An Overview on the Topologies and Control Strategies for Solar Photovoltaic Emulators

K. R. Jeswanth Kumar, S. Kamatchi Rajeswari, S. Sridharan, and K. Sundararaman

1 Introduction

The rapid depletion of fossil fuels and the consequent apprehensions on energy security have sent the governments of the world scurrying towards finding alternate forms of energy which would be everlasting. This coupled with the concerns on global warming and pollution have made solar and wind energy systems popular. The Government of India has planned a stiff target of generating 100 GW of power through solar energy by 2022. Research and development into the issues connected with solar energy have also kept pace, and the cost of generation for every unit of solar energy is now even less than traditional forms of energy.

However, solar energy has its own issues, the major one being intermittency. Hence, it has to be necessarily used along with other forms of energy or in parallel with the grid or would need substantial storage options. A researcher intending to test a new design of an inverter or a battery charger or a new control algorithm would be handicapped by the fact that the solar power is intermittent and is also highly fluctuating due to climatic conditions or due to shading of the panels. A photovoltaic emulator would help to carry out experiments without depending on the solar power and without bothering about climatic variations. They require much less area than actual solar panels and the testing cost is substantially less. They are also portable and programmable and can be incorporated with protection features.

A photovoltaic emulator, as the name suggests, emulates the actual performance of solar photovoltaic panels in that it is able to produce the same current–voltage characteristics for a given load and for different climatic conditions as that of the chosen solar panels. Photovoltaic panels are connected in arrays in series or parallel or series–parallel or in many other different configurations and the emulator should be able to show the same output characteristics as that of the array.

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A photovoltaic emulator would be very useful during the design and development phase for building a stand-alone or a grid-connected inverter system and for trying out new control algorithms like maximum power tracking. It could also be used to estimate the amount of energy production during the operational phase.

An ideal emulator should not only be able to closely reproduce the static nonlinear I-V characteristics of a solar panel array under varying climatic and shading conditions but also have a good transient response and match the dynamic characteristics of the panel array. Since the emulator may have to work with converters of different topologies and of different manufacturers, it has to be flexible in terms of compatibility. It would do well to have a low power consumption while being cheap, compact and efficient.

Existing papers which review the photovoltaic emulators described in the literature are given in [1–3]. This paper endeavours to give a general overview to research scholars and working professionals who wish to build a PV emulator in the laboratory for further experimental work. The paper briefly describes the major topologies and control strategies in the literature that have been used for building PV emulators and the issues associated with them.

2 Approaches to Emulation

Seo et al. [4] outline clearly the two approaches towards configuring a photovoltaic emulator with a power electronic converter, as shown in Fig. 1. The climatic conditions in the form of temperature, irradiance and even wind should be obtained as input parameters. The solar array simulator engine emulates a photovoltaic panel by generating a suitable reference which takes into account these climatic conditions. This reference drives the power electronic converter to generate the physical output. The engine could be a microcomputer or a digital signal processor or a field-programmable gate array (FPGA) or a hardware-in-loop (HIL) system. It could even be a software in a computer, like LabView. MATLAB has been used very often but occasionally other softwares like PSIM have also been used [5].

In the first approach, the engine could use a lookup table which is generated offline through experiments conducted on real PV panels or on PV models. During operation, the data has to be simply picked up from the tables which could be very fast. However depending on the number of points stored in the memory, some interpolation may be required to fetch the specific values and there could be a little loss of accuracy. Also, the lookup table data is panel specific and has to be regenerated if the panel is changed.

