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Modeling and Control of PV Emulator with Different Controllers and Transient Load Conditions

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To keep up with the pace of renewable energy, PV Emulators are encouraged during the design and installation stages. Short circuit current, maximum power point and open circuit voltage are required to analyze the complete characteristic plot of PV panel.This paper focuses on the modeling and control of PV Emulators, as well as the comparison of the results obtained by implementing P,PI, PID and FOPID as conventional controllers with AI-based PSOPI, PSOPID and ANFIS controllers. This work will aid in minimizing time, cost and on-site constraints, allowing timely installation of PV panels after covid. Another distinguishing feature of this paper is the comparative analysis of designed models with various control strategies and their associated performance indices over complete range of PV characteristics.

Keywords: Accuracy, AI based controllers, Conventional controllers, MATLAB Simulation, Performance Indices, State space analysis

1 Introduction

Solar energy is an ancient and widely accepted form of renewable energy. Research for its less maintenance, low operating cost and no harm to the environment will make it a primary alternative of other energy resources. India has witnessed rapid increase in solar capacity from 2.6 GW to 34 GW. It has plans of attaining highest renewable energy generation of 175 GW till 2022. Renewable energy has contributed 26% to the total installed generation capacity of India till 2020[1]. Important projects intent installation of solar street lights throughout the country, especially the areas where there is no facility for street lighting systems through grid power like North Eastern States. Installation of solar power plants of individual size up to 25 kW in areas where grid power has not reached or is not reliable are also prime concerns. These solar plants mainly target to provide electricity to schools, hostels and other public service institutions. Rapid installation of panels, thus hold a strong base for growth and easy access of solar energy. PV Emulator can be a good choice to achieve this target.PV Emulator is an alternative of solar panels at designing stage and testing in laboratories or off-site locations before actual installation. Agarwal and Aware[2], M. Ajaamoum *et a*l.[3],M. Tauquir *et al.*[4] and Di Piazza *et al.*[5] reported notable contribution in PVE. It provides voltage-current (VI) characteristic similar to real PV panels. An Emulator responds to change in load conditions[6], temperature, irradiance and shading on characteristics of solar panel[7]. An operator can input parameters of a PV panel such as Open circuit voltage (V_{oc}), Short circuit current (I_{sc}), Temperature (T), Irradiation, Load to simulate the characteristics of a real PV panel. It provides expedient appraise for faster and systematic testing. It is an important device for research and industrial sector to study the solar energy systems. This paper intends to give better understanding of system for improving the performance of PV by providing feasible testing solutions. Prasanth *et al.*[7] and Intissar *et al.*[8] discussed PVE as low-cost, efficient and a nonlinear power supply replacing the real PV system for any operating point irrespective of the environmental condition changes. However, pitfalls using actual panels at designing stage such as high manufacturing costs, large area requirement for panels to be tested and on-site/ far off locations of installation of solar panels are noted and led to research of Emulator which can be preferred over actual panel before installation. Zhou *et al.*[9] shows maximum power extraction aroused the necessity of PV Emulator for indoor solar panel. Raul *et al.*[10], Chalh *et al.*[11] and De Melo *et al.*[12] have proposed PV

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Emulators which can control testing conditions accurately and at low cost. Moreover, research in accurate designing and modeling are must for exponential growth in solar sector. These goals can be achieved by improvising research focused on reducing the cost of panels, improving transient response of Emulators, closely working on performance parameters and implementing techniques for fast and reliable results. Literature review of PV Emulators culminates that research areas of stepwise designing of PV Emulator control strategies can be explored for better analysis. Thus, the aim of this paper is to explain the basic designing and modeling of PV Emulator to implement it with more clarity and reasoning. Earlier used mathematical equations-based model is also taken into consideration to get a clear outlook and understanding about why Emulator is advantageous in research areas related to solar energy sector. This paper is organised into sections. The following section discusses the fundamental materials and methods of PVE design. The section Results and Discussion summarises and compares the work's findings in the form of plots and tables. The final conclusion section summarises the obtained results and the future scope of the research work.

