“Bodh”, BPIT’s International Journal of Technology & Management
BBJITM, ISSN: 2454-8421, Volume 8, Issue 2, July-Dec 2022,

Modeling and Control of Photo Voltaic Emulator by Robust Controller

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Abstract-This research presents signal flow graph method for transfer function calculation and emulating V-I and P-V characteristic of PV panels. The usage of robust sliding mode controller, a diode model and a lookup table add to this. If several panels are to be replicated on the same model, the system does not require complicated calculations. Circuits with non-ideal components will also benefit from the proposed method, which will make mathematical modeling easier. The testing and installation process for solar electricity in rural and distant areas will thus be accelerated. To achieve a viable solution for this Nonlinear model, a sliding mode controller is implemented with stability constraint. The use of a diode model will incorporate variables such as temperature change and partial shading. The suggested system provides a simple and stable testing environment 24 hours a day, seven days a week for Non-linear PV panels before installation to save time and money. The MATLAB results match the actual shell 115 PV panel properties, demonstrating model and control correctness.

Keywords: Diode model, lookup table, mathematical modeling, PV Emulator, graph theory, robust sliding mode controller, MATLAB Simulation.

I. INTRODUCTION

The world's energy consumption is rapidly rising and research reveals that electricity generation solely from non-renewable energy resources will be unable to meet these rising demands. This ushered in a revolution in the energy sector and established the renewable energy sector on a global scale. Traditional and hybrid types of solar, wind and hydro energy have reframed research topics due to technological improvements and advantages linked with renewable energy. Solar and wind power account for the majority of renewable energy capacity in India. Wind energy's reliance on geographical locations and meteorological conditions limits its applications in countries like India, where harsh weather occurs throughout the year. India is positioned on the equator, which receives the most sunlight, making it the best location for solar energy development. To improve the usage of solar energy, factors such as setting up 24hour labs for testing, space for panel installation, changing environmental conditions and panel shading require substantial research. As India is partly tropical and subtropical in climate, it receives sunlight all year. Every year, close to 5000 trillion kW-hr of solar energy is received. With the growing population, the potential for trappable solar power has increased to 750 GW. The goal of the National Solar Mission, which began in 2010, was to reach 20 GW of solar installed capacity by 2022, but that goal was then raised to 100 GW by 2022. This aim of 20 GW installed capacity was met in 2018, resulting in a 370 percent [1] increase in India's solar capacity. Energy demand has risen dramatically in recent decades and is likely to continue to rise in the coming years as the world's population and industrialization grow. However, because of policy incentives, simplicity in structure and cost effectiveness, the use of clean technologies in the power sector is a top priority for global consumers. Solar PV and wind energy are the most cost-effective electricity generation options in many far-off areas [2]. The introduction of PV Emulators can improve laboratory-based testing of solar panels of various ratings [3]. A wide range of solar panels are available for purchase in the market. Purchasing each type of panel for testing separately is prohibitively expensive and not feasible. Under variable temperatures and shadowing situations, a PVE will be able to simulate these many types of solar panels. It protects itself from overloading and short circuit events that occur frequently during panel testing because it is a programmable device. PVE is used in both commercial and academic research. Since PV systems are connected to dynamic loads via inverters and maximum power point (MPPT) trackers, a lot of work can be carried out to optimize the quality of the emulated output. The most common power electronic topologies for emulation circuits include buck, boost, and buck-boost converters that operate as DC sources. According to research, the cost of production and installation, the area covered, the panel's shading condition and the maximum power tracked all play a role in solar panel selection, and a PVE will be a faster and more efficient technique to determine the best alternative. When planning a solar plant, an emulator can be used to estimate how a panel or module will perform. It should be able to change its operating point in response to changing loads. A controller, a reference model, and a PWM circuit are the other crucial components. Diode model [4] and lookup table [5] are employed as reference models. To finalize the single diode model, five parameters are required: load current, panel current, shunt resistance, series resistance, and ideality factor. The model is also confirmed by replacing the look-up table for one of the diode models. Because of its great efficiency, switched-mode power supplies are widely applied in PVEs. Signal Flow Graph is used to estimate the converter's transfer function in transient states (SFG). Mason's gain formula replaces the complex equations in this method. The details will be discussed in the following section. The robustness and stability of sliding mode controllers (SMC) are well established. P, PI, and PID controllers used for power converter control do not provide the best results in dynamic situations [6] of non-linear systems. SMC was conceived for variable structure systems, and it is well known that dc-dc converters are inherently variable structured, enabling SMC implementation easier [7- 9]. It aids in the design of a PV system with dynamic loading that is both resilient and accurate. The paper is divided into three sections, the first describing the mathematical derivation of a converter using SFG at switching states, the second explaining the construction of a PVE model including a buck converter in a closed loop configuration and the third explaining SMC implementation in a feedback loop using one diode and LUT as reference models. The characteristic plots obtained from designed models are detailed in the following part. Finally, the conclusion and scope of future research are discussed.

