

PERFORMANCE IMPROVEMENT OF A THEORETICALLY DESIGNED STAND-ALONE PV SYSTEM THROUGH THE UTILIZATION OF MATLAB/SIMULINK MODELING

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Abstract

This paper focuses on modelling and simulation of a theoretically designed stand-alone photovoltaic (PV) system composed of PV panels, DC/DC converters, Maximum Power Point Tracker (MPPT), lead-acid battery and controllers for constant DC voltage output PV system. Theoretically designed system from the literature is taken as a reference, modelled and simulated with MATLAB/Simulink-SimPowerSystems toolbox which is specifically developed to simulate electrical power systems. Direct simulation of the designed system shows that there are some unexpected behaviours of the system when subjected to irradiation/temperature and load changes. These outputs arise since the system is not designed by taking into account the parameters and dynamics of real circuit elements. Controllers of the system are redesigned with MATLAB/Simulink to improve the performance. Commonly used conventional linearization methods of MATLAB are not available for some controllers' design for such a system having pulse width modulation (PWM) switching DC/DC converters causing high nonlinearity, forces the use of a new alternative technique based on simulated input/output data. PV system is simulated under different atmospheric and load conditions with variable temperature/irradiation and load levels, system performance and efficiency is evaluated and it is observed that the designed controllers are capable to operate PV panel at its maximum power point under different atmospheric and load conditions and provide constant DC voltage to the load while charging the battery with excess power.

Keywords: PV System, Voltage Regulation, MPPT, SimPowerSystems.

1. Introduction

Traditional energy resources are inevitably expected to exhaust in the near future which cannot satisfy the requirement of increasing population and industrialization and the gap between production and consumption of energy increases continuously [1]. Additional environmental issues arising from the production and consumption of traditional energy resources have increased the interest in renewable energy sources worldwide. PV research and development activities increased the demand with an average of 20-25% each year in the last 20 years [2,3].

Load profile and atmospheric conditions changes the amount of solar power obtained from PV panels [4,5]. Through the use of maximum power point tracking algorithms, higher energy conversion efficiency can be achieved with less number of PV panels and lower cost PV systems [6]. Other than MPPT, inverters, DC/DC converters and electric batteries (lead acid/lithium-ion) can be used to improve the utilization of solar energy and output voltage regulation [7].

Several papers in the literature can be found regarding the design of stand-alone PV systems [8-20]. Those papers include the overall system design and specific converter design but do not include the controller design and how the controller coefficients are obtained which prevents the direct modelling of the system indicated in the article in MATLAB/Simulink and use for comparison/improvement purposes. For this reason, an article including the design of most of the coefficients of the controllers in the overall PV system is selected as a reference for comparison [21].

In this study, theoretically designed PV system, incorporating PV panels, DC/DC converters, battery, load and controllers, is modelled with MATLAB/Simulink and simulated under different irradiation/temperature and load conditions. System performance of the designed and modelled systems are compared and improved through the use of MATLAB controller design tools. Results regarding the output voltage regulation, battery charging and future studies are discussed.

2. System Configuration and Control Design

2.1. System Configuration

System configuration as given in reference article is provided with Fig.1. A unidirectional boost converter is used between solar panels and load for MPPT control and a bidirectional boost converter is used between the battery and the load for battery charging/discharging control.

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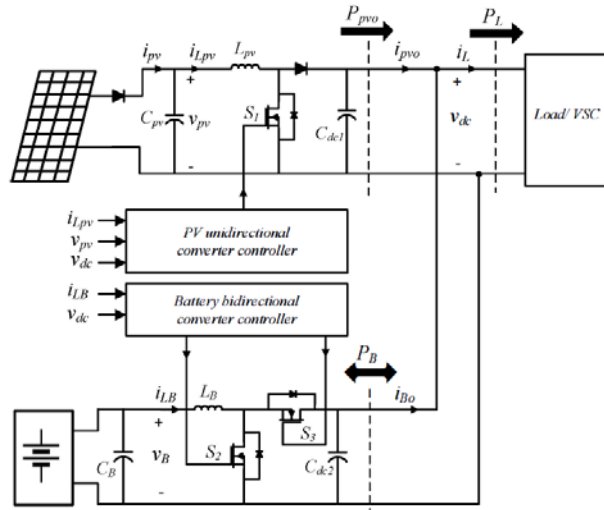


Figure 1. PV system configuration [19].