2 Materials and Methods

2.1 PV Emulator-Basics

A PV Emulator model can be described by three main parts: Power converter, Control strategy and PWM circuit. Converter based PV Emulator design is robust, reliable and efficient. Lee *et al.*[13], Ickilli *et al.*[14] Rachid *et al.*[15], Iqbal and Tariq[16] have shown notable implementation of converters like buck, boost, buck-boost in their PV Emulator models This paper explains various design aspects using different controllers with resistive load switching at standard test conditions. Buck converter is suitable for PV Emulator as it is simple in construction with lesser number of components[15.16,17]. The selection of converter in this research work is based on the fact that in the selected solar panel, the open circuit voltage is lower than the input voltage, $V_{in.}$ So, a buck converter can satisfy this condition in a simplest and cheapest way. The main components used in designing are MOSFET, Diode, inductor, capacitor, resistor, DC source, signal generator and controller. The basic block diagram shown in Fig. 1 represents a closed loop control of PV Emulator. The feedback path consists of a controller and a PWM circuitry. State Space Analysis is carried out to obtain a transfer function that represents the power converter. By using this transfer function, controller designing becomes efficient[18]. The duty cycle obtained from the pulse width modulator in the form of pulses is send as input to the power switch. The values available in the datasheets of solar panels like V_{OC} and I_{SC} are fed to lookup table as reference values. These values are used in closed loop containing a controller that works on error signal generated by comparing reference values with actual values and a PWM circuitry for switching of MOSFET. A controller sends signals to the converter through PWM to provide minimum error. A power converter functions to trace the reference signal and give output values that are homogeneous to the actual PV panel. PV panel manufacturers commonly provide the parameter at STC i.e. solar irradiance of 1000 W/m^2 and specified temperature as25°C.

Youssef *et al.*[19] has presented modeling of PV Emulator using mathematical model. But in this work, Look up Table (LUT) approach is used to feed reference values to the model for comparison with the actual value of output and to generate error signal as controller input. The selection of this

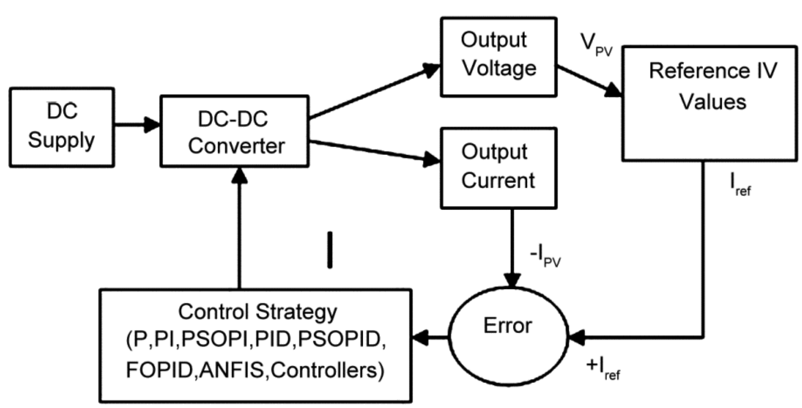

Fig. 1 — Basic block diagram of PV Emulator.

