A Photovoltaic Array Simulation Model for Matlab-Simulink GUI Environment

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***Abstract*—A photovoltaic array (PVA) simulation model to be used in Matlab-Simulink GUI environment is developed and presented in this paper. The model is developed using basic circuit equations of the photovoltaic (PV) solar cells including the effects of solar irradiation and temperature changes. The new model was tested using a directly coupled dc load as well as ac load via an inverter. Test and validation studies with proper load matching circuits are simulated and results are presented here.**

***Index Terms*—Photovoltaic models, Photovoltaic power systems, Power generation, MOSFET Model, Motor drives, Digital control.**

I. Introduction

THE use of new efficient photovoltaic solar cells (PVSCs) has emerged as an alternative measure of renewable green power , energy conservation and demand-side management. Owing to their initial high costs, PVSCs have not yet been a fully attractive alternative for electricity users who are able to buy cheaper electrical energy from the utility grid. However, they have been used extensively for water pumping and air conditioning in remote and isolated areas where utility power is not available or is too expensive to transport. Although PVSC prices have decreased considerably during the last years due to new developments in the film technology and manufacturing process [1], PV arrays are still widely considered as an expensive choice compared with existing utility fossil fuel generated electricity. After building such an expensive renewable energy system, the user naturally wants to operate the PV array at its highest energy conversion output by continuously utilizing the maximum available solar power of the array. The electrical system powered by solar arrays requires special design considerations due to varying nature of the solar power generated resulting from unpredictable and sudden changes in weather conditions which change the solar irradiation level as well as the cell operating temperature. Salameh and Dagher [2] have proposed a switching system that changes the cell array topology and connections or the structural connections of the arrays to establish the required voltage during different periods of a day. A steady-state analysis of a scheme employing direct coupling between a series/shunt or separately excited dc motors and the photovoltaic solar arrays has been given by Roger [3]. The dynamic performance of a dc shunt motor-photovoltaic system has been studied by Fam and Balachander [4]. The starting and steady-state characteristics of dc motors powered by a solar cell array source have been studied by Appelbaum [5] to select the suitable parameters and type of dc motor for a desired utilization scheme. All these studies concerning dc motors or permanent magnet (PM) dc motors powered by PV generators have been done by considering the direct interface between the motor load and the PV source generator. For direct coupling of dc motors to PV solar arrays, the separately excited or PM motors with a ventilator type load are the most suitable [5]. Owing to changes in the solar radiation energy and the cell operating temperature, the output power of a solar array is not constant at all times. Consequently, during the design process of PVA powered systems; a simulation must be performed for system analysis and parameter settings. Therefore an efficient user friendly simulation model of the PVAs is always needed. The PVA model proposed in this paper is a circuitry based model to be used with Simulink. The proposed model was simulated with various types of loads for performance checking.

II. PVA Modeling

PV arrays are built up with combined series/parallel combinations of PV solar cells, which are usually represented by a simplified equivalent circuit model such as the one given in Fig. 1 and/or by an equation as in (1).

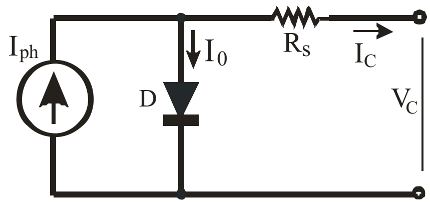

Fig. 1. Simplified-equivalent circuit of photovoltaic cell.

The PV cell output voltage is a function of the photocurrent that mainly determined by load current depending on the solar irradiation level during the operation.

$$V_C = \frac{AkT_C}{e} \ln\left(\frac{I_{ph} + I_0 - I_C}{I_0}\right) - R_S I_C \tag{1}$$

Where the symbols are defined as follows:
e: electron charge (1.602×10^{-19} C).

k: Boltzmann constant (1.38×10^{-23} J/^{o}K).
I_c: cell output current, A.
I_{ph}: photocurrent, function of irradiation level and junction temperature (5 A).
I_0: reverse saturation current of diode (0.0002 A).
R_s: series resistance of cell (0.001 Ω).
T_c: reference cell operating temperature (20 °C).
V_c: cell output voltage, V.