The second approach uses a PV model like 1D2R or 2D2R, and the reference is determined in real time from the governing equations of the model. The parameters of the model have to be extracted based on the climatic conditions using iterative methods like Newton–Raphson method or by techniques like evolutionary computing. Seo et al. [4] suggest an optimisation method known as conjugate gradient

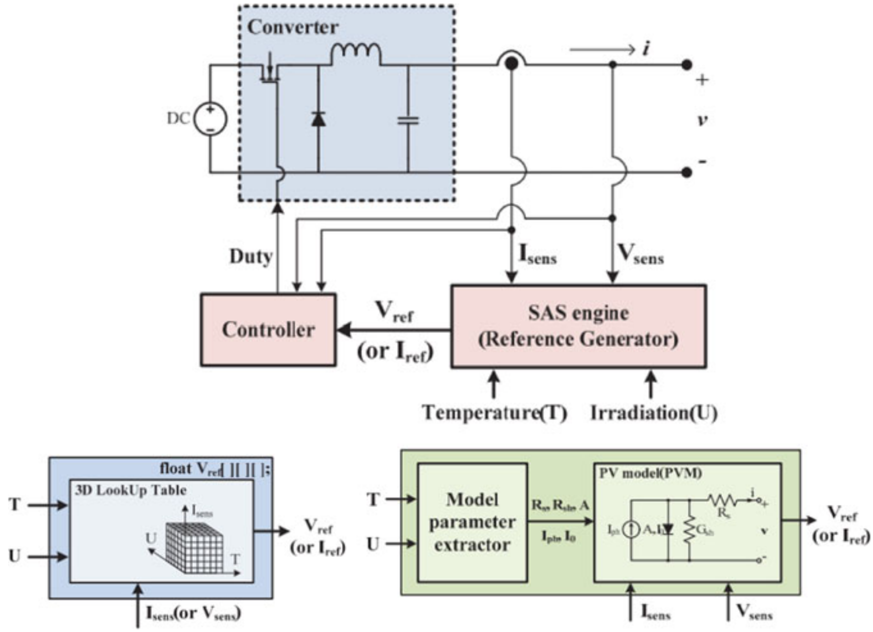


Fig. 1 Simulator engine and the two approaches for the emulator [4]

that uses the gradient of an error function. The memory requirement is less but calculations have to be fast. With the three known operating points, namely current at short circuit, voltage at open circuit and maximum power point, any suitable algorithm can be used to determine the other points. The reference generated by the controller is input to a power electronic converter which actually brings about the operating point in terms of load current and voltage, which should be identical to that of a real PV array.

3 Photovoltaic Models

To determine the points on the current–voltage (I-V) characteristics of a PV cell at different temperature and irradiance conditions, a model of the photovoltaic cell is required. Some of the models often used by researchers are summarised in Figs. 2, 3 and 4. In all the cases, the PV output is modelled with a current source. In the 1D2R model, a diode is in parallel with the current source and additional series and shunt resistances are represented. In the double diode model, two diodes are placed in parallel instead of one. Both the above models are known as DC models. In the AC model, a capacitance is inserted in parallel to the diode which becomes important to study transient conditions [A7]. The 1D2R model is simplest to analyse while the

Fig. 2 1D2R model

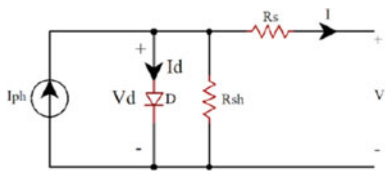


Fig. 3 2D2R model

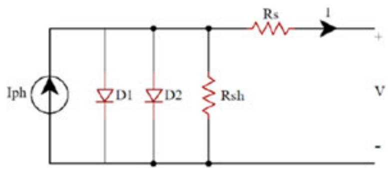
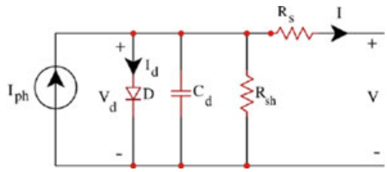


Fig. 4 AC model of a PV cell



other two models have more computational overheads, while being more accurate during variations in irradiances.

The parameters of the model are extracted from datasheets of the PV panels by an iterative process like Newton–Raphson method. Once the parameters are extracted for a set of climatic conditions, the operating points on the I-V curve can be determined for any load condition. Normally, the climatic conditions that are considered are only temperature and irradiance. But since wind speed and its direction also have the effect of influencing the temperature, wind effects have also been considered recently [6]. Abdelghani and Sethom [7] present an approach to estimate the parameters of a 1D2R model of a PV array. The array could have a series–parallel combination, and a part of the array could also be partially shaded.