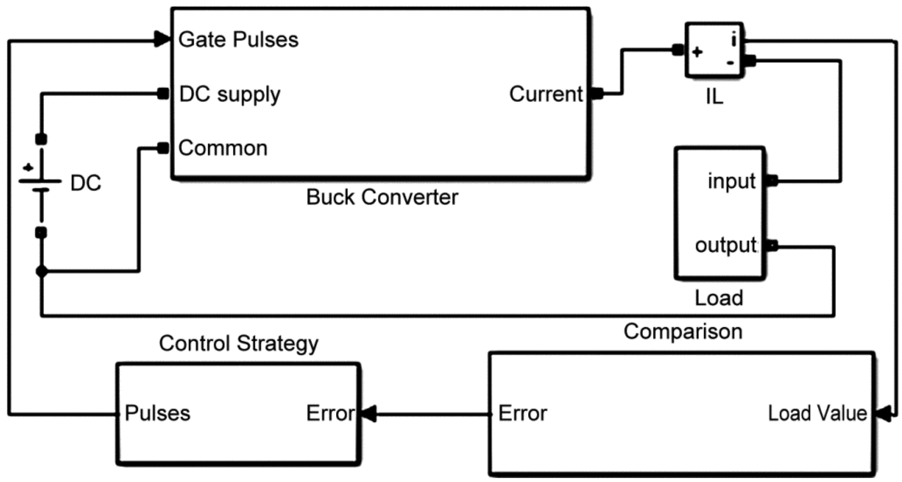

Fig. 2 — MATLAB Simulink proposed PVE Model.

approach is to reduce the processing burden of PV Emulator model. State space averaging method is useful in modeling of converter structure and small signal analysis[18]. The analysis of ON and OFF states of converter are averaged according to the duty cycle and then restructured according to the state space representation. Classical PV Emulator topologies implemented low-cost OP-AMPs with diode-based approximation, but their simulation lacked elucidation. So, PV Emulators based on converters easily replaced them.

To ensure accuracy, stability, better controller mechanism and to enhance the dynamic response, non-linear control methods are also studied. State space averaging is used to derive steady state models.

Literature shows that the closed loop control structure of Emulator plays significant role in its functioning. The non-linear characteristics also affect response of PVE. The analysis of control strategy in this research paper considers conventional control using P, PI controllers as its basic controllers. PID controller is then implemented to improve response of the model and comparative work. The scope of further modifications to reach values closer to Isc and Voc resulted in advanced tuning methods.

Table 1 shows the reference panel values that need to be traced to design the best control strategy. Fractional Order PID and Particle Swarm Optimized PI and PID are then implemented on PVE model for the desired Isc and Voc values. Modifications in traditional controller i.e. by involving order of integral (λ) and order of derivative (μ) in fractions is the base of FOPID controller. The new transfer function is then represented by:

Table 1 — PV Panel reference Value

Parameters	Values
Open Circuit Voltage, V_{oc}	32.8V
Short Circuit Current, I_{sc}	4.7A
Voltage at Maximum Power Point, V_{MP}	26.8V
Nominal Voltage	18V
Peak Power	115W

$$G(s) = k_p + \frac{K_i}{S_\lambda} + k_d s^\mu \quad \ldots (1)$$

This implementation of FOPID favored in fast settling time and minimizing the overshoot. PV Emulator analysis based on different controllers is thus a perfect approach for comparison of results while designing. Different conventional and AI based controllers are tuned to conceptualize the implementation at transient loading conditions. Further, the designing and modeling of Emulator controllers is carried out for the accuracy of the output i.e. ability of the system to swiftly predict the operating point. In literature, papers related to designing of PV Emulator have considered fix load values. In this work the loading is varied to obtain a wide response of Emulator for better understanding. Conventional controllers (P, PI and PID) resulted in slow dynamic performance and oscillating output. It is thus realized that the issues related to dynamic performance and transient loading can be improvised by using hybrid-mode controlled methods[20]. PSOPI and PSOPID[21,22] controllers are thus designed to minimize transient time like rise time and settling time along with error component of the system. An objective function is formed with the above parameters to obtain tuned value of gains kp, ki and kd, thereby resulting infaster and easy process for controller tuning and action. Research suggests that Fuzzy logic controller prompts improving the dynamic response of non-linear system in the absence of the exact model, possibility of multi objective control, use of imprecise language and robust control[23].But tuning of membership functions remains a cumbersome task. These factors compliment use of Adaptive Neuro-Fuzzy Inference System (ANFIS) controller for PV Emulator design. ANFIS is an Artificial Intelligence popularly known as Artificial Neural Network (ANN) based on Takagi-Sugeno Fuzzy Inference System. It integrates Neural Networks (NN) and Fuzzy Logic(FL) principles[24,25] and has the ability to provide advantages of both methods within a framework. It is expected to produce accurate predictions for the highly nonlinear systems[26] also. Fig. 3 shows the relationship between input-output membership functions in the form of block diagram. The membership function values are assigned to linguistic variables using subsets: FSC, SC, MP, OC,COC for inputs error and error change.