The power flow within the system is categorized as normal operation, PV/SOC regulation and PV/DC-link regulation. According to these scenarios control structure is designed as given in Fig.2. During normal operation, v_{pv-ref} is generated only by the MPPT module and the other two loops, PI_1 and PI_2 remain idle. Unidirectional converter provides maximum power to the load and the bidirectional converter provides the power balance. During PV/SOC regulation, PI_1 loop controls that the battery is not charged beyond the maximum state of charge level by disturbing the MPPT reference voltage. During PV/DC-link regulation, PI_2 loop controls that the DC-link voltage is not increased beyond the defined limit ($v_{dc-ref} + \Delta v = 410$ VDC) by disturbing the MPPT reference voltage.

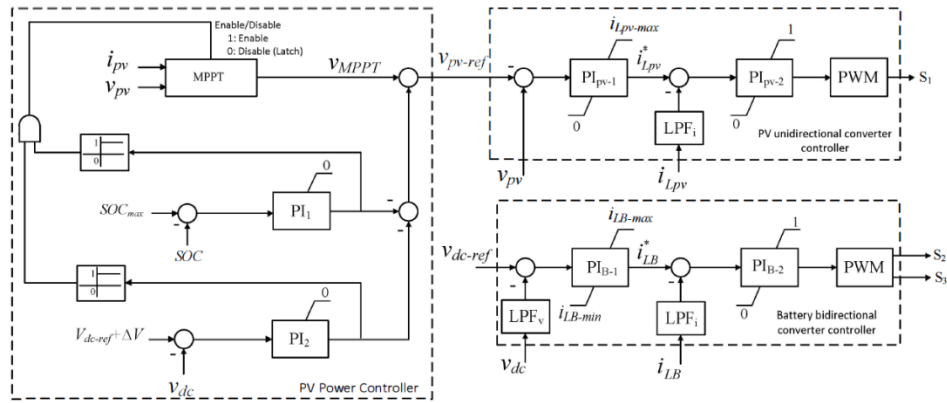


Figure 2. PV system control structure [19].

2.2. Control Design

Linearized averaged state-space equations for unidirectional converter are given in Eq.(1) and Eq.(2) and for bidirectional boost converter linearized averaged state-space equations are given in Eq.(3) and Eq.(4).

$$L_{pv} \frac{di_{Lpv}}{dt} = v_{pv} + V_{dc}d \quad (1)$$

$$C_{pv} \frac{dv_{pv}}{dt} = -i_{Lpv} + \frac{v_{pv}}{r_{pv}} \quad (2)$$

$$L_B \frac{di_{LB}}{dt} = -(1-D)v_{dc} + V_{dc}d \quad (3)$$

$$C \frac{dv_{dc}}{dt} = (1-D)i_{LB} - \frac{v_{dc}}{R} - V_{dc}d \quad (4)$$

Transfer functions for the PI controllers are selected as given in Eq.(5) to Eq.(8) in the reference article [19].

$$G_{PI-pv1} = \frac{0.5s+250}{s} \quad (5)$$

$$G_{PI-pv2} = \frac{0.01s+40}{s} \quad (6)$$

$$G_{PI-B1} = \frac{1s+250}{s} \quad (7)$$

$$G_{PI-B2} = \frac{0.03s+30}{s} \quad (8)$$

Since there are no equations for the design of PI_1 and PI_2 controllers, reference article does not provide any transfer functions and coefficients which necessitates finding a method for the MATLAB/Simulink modelling.

For the MPPT, there are several methods in the literature such as Perturb & Observe, Incremental Conductance, Current Sweep and Constant Voltage. In the reference article, MPPT method is not mentioned so for the MATLAB/Simulink modelling Perturb & Observe method is utilised.

3. System Modelling and Simulation with MATLAB

3.1. System Modelling and Simulation

PV panel model shall include variable irradiation and temperature inputs. Taking into account of the temperature and irradiation effects on the output current of a solar cell, PV array output current can be calculated with Eq.(9) [22].

$$I_{pv} = N_p I_{ph} - N_p I_s \left(e^{\frac{q(V+I_{pv}R_s)}{aKT}} \right) - \frac{1}{R_p} \left(\frac{V}{N_s} + \frac{I_{pv}R_s}{N_p} \right) \quad (9)$$

R_s is the series resistance in the cell model, R_p is the shunt resistance in the cell model, I_{ph} is the light generated current, I_s is the reverse saturation current of the diode, q is the electron charge, a is the diode ideality factor, T is the temperature in degrees Kelvin, N_s is the number of solar cells connected in series and N_p is the number of solar panels connected in parallel in the array.

PV array model which takes into account variable irradiation and temperature is developed according to Eq.(9) and using the Simulink blocks as shown in Fig. 5.