As an alternative to the PV model + converter combination, Park et al. [8] propose a topology which consists of a PV module in parallel with a power supply and a resistor *R*add in addition, as shown in Fig. 5. The model is claimed to be accurate near the maximum power point. Zhou and Macaulay [9] use a current source without the resistor to represent the power supply. The bypass diode of the PV panel which prevents hotspots during partial shading conditions is incorporated in the model.

Leaving out the knee region, the I-V curve for a PV panel has a region where the current is more or less constant and a region where the voltage is almost constant as shown in Fig. 6. Effectively, it behaves as a nonlinear current source. Nousiainen et al. [10] define the necessary properties for a source to satisfy the emulation requirements of a photovoltaic generator. PV emulation can broadly be done either by artificial illumination of a PV panel with a light source or by using a power electronic converter which derives its reference from a controller driven by a PV model.

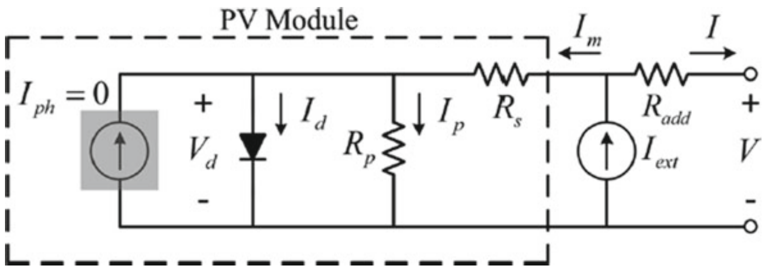


Fig. 5 PV panel with a power supply in parallel [8]

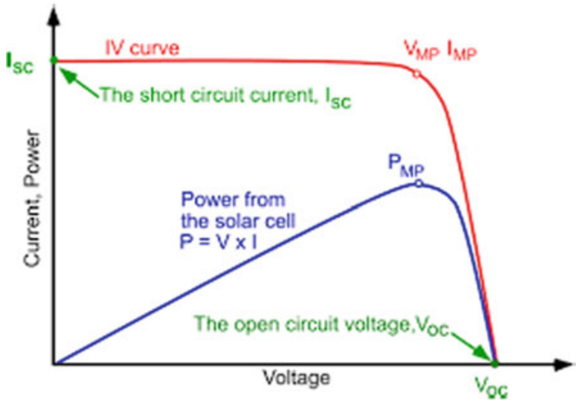


Fig. 6 P-V and I-V characteristics of a solar cell

3.1 PV Panels Illumined by Light Sources

One way to construct an emulator would be to use a light source whose intensity and spectrum can be varied. This method does not require a reliable model for the PV panel. For the light source, halogen lamps would be economical but they do not match exactly with the solar spectrum. They also generate a lot of heat. A combination of LED and halogen bulbs or halogen in combination with Xenon bulbs gives a better performance.

Buso et al. [11–13] outline the design of photovoltaic emulators where a modulated light source comprising LED, Xenon or halogen bulbs or a combination thereof is used to illuminate PV panels and thereby generate the required I-V characteristics. The light source illuminates the PV module and causes photogeneration. The light source should match the spectral radiation distribution of the sun for higher accuracy. To have fast response to load and climatic variations, the bandwidth of the driver circuit should be large.

4 Power Electronic Converters

Linear regulators have fast response but are no longer preferred due to their low efficiencies. The power electronic converter that is most commonly used for generating the physical output from the reference generated by the controller is the pulse width modulated buck converter. The output voltage of the photovoltaic panel is the open-circuit voltage (Voc) of the panel when no load is connected and is zero when the panel is short-circuited. Hence, the voltage has to vary from 0 to 'Voc' and a buck converter is ideally suited for the application. But other non-isolated converters have also been used sporadically. A multiplier SEPIC converter with a Dickson charge pump for a higher gain has been used in [14] along with dSPACE 1104 power-hardware-in-the-loop (PHIL) controller. A PHIL controller has also been used in [15]. A boost converter and a buck converter in cascade with a double current mode controller have been outlined in [16] based on the lookup table principle and uses a TMS320 DSP.