Both k and T_c should have the same temperature unit, either Kelvin or Celsius. The curve fitting factor A is used to adjust the I-V characteristics of the cell obtained from (1) to the actual characteristics obtained by testing. Eq. (1) gives the voltage of a single solar cell which is then multiplied by the number of the cells connected in series to calculate the full array voltage. Since the array current is the sum of the currents flowing through the cells in parallel branches, the cell current I_C is obtained by dividing the array current by the number of the cells connected in parallel before being used in (1), which is only valid for a certain cell operating temperature Tc with its corresponding solar irradiation level Sc. If the temperature and solar irradiation levels change, the voltage and current outputs of the PV array will follow this change. Hence, the effects of the changes in temperature and solar irradiation levels should also be included in the final PV array model. A method to include these effects in the PV array modelling is given by Buresch [1]. According to his method, for a known temperature and a known solar irradiation level, a model is obtained and then this model is modified to handle different cases of temperature and irradiation levels. Let (1) be the benchmark model for the known operating temperature Tc and known solar irradiation level Sc as given in the specification. When the ambient temperature and irradiation levels change, the cell operating temperature also changes, resulting in a new output voltage and a new photocurrent value. The solar cell operating temperature varies as a function of solar irradiation level and ambient temperature. The variable ambient temperature Ta affects the cell output voltage and cell photocurrent. These effects are represented in the model by the temperature coefficients C_{TV} and C_{TI} for cell output voltage and cell photocurrent, respectively, as:

$$C_{TV} = 1 + \beta_T \left(T_a - T_x \right) \tag{2}$$

$$C_{TI} = 1 + \frac{\gamma_T}{S_C} \left(T_x - T_a \right) \tag{3}$$

Where, $\beta_T = 0.004$ and $\gamma_T = 0.06$ for the cell used and T_a=20 ^{o}C is the ambient temperature during the cell testing. This is used to obtain the modified model of the cell for another ambient temperature Tx. Even if the ambient temperature does not change significantly during the daytime, the solar irradiation level changes depending on the amount of sunlight and clouds. A change in solar irradiation level causes a change in the cell photocurrent and operating temperature, which in turn affects the cell output voltage. If the solar irradiation level increases from S_{x1} to S_{x2}, the cell operating temperature and the photocurrent will also increase from T_{x1} to T_{x2} and from I_{phl} to I_{ph2}, respectively. Thus the change in the operating temperature and in the photocurrent due to variation in the solar irradiation level can be expressed via two constants, C_{SV} and C_{SI}, which are the correction factors for changes in cell output voltage V_C and photocurrent I_{ph}, respectively:

$$C_{SV} = 1 + \beta_T \alpha_S \left(S_x - S_C \right) \tag{4}$$

$$C_{SI} = 1 + \frac{1}{S_C} \left(S_x - S_C \right) \tag{5}$$

where S_C is the benchmark reference solar irradiation level during the cell testing to obtain the modified cell model. S_x is the new level of the solar irradiation. The temperature change, *ΔT_C*, occurs due to the change in the solar irradiation level and is obtained using

$$\Delta T_C = \alpha_S \left(S_x - S_C \right) \tag{6}$$

The constant α_S represents the slope of the change in the cell operating temperature due to a change in the solar irradiation level [1] and is equal to 0.2 for the solar cells used. Using correction factors C_{TV}, C_{TI}, C_{SV} and C_{SI}, the new values of the cell output voltage V_{CX} and photocurrent I_{phx} are obtained for the new temperature T_x and solar irradiation S_x as follows:

$$V_{CX} = C_{TV} C_{SV} V_C \tag{7}$$

$$I_{phx} = C_{TI} C_{SI} I_{ph} \tag{8}$$

V_C and I_{ph} are the benchmark reference cell output voltage and reference cell photocurrent, respectively. The resulting I-V and P V curves for various temperature and solar irradiation levels were discussed and shown in [6, 8, 9], therefore they are not going to be given here again.