DC/DC converters are modelled as shown in Fig.3 using the parameters provided in the reference article and SimPowerSystems blocks of MATLAB/Simulink.

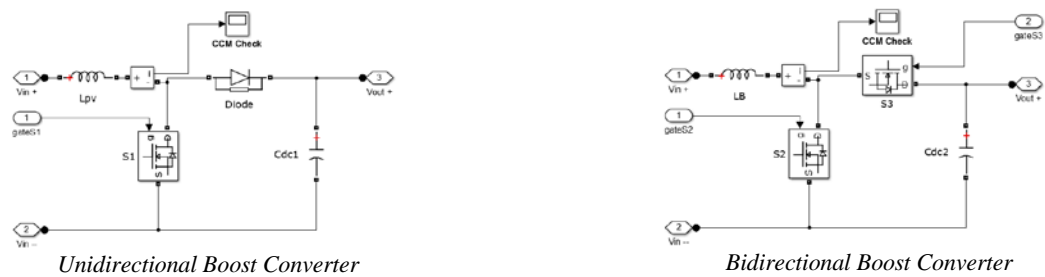


Figure 3. DC/DC converter models of the PV system.

SimPowerSystems Battery model is utilized for the lead-acid battery modelling and control system is built exactly the same as given in the reference article. But as indicated in Section 2.2, PI_1 and PI_2 coefficients are not given in the reference article since there are no state-space equations for their design. Their design is realised with MATLAB. Since there are two-level and three-level cascaded controllers and PWM driven switches in the system, it is difficult to design the controllers theoretically. Attempts were made to design these controllers numerically (using ‘Tune’ option for ‘Discrete PID Controller’ block of Simulink) but due to high nonlinearities, this approach resulted in a zero system and failed. We have therefore employed an alternative linearization method based on bringing the system to a typical operating point using the system input and then providing a step change around this point, the data from which is used in the linearization procedure. (In MATLAB/Simulink this can be carried out using steps: Plant → Identify New Plant → Plant Identification → Get I/O Data → Simulate Data → Simulate I/O Data, the results of which can be seen in Fig. 4.)

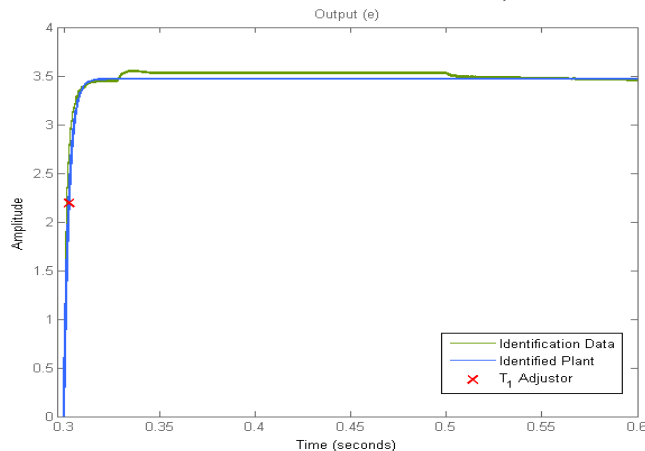


Figure 4. Identification data and the identified plant.

Using predefined control structures such as one pole, two real poles, state-space model and underdamped pair + real pole, controlled system data is fitted into the identification data on the graph. When these two data fit well as shown in Fig.4, plant equation is obtained as given in Eq. (10).

$$G_{Plant,PI_2} = \frac{12.08}{8.766 \times 10^{-6} s^3 + 10.39 \times 10^{-5} s^2 + 0.5973s + 1} \quad (10)$$

The final model of the whole system in Fig.1 is built in MATLAB/Simulink environment as shown in Fig.5, after the completion of the design and modelling of all subsystems of PV system.