Fig. 4 shows the ANFIS structure corresponding to Emulator design. Once all controllers are designed and incorporated in the PV model, the system performance indices and accuracy are finally compared. The performance index implies the quantitative measure of the system to understand system specifications. The innate objective is to track error at transient load conditions and to explain performance in terms of ISE, IAE and ITSE. When the error becomes negative, these performance measures are mostly expressed in terms of either absolute value of error or in terms of square error. So, to get a wide range analysis including positive and negative error, these become significant. An Emulator is termed “accurately designed” when it replicates the VI characteristics of the desired panel and requires minimum moderations for panels whose ratings are

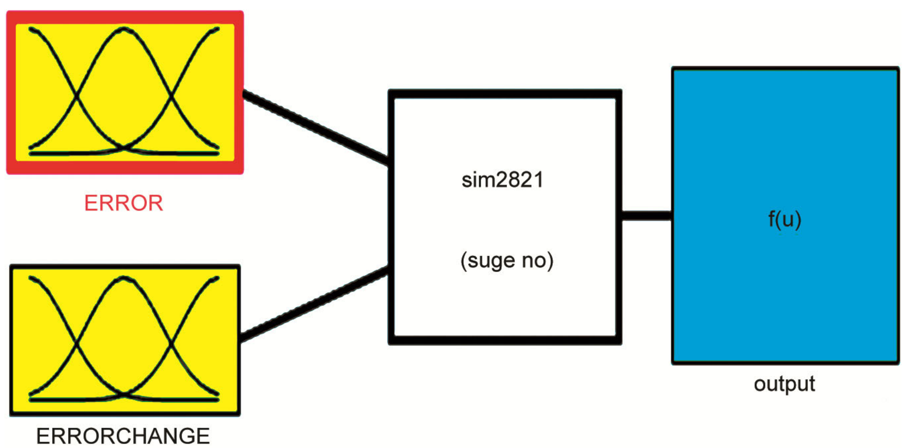

Fig. 3 — Fuzzy Logic Block diagram.

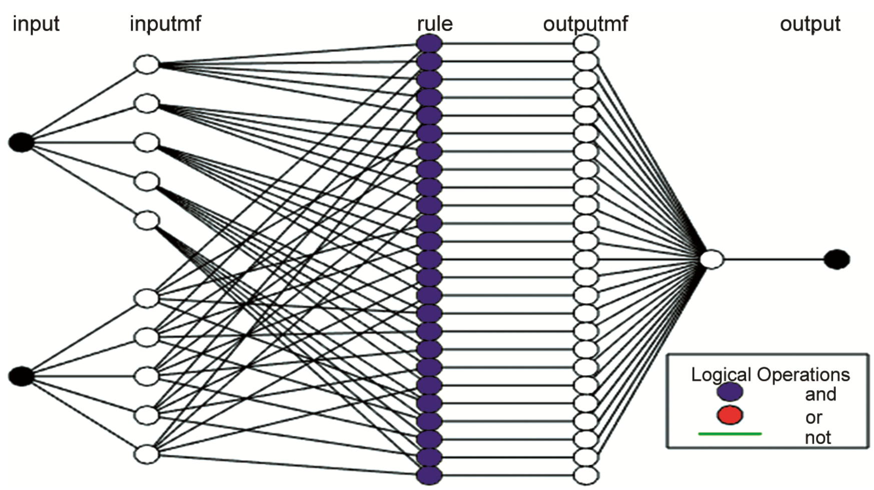

Fig. 4 — Obtained ANFIS structure.

nearly similar to reference panel. Thus, after analysis, the accuracy of buck converter-based Emulator is calculated. Major losses occurring in buck converter that reduce the efficiency of the system are divided into three categories[27,28] namely Conduction Losses, Switching Losses and Static Losses.