III. PVA MODELING FOR SIMULINK

A general block diagram of the PVA model for GUI environment of Simulink is given in Fig. 2 along with filter and load models. The block called *PVA model for GUI* is the last stage of the model. This block contains the sub models that are connected to build the final model. A diode (D1) is connected in series with the load circuit to prevent the reverse current flow. A filter is connected before the load to maintain a stable voltage. The filter contains a series R-L and parallel C elements. The PVA consists of 8 PV cells all connected in series to have a desired voltage output. Depending on the load power required, the number of parallel branches can be increased to 2 or more. The effects of the temperature and solar irradiation levels are represented by two variables gains. They can be changed by dragging the slider gain adjustments of these blocks named as *variable temperature* and *variable solar irradiation.*

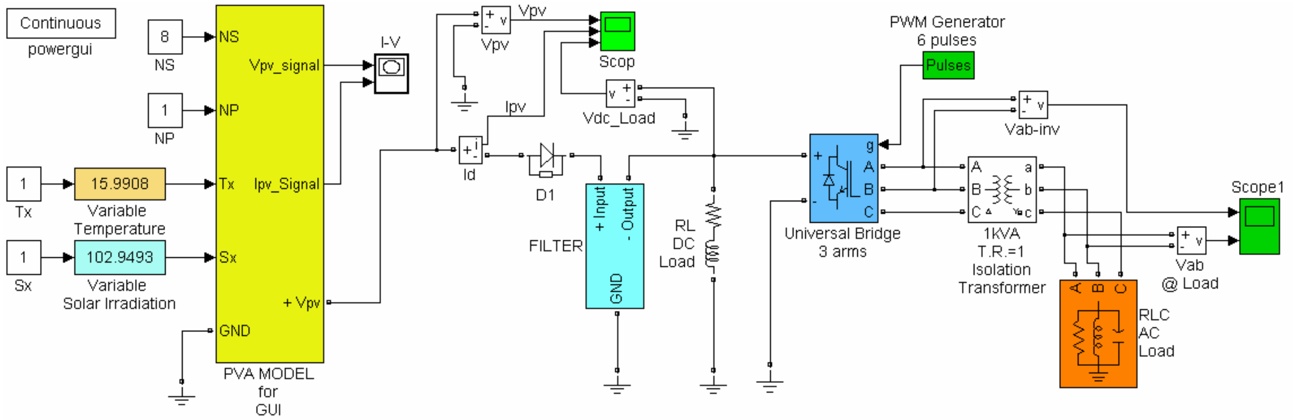

Fig. 2. Operational functional block diagram of the PVA model.

Since the main objective is the development of the PVA functional model for the Simulink environment, the other parts of the operational block diagram given in Fig. 2 are not going to be explained in full detail. However, just to describe the main diagram, as it can readily be seen, the system is modeled to supply power to both dc and ac loads. The dc load is directly coupled while the ac load is fed through a three-phase inverter and an isolation transformer with a turn ratio 1.

The last stage of the PVA model is shown in Fig. 2. The other stages are masked as subsystems under the last stage. The first stage of the PVA modeling is depicted in Fig. 3 where the mathematical model of a single PV cell given by (1) is represented with the block called *Equation 1*.

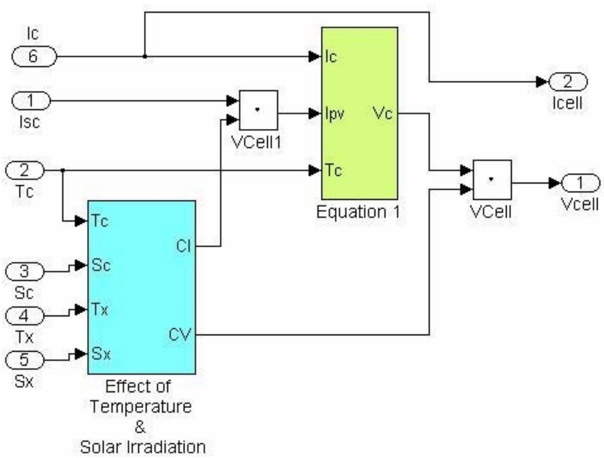

Fig. 3 Modeling stage 1.

The effects of the changing temperature and solar irradiation level are modeled inside the block called *Effect of Temperature & Solar Irradiation*. This block represents the equations given from (2) to (8) with the modification of (7) and (8) as follows.

$$V_{CX} = C_V V_C \tag{9}$$

$$I_{phx} = C_I I_{ph} \tag{10}$$

Fig. 3 is a sub-mask of the stage 2, which is given in Fig. 4. Major inputs and outputs and the conversion of discrete simulation model into continues circuit model are shown in Fig. 4.