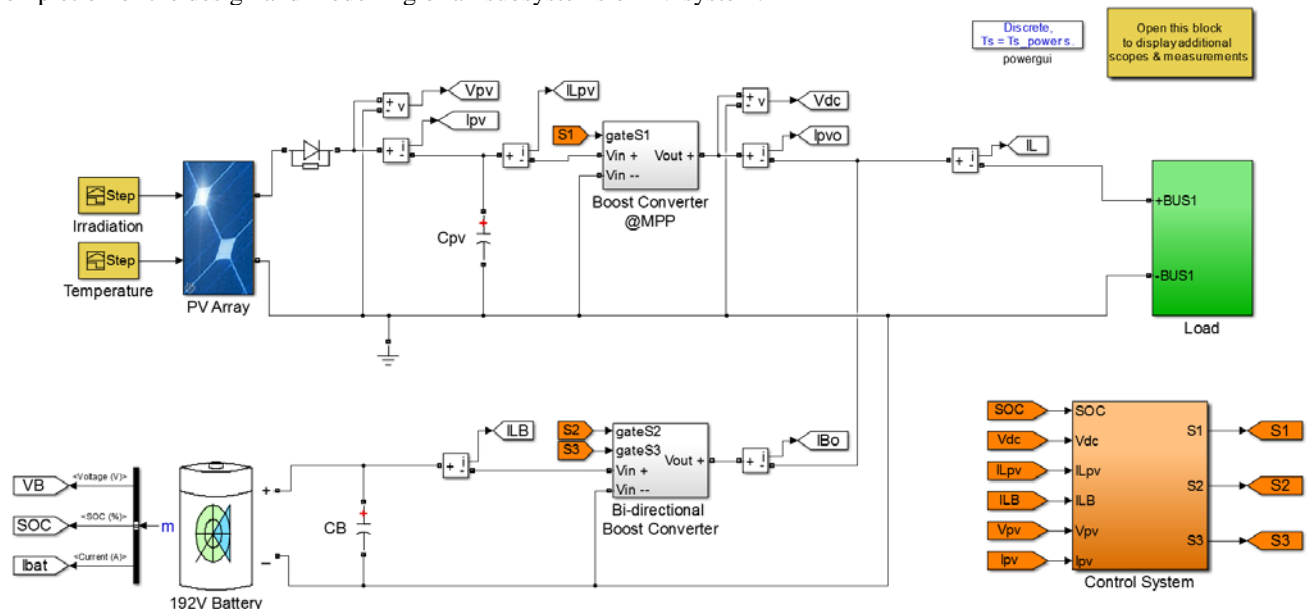


Figure 5. MATLAB/Simulink model of the whole PV System.

3.2. Performance Improvement with MATLAB/Simulink

PV system is simulated under different irradiation, temperature and load conditions. It showed good results against irradiation and temperature changes which proves its robustness against changing atmospheric conditions. But its response against load variations (between the maximum and minimum load limits indicated in the reference article) is not within the allowed limits. When the load resistance is changed from 500Ω to 111Ω , load voltage goes down to 350 VDC (less than the acceptable limit 400 VDC), battery current goes up to 10 A (max. discharging current) and suddenly and temporarily changes its state from charging to discharging and load voltage goes up to 420 VDC (more than the acceptable limit 410 VDC). These current peaks on battery are not healthy for the battery and shorten its life cycle, also for critical loads that much variation on the voltage may cause an undesirable damage.

It is observed that the theoretically designed controllers cannot meet the defined voltage and current limits on the load and battery which necessitates the redesign of the control system. Such an improvement is performed with the MATLAB toolboxes. Sisotool toolbox is utilized for the controller having the transfer function as shown in Eq. (10) and the stability of the controller designed with 'Internal Model Control (IMC) Tuning' design method is shown in Fig.6.

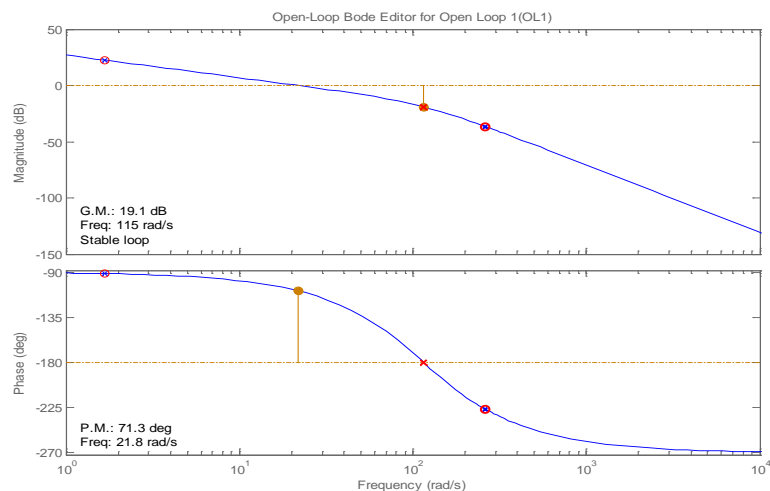


Figure 6. Bode plot of the re-designed PI_2 controller.