3 Results and Discussion

This work has primarily focussed onthe DC-DC buck converter-basedPV Emulator designing and modeling through MATLAB.

Fig. 5 summarizes voltage transients of different controllers. The effect of load variation on output voltage of PVE are represented in different parts. Fig. 5(a) shows the response of the designed model with P with rise time 438μsec and settling time of 19.8msec. 5(b) with PI controllers with rise time 456μ sec and settling time of 18m sec. Fig. 5(c) shows response of PSOPI controllerwith rise time 418μsec and settling time of 18msec. 5(d) represents response of PID controller with rise time 493μsec and settling time of 19msec. 5(e) shows response of PSOPID controller with rise time 533μ sec and settling time of 16.4msec. 5(f) shows response of FOPID controller with rise time 523μsec and settling time of 8.5msec and 5(g) shows response of ANFIS controller with rise time 530μsec and settling time of 19msec. However, considering the error, ANFIS has attained the minimum error criteria with accurate characteristics. Fig. 5(h) concludes response of FOPID Vs ANFIS controller. The obtained characteristics are giving satisfactory values with rise time and settling time by conventional methods of controlling, but the initial voltage at constant current region requires better tuning. So, AI based methods have improved the voltage characteristics in constant current region and constant voltage region.This results in accuracy in terms of characteristics similar to actual PV Panel.

The performance indices ISE, ITAE and ITSE are shown in Fig. 6 , Fig. 7 and Fig. 8 respectively. There parameters play an important role in deciding the accuracy and efficiency of the designed models. Fig. 9 and Fig. 10 show voltage and current characteristics with respect to load resistance. The results are obtained by varying the load in the range of 3 ohm to 100 ohm. The above plots conclude the voltage and current path from short circuit current to