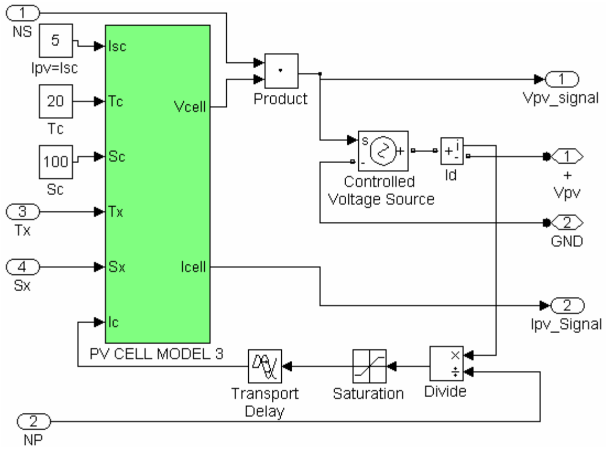

Fig. 4 Modeling stage 2.

IV. Simulation Results

The proposed PVA model is simulated using the scheme given in Fig. 2. The system supplies power to a mainly resistive dc load and an RLC ac load with 500 W, 200 VAr inductive and 500 VAr capacitive. The system does not have any controller. The loads are just chosen to match the power generated by the PVA. Actually the voltage at dc load bus and the both voltage and frequency at ac load bus must be controlled and kept constant for the users. The control part is also done as a part of this work. However, only the PVA modeling is included in this paper since both parts require more space.

The current-voltage (I-V) characteristic of the PVA during operation is given in Fig. 5. Since the voltage of the PVA is equal to the open circuit voltage at stand-still, the I-V characteristics start at open circuit voltage with current equal to zero. As the simulation starts an the loads begin draw current from the PVA, the voltage and the current start moving toward the operating values, which are shown in Figs. 7 and 8 for voltage and current, respectively. PVA power is given in Figs. 6 and 9. Although the maximum power is above 750 W for the current solar irradiation and temperature levels, the operating power is approximately 750 W. Since there is no control or maximum power point tracker (MPPT), this is a reasonable operating power.

The dc bus voltage is given in Fig. 10. Due to the effects of the inverter switching and there are some oscillations on the dc bus voltage, which is also the input voltage to the inverter. The output ac voltage of the inverter is shown in Fig. 11 where the PWM mode operation of the inverter can be seen on the output voltage. The output voltage of the inverter is applied to the load over an isolation transformer with the turn ratio 1. The effects of the transformer on the voltage can be seen in Fig. 12 where the there phase line to line voltages have sinusoidal wave shapes including some harmonics. The harmonics can be eliminated or reduced by applying proper filter circuits, which are not considered here for the moment.

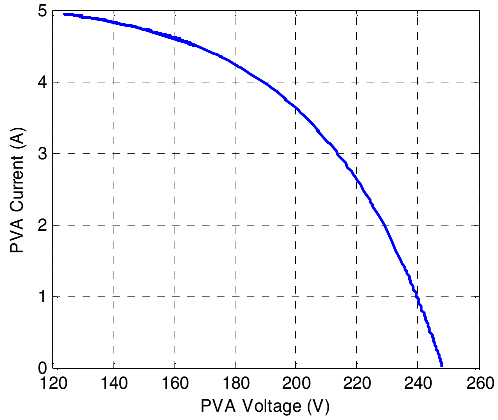

Fig. 5 Current-Voltage (I-V) Characteristics of PVA.

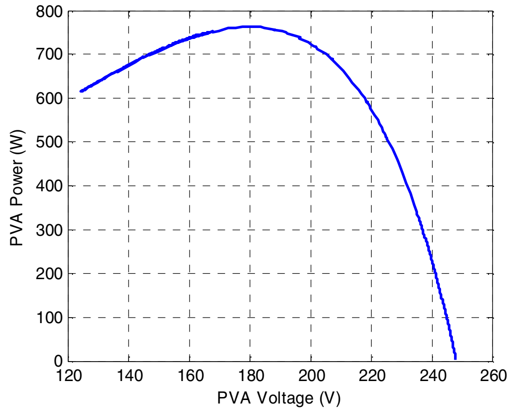

Fig. 6 Power-Voltage (P-V) Characteristics of PVA

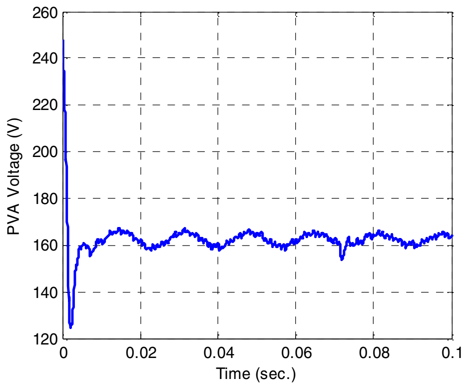

Fig. 7. Time response of the PVA voltage.