II. SIGNAL FLOW GRAPH (SFG)

A signal flow graph, also known as a switching flow graph, is a graphical approach for calculating a system's transfer function. The benefits include a simplified approach for determining the transfer function without having to draw the system repeatedly and a reduction in the number of components by replacing them with nodes and loops. The whole system's transfer function is determined using Mason's Gain formula. Due to its simple structure, a DC-DC buck converter was used to imitate the electrical behavior of a PV panel under various situations. The internal resistance of the components is either zero or ignored in an ideal buck converter model. To obtain the transient equations characterizing the switch's behavior, the ON-OFF states are studied. The equations for transient circuits are as follows:

$$L\frac{di_L}{dt} = -v_0 + V_{in}$$

$$C\frac{dv_o}{dt} = i_L - \frac{v_0}{R} \qquad (1)$$

$$L\frac{di_L}{dt} = -v_0$$

$$C\frac{dv_o}{dt} = i_L - \frac{v_0}{R} \qquad (2)$$

On averaging equations, (3) and (4) becomes:
and it is well known that dc-dc converters are inherently variable structured, enabling SMC implementation easier [7-

$$L\frac{\overline{di_L}}{dt} = -\bar{v}_0 + \overline{d_1}\,\overline{V_{in}} \qquad (3)$$

$$C\frac{\overline{dv_o}}{dt} = \overline{I_L} - \frac{\bar{v}_0}{R} \qquad (4)$$

Small Signal Analysis of above two average equations (3) and (4) gives:

$$sL\tilde{i}_L = -\widetilde{v_o} + \overline{D_1}\,\widetilde{v_{in}} + \widetilde{d_1}\,\widetilde{v_{in}} + \widetilde{d_1}\,\overline{V_{in}} \qquad (5)$$

$$sC(\widetilde{v_o}) = (\tilde{i}_L) - \left(\frac{\widetilde{v_o}}{R}\right) \qquad (6)$$

$$s\tilde{i}_L = \left[-\frac{\widetilde{v_o}}{L} + \frac{\overline{D_1}}{L}\widetilde{v_{in}} + \tilde{d}\,\frac{\overline{V_{in}}}{L}\right] \qquad (7)$$

$$s\widetilde{v_o} = \frac{\tilde{i}_L}{C} - \frac{\widetilde{v_o}}{RC} \qquad (8)$$

Equations (5), (6), (7) and (8) represent AC component expressions. From DC component expression;
The duty cycle equation is derived as $\bar{V}0 / \bar{V}in = \bar{D}in$ (9)

$$\overline{I_L} = \frac{\overline{D_1}\,\overline{V_{in}}}{R} \qquad (10)$$

Using equations (5) and (6), following signal flow graph also termed as switching flow graph in this case is obtained [10-11] as shown in Fig.1.