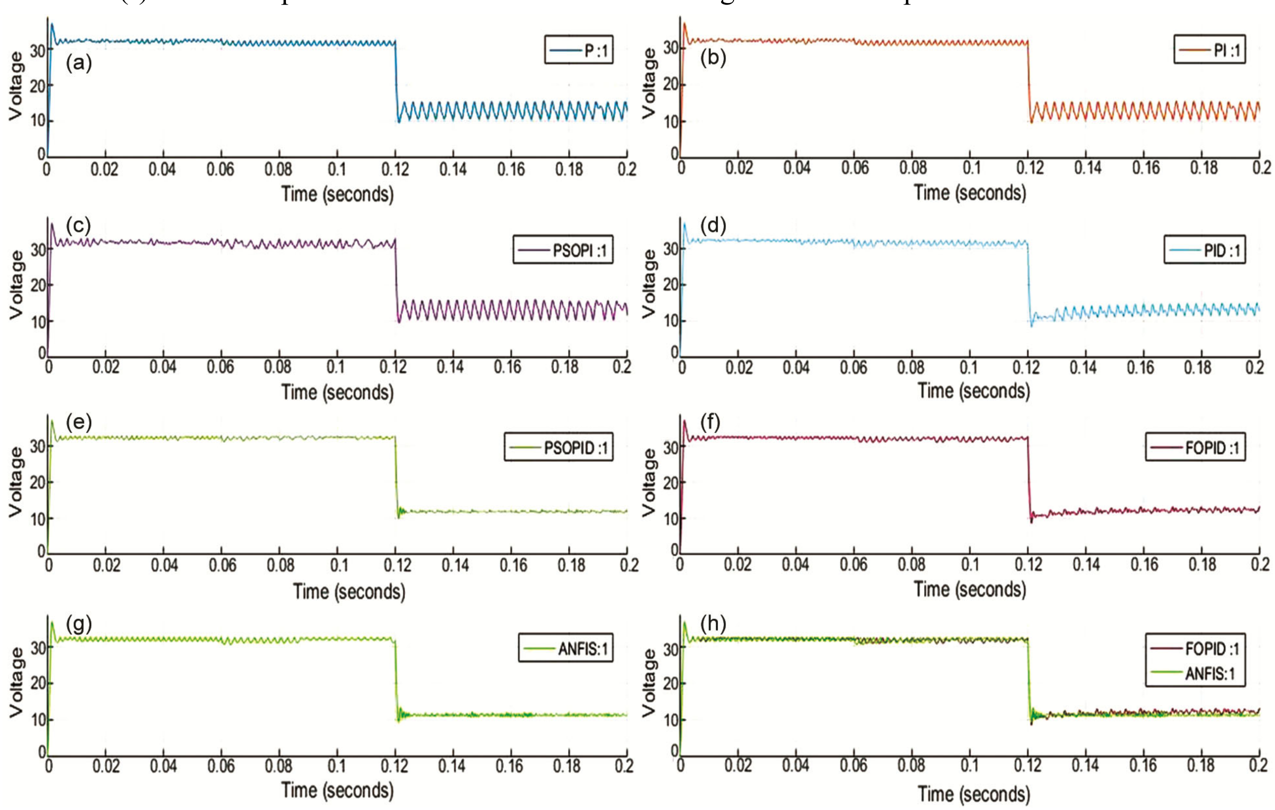

Fig. 5 — Top left to right 5(a) Response of P controller ;5(b) Response of PI controller; 5(c) Response of PSOPI controller; 5(d) Response of PID controller; 5(e) Response of PSOPID controller; 5(f) Response of FOPID controller; 5(g) Response of ANFIS controller & 5(h) Response of FOPID Vs ANFIS controller.

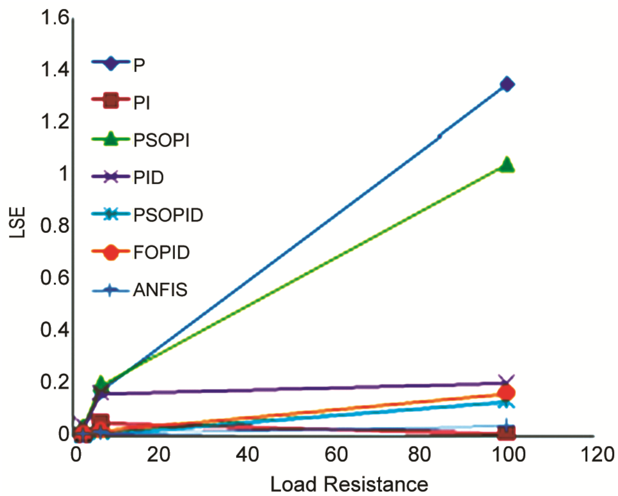

Fig. 6 — Performance Index, ISE.

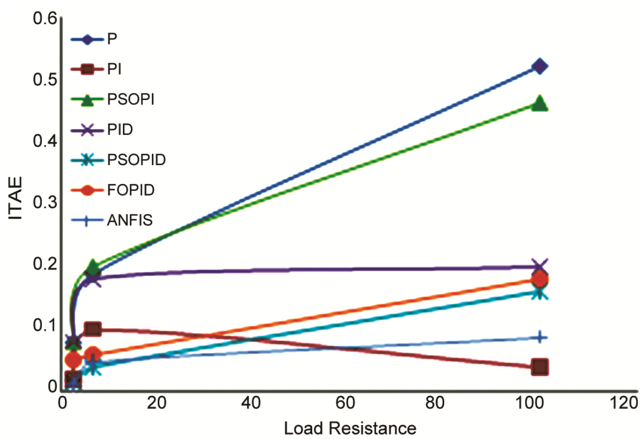

Fig. 7 — Performance Index, ITAE.