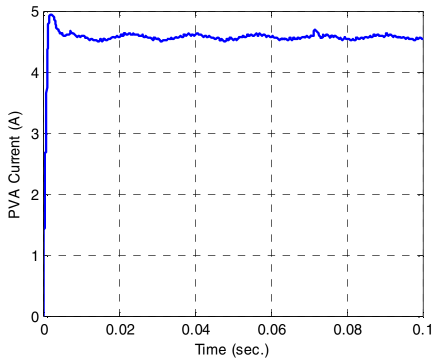

Fig. 8. Time response of the PVA current.

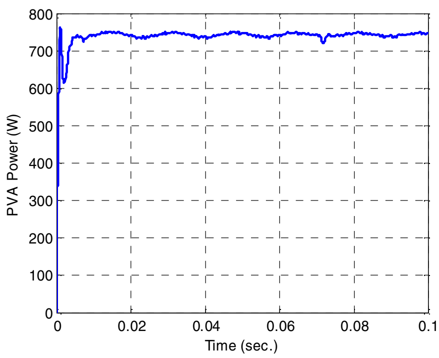

Fig. 9. Time response of the PVA power.

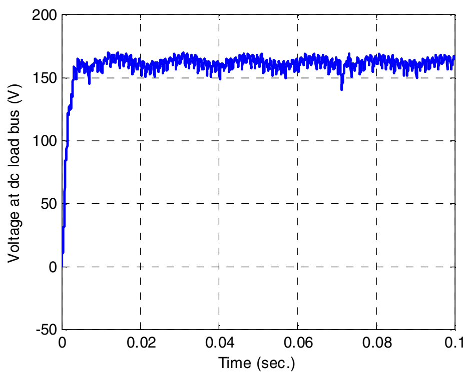

Fig. 10. Voltage at dc load bus.

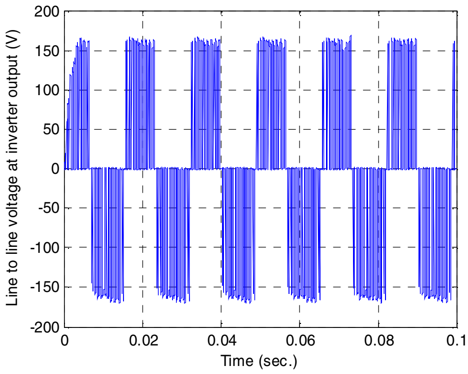

Fig. 11 . Line to line voltage at the output of the inverter.

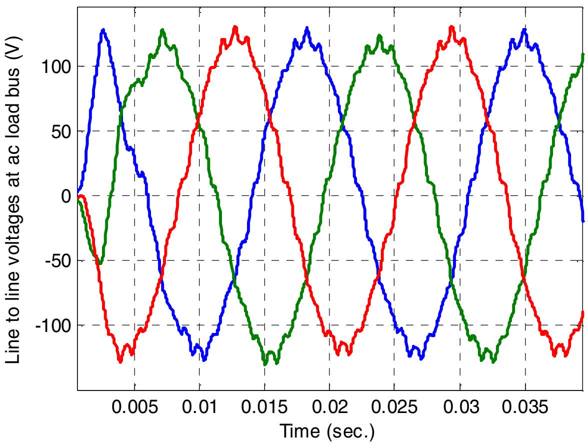

Fig. 12. Three phase line to line voltages.

V. Conclusions

This paper introduces a simulation model for photovoltaic arrays (PVA) to be used in Matlab-Simulink GUI environment. The proposed model has a generalized structure so that it can be used as a PV power generator along with wind, fuel cells and small hydro system by establishing proper interfacing and controllers. The model is simulated connecting a three phase inverter showing that, the generated dc voltage can be converted to ac and interfaced to ac loads as well as ac utility grid system. Therefore the model proposed here can be considered as a part of distributed power generation systems.

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