is reconnected on the stand-alone PV system.

In the moment when the set data of inputs are modification: solar radiation G$_a$=1000W/m^2, ambient temperature T$_a$=25°C, the battery is charging. In the moment when battery voltage reaches the limit of the charging voltage V_{max_off}=14V, the PV generator is disconnected by the PV controller of the stand-alone PV system, in order to avoid overcharging. The battery is discharging because the load is connected on the system.

When battery voltage reaches the limit V_{max_on}=12.5V, the PV generator is reconnected on the stand-alone PV system.

At a solar radiation G$_a$=800W/m^2 and an ambient temperature T$_a$=20°C, the battery voltage increasing, because I$_{PV}$>I$_{Load}$.
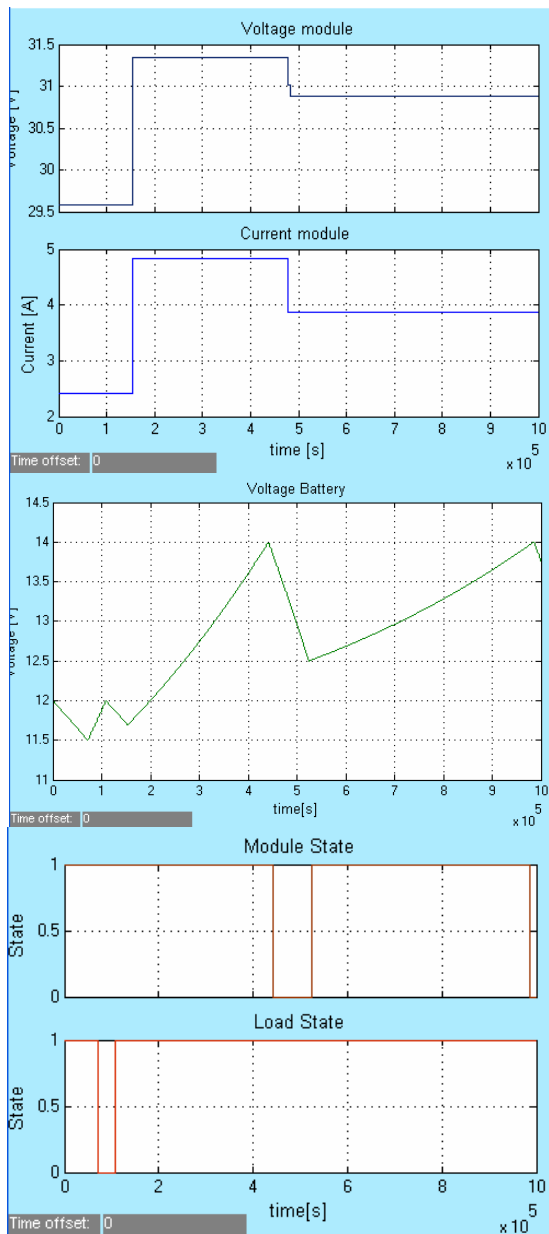
Fig. 9: Simulation results for several data set of input of PV system

simulation of the PV module for different values of irradiation and cell temperature – see Figure 9.

Also, information about the controller system has been achieved based only on the modelling and simulation. The PV controller acts only on PV generator, connecting or disconnecting them gradually. A disconnection of the PV generator, due to the high irradiation and to the overcharged battery, was illustrated in figure 9. Such as the strategy of control for disconnects/connects the load to the stand-alone system, has been implemented in Simulink.

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5 Conclusion

The Simulink simulation program offers the advantage of building hierarchical models, namely to have the possibility to view the system at different levels. Simulink provides also the possibility to build modular models, which have the advantage that in this way the models can be easily connected together in order to simulate a certain system (stand-alone or not stand-alone). Such models also help system designers to optimise the size of the components of the stand-alone PV system.

The Simulink implementation of the PV module, illustrated in figure 8, is used to perform a