At operating points close to open-circuit voltage the current is low and the converter may go into discontinuous mode and voltage may rise. This may call for a dummy load to be connected in shunt. Similarly at low duty cycles which typically happen when the operating point is close to short-circuit condition, the current pulses may be spiky and current limiting resistances may be called for. These resistances tend to reduce the efficiency. Moreover, a simple buck converter is hard switched and has more switching losses at higher frequencies besides causing electromagnetic interference.

Some of these issues could be solved by going for isolated converters, albeit at higher expense. Wandhare and Agarwal [17] discuss a flyback topology for the power electronic converter and controlled with a dsPIC microcontroller as shown in Fig. 7.

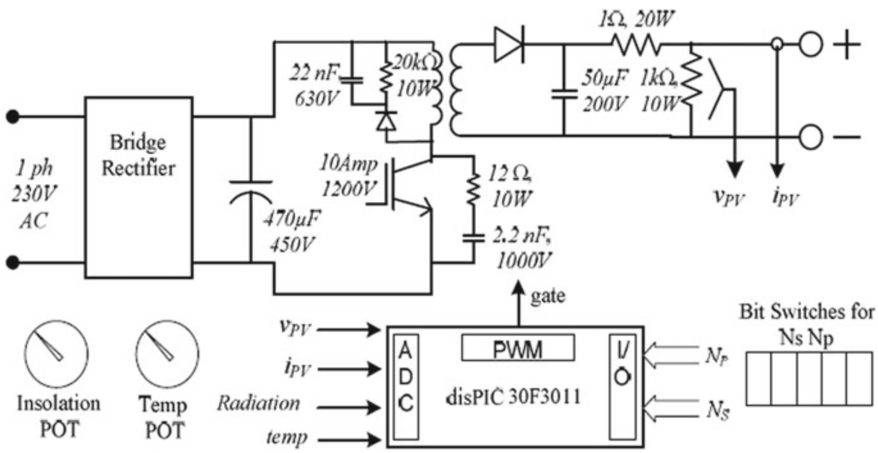


Fig. 7 Schematic of the flyback converter-based emulator in [17]

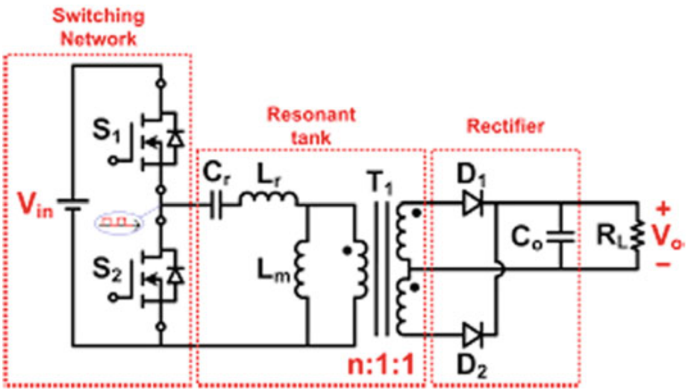


Fig. 8 Half-bridge LLC resonant converter

Due to isolation with a high-frequency transformer and operation at a high switching frequency, the converter is compact.

Load resonant converters like series or parallel resonant converters can be varied over the full range by frequency modulation. They have zero voltage switching of the main switches, and the rectifier diodes are also zero current switched. Hence, they have lesser switching losses and higher efficiency. The resonant capacitor in series with the transformer prevents it from getting saturated. The converter could also have a front-end power factor controller.