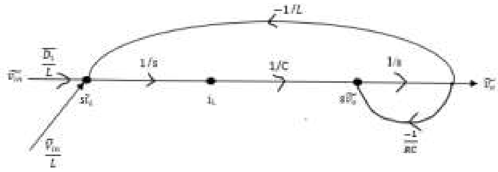


Fig. 1 SFG of ideal Buck converter

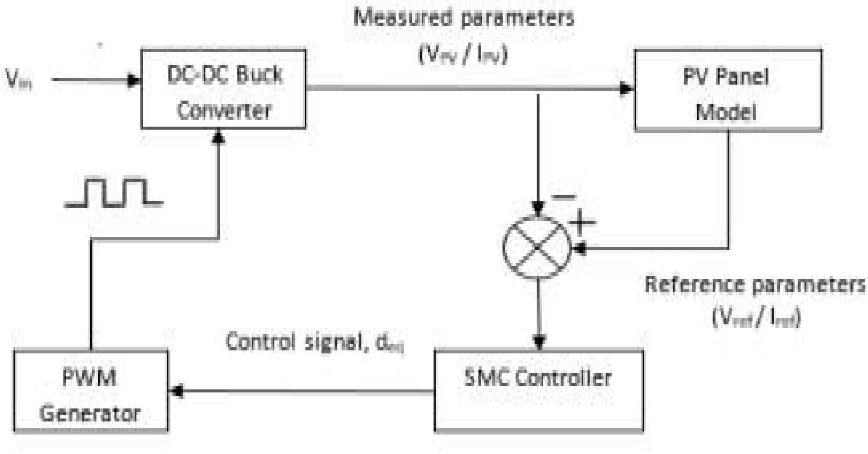


Fig.2 Schematic Diagram of PV Emulator

Fig. 2 shows schematic diagram of PVE showcasing the role of reference model and controller in PVE model. Further, equations (5) to (6) are used to calculate the transfer function of the buck converter using Mason's Gain formula and transformed to a signal flow graph as shown in figure 1. Small signal transfer functions, as well as big signal and steady-state models, can be calculated using the SFG approach [12]. The transfer function is produced by substituting the values of forward path gain and loop gains for individual and nontouching loops in Mason's gain calculation, according to the signal flow graph. This strategy is simple to devise and put into practice. It reduces calculation time, reducing the overall duration of the emulator design process. PVE considers converters in a closed loop circuitry. Mason's Gain Formula gives:

$$\text{Forward Path Gain} = \frac{\breve{D_1}}{L} * \frac{1}{s} * \frac{1}{C} * \frac{1}{s}$$

$$\text{Loop Gain, } L_1 = \frac{-1}{sRC}$$

$$\text{Loop Gain, } L_2 = \frac{-1}{s^2RC}$$

$$\Delta = 1 + \frac{1}{sRC} + \frac{1}{s^2RC}$$

$$\text{Transfer function; } \frac{\tilde{V_o}}{\tilde{v}_{in}} = \frac{\tilde{D}_1 * R}{RLCs^2 + Ls + R} \quad (11)$$

$$\text{Transfer function; } \frac{\tilde{V_o}}{\tilde{d}} = \frac{V_{in}}{LC(s^2 + \frac{1}{RC}s + \frac{1}{LC})} \quad (12)$$

III. SLIDING MODE CONTROLLER (SMC)

The goal of PVE's control strategy is to properly follow PV model signals, decrease processing load, generate reliable emulator output and simulate a range of PV modules without having to rethink the entire control strategy and influencing the power converter system and load. Nonlinear control approaches are investigated in order to maintain stability and effective control in massive signal conditioning, as well as to increase the model's dynamic response or robustness. SMC provides robustness and quick reaction to fluctuations in supply, load, and circuit parameters [13][14]. PV emulator configuration uses a buck converter in closed loop with SMC and diode model. T and d are the switching interval and duty cycle, respectively.

From above equations (1) and (2)

$$\dot{X} = f(X, t, d) \quad (13)$$

When the system approaches the sliding surface, the controller aims for the output to reach the desired value (given by either a diode model or a LUT). Partial or complete state variables can reach this surface. A new portion akin to an integral with a constant is added to the surface equation to minimize the error between the actual and intended value. As a result, the new sliding surface looks like this:

$$S = ain + bvo + m\int edt \; t\; 0 = 0 \quad (14)$$

S > 0 in open state and S < 0 in closed state. In steady state, when the system is kept on sliding surface, the derivative of S becomes zero and the stable point is when e=0, vr = vo. So, sliding surface equation becomes; ain= - bvo . For buck converter;

$$\dot{S} = [a \quad b] * \dot{X} + m\int_0^t e\,dt = 0 \quad (15)$$

$$\dot{X} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix}.$$

$$\dot{x}_1 = \frac{v_i}{L}\, d_{eq} - \frac{x_2}{L}$$

$$\dot{x}_2 = \frac{x_1}{C} - \frac{x_2}{RC} \quad (16)$$

At steady state, placing $\dot{S} = 0$ gives;

$$d_{eq} = \frac{aRCx_2 - Lb(x_2 - Rx_1) + RLC\,m(V_r - x_2)}{aRCV_i} \quad (17)$$