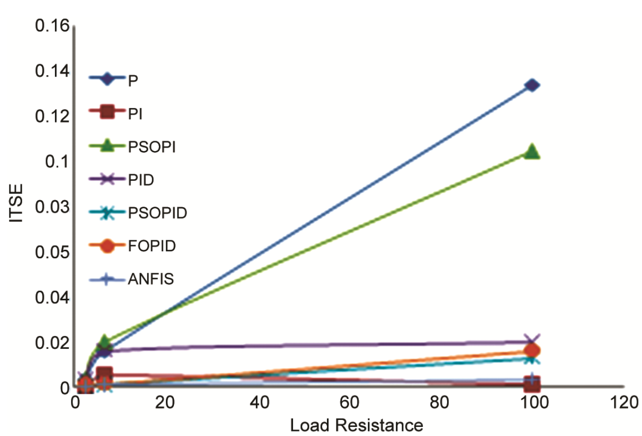

Fig. 8 — Performance Index, ITSE.

open circuit voltage zone. These results show that AI based controllers provide best results in these zones. They also help in reducing the tuning time and improving the transient response of non-linear systems.

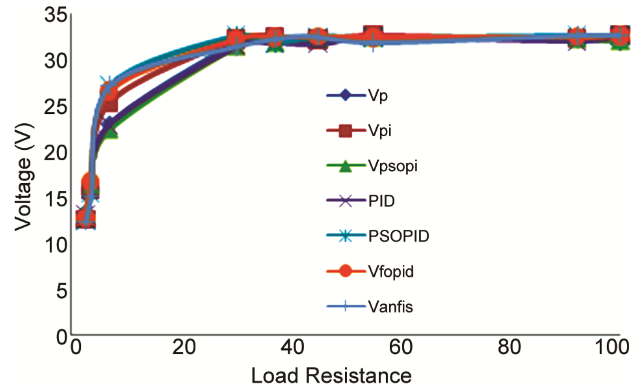

Fig. 9 — Analysis based on VR characteristics of different Controllers.

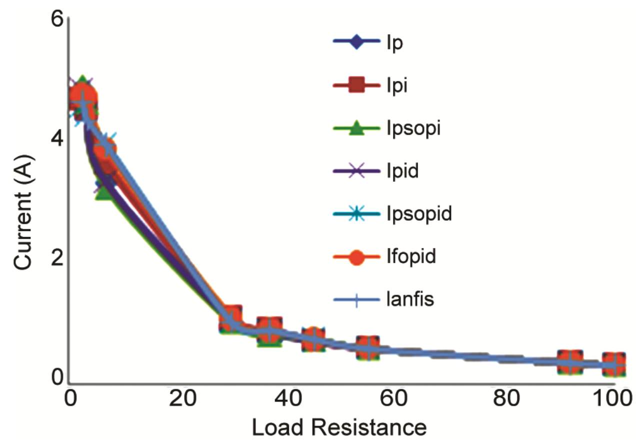

Fig. 10 — Analysis based on IR characteristics of different Controllers.

4 Conclusion

The paper outlines how to design a PV Emulator using a buck converter while maintaining accuracy and simplicity in modeling. Progressive modelling is used to compare and analyse the fundamentals of designing an emulator with existing conventional controllers and new AI control schemes. Robust control for accuracy in non-linear PV characteristics is fulfilled by implementing ANFIS. Various controllers show satisfactory results but accuracy and robustness are attained by AI based controllers. Fig.5 represents voltage transients obtained by implementation of P,PI, PID, FOPID, PSOPI, PSOPID and ANFIS controllers in a comparative manner. PSOPI's transient time analysis ensures design improvement. PSOPID performs well in terms of overshoot. ANFIS shows best implementation for accuracy in this non-linear system. The performance indices ISE, ITAE and ITSE shown in Fig. (6-8) compare errors of the designed models using different control strategies at transient loading conditions. Fig.9 and Fig.10 show the voltage and current variations with resistive load transients for comparing I_{SC} and V_{OC}. The obtained open circuit voltage and short circuit current values match with real PV panel. Post covid the installation process can be sprinted by implementation of such models to achieve the foresaid target of 100GW by 2022 in India. In future, this paper can be extended by taking other non-linear controllers, implementing other methods for reference values on high rated panels.

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