Simulink PID design method explained in Section 3.1 is utilized for the design bi-directional converter controllers PI_{b-1} and PI_{b-2} and all redesigned controllers' transfer functions are given in Eq.(11)-Eq.(13).

$$G_{PI_2} = \frac{0.21498(s+1.675)(s^2+10.18s+6.812 \times 10^4)}{s(s^2+200s+1.333 \times 10^4)} \quad (11)$$

$$G_{PI_{b-1}} = \frac{9.739s^2+6424s+1.134 \times 10^5}{s^2+1.101 \times 10^4s} \quad (12)$$

$$G_{PI_{b-2}} = \frac{0.07721s^2+19.69s+328}{s^2+187.9s} \quad (13)$$

Overall system performance with the redesigned controllers is shown in Fig.7 for the theoretically designed system and the improved system.

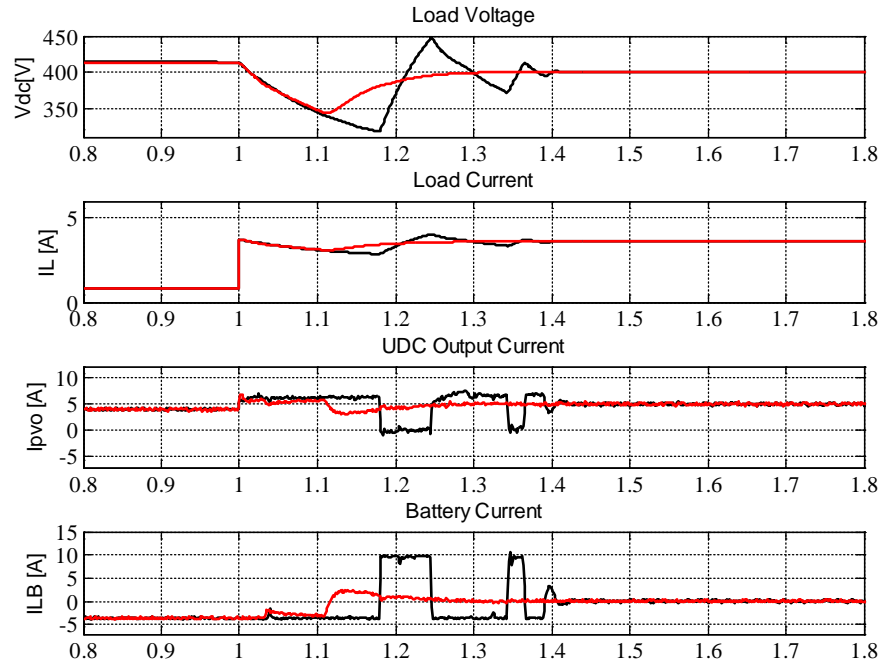


Figure 7. Effects of load variation on PV system's performance.

4. Conclusions

In this paper, a theoretically designed reference PV system, composing PV panels, DC/DC converters, Maximum Power Point Tracker (MPPT), lead-acid battery and controllers for constant DC voltage output, taken from the literature is modelled with MATLAB/Simulink-SimPowerSystems toolbox and system performance with variable atmospheric conditions such as irradiation/temperature and load conditions is observed. MATLAB/Simulink modelling and simulation shows that there are some unexpected behaviours of the system when subjected to irradiation/temperature and load changes which cannot be considered during the design since the design is not made by taking into account the parameters and dynamics of real circuit elements.

System performance of the designed system against load changes is obtained as shown in Fig.7. When the load resistance is changed from maximum (500Ω) to minimum (111Ω), load voltage goes down to below 350 VDC (less than the acceptable limit 400 VDC), battery current goes up to 10 A (max. discharging current limit) and suddenly and temporarily changes its state from charging to discharging and load voltage goes above 420 VDC (more than the acceptable limit 410 VDC). These current peaks on the battery and voltage variations on the load may cause undesirable damages to the battery and critical loads.

To prevent such damages controllers are redesigned using MATLAB/Simulink toolboxes. Sisotool toolbox is utilized for the controllers having the transfer function and Simulink PID design method explained in Section 3.1 is utilized for the controllers without any equations or transfer functions for the design. System performance of the improved system is shown in Fig.7. When compared to theoretically designed system, stress on the battery is reduced and voltage regulation on the load is improved which proves the importance of modelling the systems after designing them for observing their performance under all conditions and apply fine tuning through simulation if necessary. Load voltage is regulated such that it is above 350 VDC and not rising above 400 VDC, but it is still insufficient since 350 VDC level is not acceptable

which needs to be modified by applying different control techniques. Also for some controllers having no equation to design, it is compulsory to model the whole system and design them from the simulation results.

In the future studies, different controllers such as SMC, LQG and LPV will be used to design the controllers and results will be compared to define if which control strategy is more robust and better adapts the dynamics of PV systems.

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