For above defined system to be stable; $v0 = vr$, the error must be zero. And $v0 = x2$ therefore $v0 = vr = x2$

Also, $i_c = x_1 - \frac{x_2}{R} = i_L - \frac{v_o}{R}$ and $d_{eq} = \frac{v_r}{V_i}$

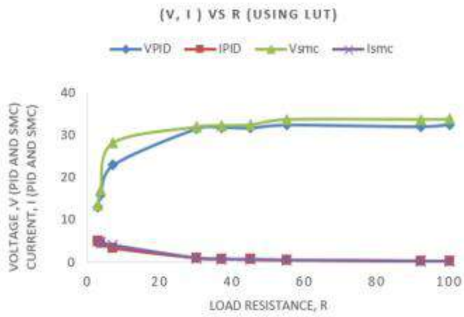
Thus, a new control input independent of load, R. The new control equation is represented below:

$$d_{eq}(t) = \frac{x_2(aC - LCm) + Lbi_c + LCm(V_r)}{aCV_i} \quad (18)$$

With deq, the system's closed loop dynamics converge towards a sliding surface. The system will reach the sliding surface in finite time if s = 0. In the presence of parametric uncertainties, a deq estimate is available. The solution of the system simulated and checked by routh Hurwitz criteria indicates that the system is stable. As a result, the inferred control law can be used to achieve desired results in ambiguous environments. The dynamic behaviour of the system is due to changing load conditions and irradiance due to partial shading of panel. Thus, it is proved that the main advantage of choosing SMC controller over the traditional controllers like P, PI and PID [15-16] is existence of stability and robustness performance in uncertain system, where these controllers fail specially in the case of uncertain environment.

IV. RESULTS AND DISCUSSION

Simulation is used to evaluate the system performance under dynamic situations. The converter's SFG methodology resulted in detailed small signal, large signal and steady state analysis with the minimum possible changes. As previously stated in section 1, SFG-based methodology assisted in obtaining transfer functions for various circuit variables in a more transparent and concise way. In the following section, the corresponding sliding coefficients are calculated. Figure 3 shows the V and I plots Vs Load resistance using a LUT-PID controller, which depicts the PVE performance of the PV model. Figure 4 depicts the viability of the PV model in conjunction with the diode model. Figures 3 and 4 demonstrate that the characteristics of the diode-SMC model also yield continuous values near MPP. LUT-PID and SMC models, on the other hand, show discontinuity at specific load points. As a corollary, the diode-SMC model is preferred for PVE implementation. For dynamic loading, the system VI and PV plots (shown in figures 5(a)(b) and 6(a)(b)) are obtained. The diode-SMC model's characteristics show a high level of accuracy for the planned solar panel. They also produce good results in conditions such as open circuit, maximum power point and short circuit. Figure 7 illustrates a comparison of the finalized model under standard test conditions with 60% irradiation. Implementation of robust diode-SFG-SMC achieves the goal of obtaining an emulator that follows the actual panel behaviour, and the results are made more efficient by computing transfer function at switching states. The suggested controller's performance is evaluated using derivations derived from mathematical modelling with SFG and simulations performed in MATLAB. The analysis in this work is based on ideal buck converter components and the results are very close to the actual panel results



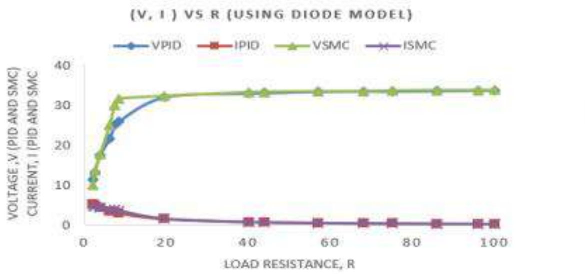
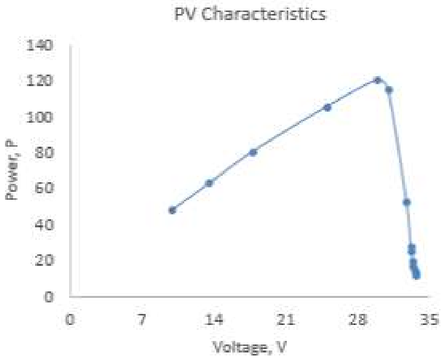
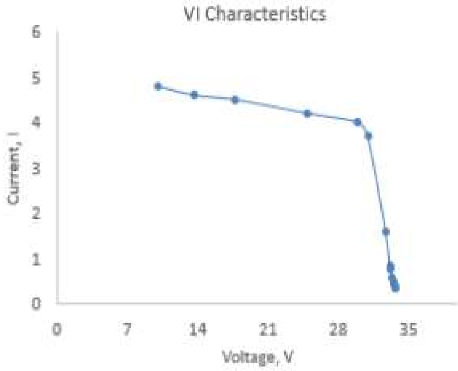
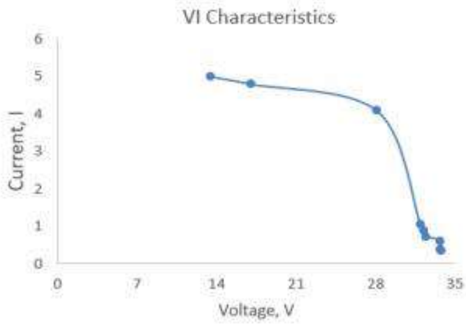


Fig 3. Voltage and Current Vs load Resistance using LUT

Fig 4. Voltage and Current Vs load Resistance using Diode







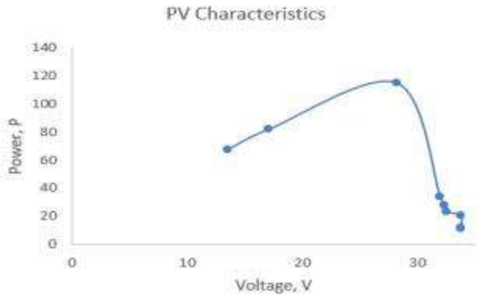


Fig. 5(a). V-I Characteristics of PVE using LUT

Fig. 5(b) P-V Characteristics of PVE using LUT

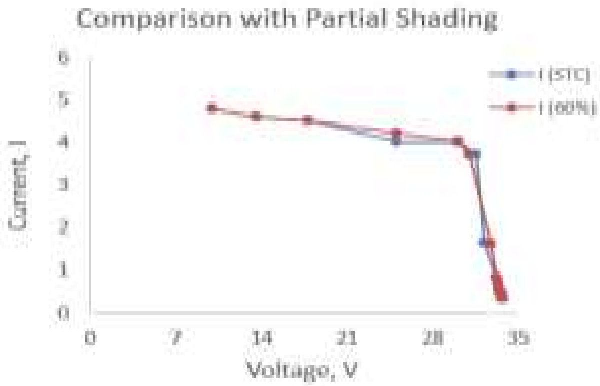


Fig. 7 V-I Characteristics of PV Emulator using diode-SMC model at STC and partial shading.

For stability study, the model's time domain performance for PID and SMC controllers is studied. Because the model is based on actual PV panel parameters, both stability and accuracy are important. Figure 6 shows the time domain analysis of the PID controller under various load conditions. Figures 8(a) and 8(b) depict PID and SMC controllers under dynamic loading (b). PID controller overshoots in various places, whereas SMC offers overshoot values that are acceptable for stability.

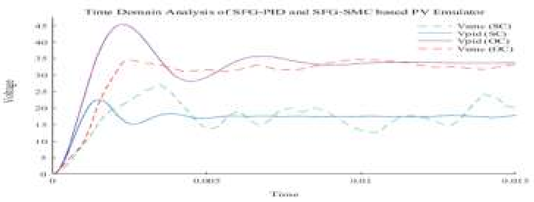


Fig 8(a) Time Domain comparison of SFG-PID and SFG-SMC at open circuit and short circuit

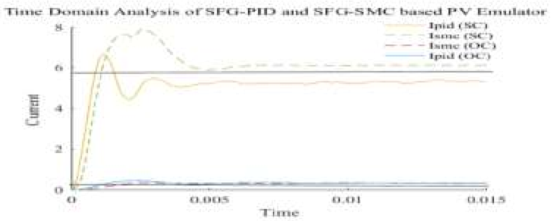


Fig 8(b) Time Domain comparison of SFG-PID and SMC at open circuit and short circuit

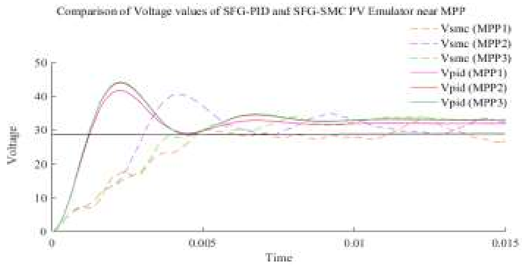


Fig 9 (a) Comparison of voltage values of SFG-PID and SFG-SMC based PVE near MPP

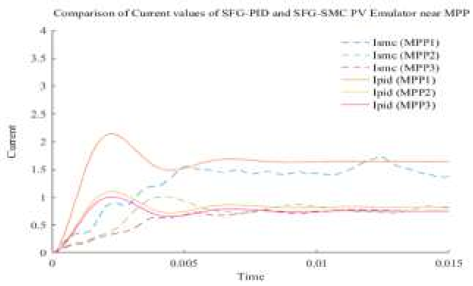


Fig 9(b) Comparison of current values of SFG-PID and SFG-SMC based PVE near MPP

The modeling and design process is described in detail, taking into account the various features of PVE operating conditions. Modeling of reference values is one of the most important factors determining computation efficiency. The main task was to estimate a non-linear characteristics curve. As a result, they are produced using a LUT and a single diode model. The SFGPID and SFG-SMC approaches use equations developed from an analysis of the converter's dynamic behaviour during sliding mode operation, as well as the system's stability criteria. SMC can be used in PVE design, as shown in Figures 6 (a) and (b), especially where the value of short circuit parameters is perhaps the most essential factor. Figure 7 depicts a comparison of the Emulator model under standard test conditions and partial shading (with only one colour) (60 percent of irradiance). The stability and accuracy of voltage and current measurements are considered in Figures 8(a) and (b). Overshoots observed at various operating ranges are used to determine system stability. The open circuit, short circuit and maximum power points are specified on the data sheet of the PV panel, hence the final comparison in figures 8 and 9 is based on these points. Figure 9 reveals that in the case of PID, there are more overshoots (voltage and current waveforms). The results depicted in the graphs above are indeed very close to the actual panel used in the model. The goal of conducting a comprehensive analysis of a PV panel is completed and the simulation results are reviewed to illustrate a comparative comparison of non-linear and dynamic PV panel behaviour.

V. CONCLUSION

The proposed methodology has developed a method for solar panel emulation considering its Non-linear and dynamic constraints. The method would speed up the installation of solar panels in rural and remote areas. The proposed approach will aid in the continual testing of Non-Linear panels with minor modifications. Regardless of the irradiance conditions, the findings obtained by SFG mathematical modeling and simulation of the PVE model in MATLAB show close agreement with the actual PV panel. The graphs illustrate that the SFG-based model is a viable alternative for representing switching converters with complex structures. The findings of the reference diode model are satisfactory at short circuit values, but LUT results lag accuracy at specific loading points, according to the research. The SFG-SMC model can solve the accuracy, robustness and stability of the system in emulator design. In the future, there is a lot of scope for research in the current system. Advanced non-linear controller designs can be used to accomplish potential research. One of the most key aspects of this system is that the methodology established here may be adapted to different converter types for use in power electronics and control systems.

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