Among the isolated resonant converters, LLC resonant converter is the converter of choice. A series resonant converter has an issue with no load regulation and parallel or series–parallel resonant converters have more circulating energy than LLC resonant converters at low output voltages. D'Cruz and Rajesh [18–21] discuss topologies with LLC resonant DC-DC converters. A typical schematic of a half-bridge LLC resonant converter is shown in Fig. 8. However, it may be noted that under changing climatic conditions, the switching frequency may have to vary widely. Additionally, because of the transformer such converters may be bulky, heavy and costly.

A PV array in conjunction with a two-stage converter has been emulated together to study a converter system connected to the grid in [22]. In [23], an additional LCL filter is introduced at the output of the simulator to minimise current ripples at the output. A three-phase galvanically isolated DC-DC converter has been used in [24] with a TMS320 DSP for controller.

5 Control Methodologies

Control of the power electronic converters can be done using analog controllers or with microcontrollers or digital signal processors. The nonlinear I-V characteristic of a PV panel necessitates a high control bandwidth for stable operation, and if digital control is used, it has to be fast-acting. Schofield et al. [25] use an analog controller but in many other papers, digital control has also been employed. An operational amplifier-based analog controller which implements an emulator on a logarithmic approximation of the 1D2R PV model is described in [26]. A linear regulator is used for the power part. Koran et al. [27] describe a simulator which has the merits of both analog and digital controllers. The analog extraction strategy for the I-V characteristics uses a controlled illumination on a PV cell. A digital signal processor is used for processing the curve information and generating the reference for the power section which constitutes a three-phase interleaved DC-DC converter which has a front-end active rectifier.

Gadelovits et al. [28] suggest a method by which an existing power supply can be modified to obtain the programmable power supply required for the emulator rather than building a converter from the scratch. This helps to achieve rapid prototyping. This is done by injecting a variable analog signal into the feedback loop of the existing power supply. The method is generic and suitable for any AC/DC power supply.

Kapoor et al. [29] suggest an adaptive strategy for control of the PV panel at different load conditions. The emulator output voltage is changed based on the deviation between the expected and the actual current of the PV module. The controller gains are changed based on the circuit conditions.

5.1 LabView-Based Implementation

Dolan et al. [30–33] discuss the implementation of a PV emulator using LabView. The PV panel parameters are generated through several analytical models. The model of the photovoltaic system is implemented in LabView, and it is interfaced with the external sensors and converter using a data acquisition system. The climatic conditions are input to the system by suitable input voltages. The details of the PV array can be suitably parameterised in LabView. Effects of partial shading and sometimes effects of panel degradation are also incorporated. The maximum power point tracking algorithm is built into the LabView interface. The PV model in LabView is executed in real time, the dynamic resistance of the panel corresponding to the operating point in I-V characteristics is tracked and the required reference is output to the converter for physical realisation. The converter is a buck or boost converter in combination with a voltage source inverter. A schematic of the emulator in [31] is shown in Fig. 9, and the front panel of the emulator in [33] is shown in Fig. 10.

5.2 FPGA-Based Implementation

Tornez-Xavier et al. [34–38] discuss implementation of emulators which make use of field-programmable gate arrays (FPGAs). FPGA enables rapid system prototyping, and due to its high clock frequency, the switching frequency of the converter can be

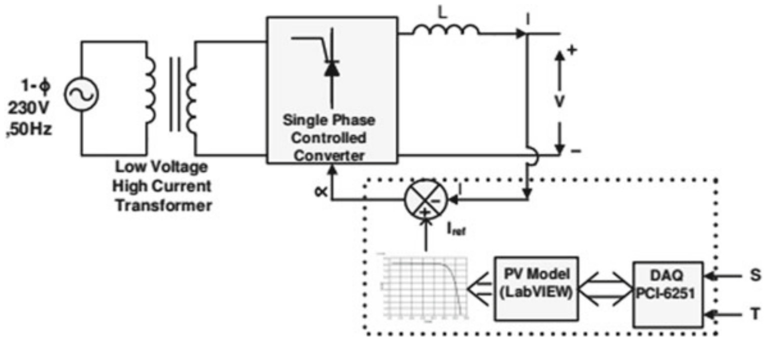


Fig. 9 Schematic model of the emulator [31]

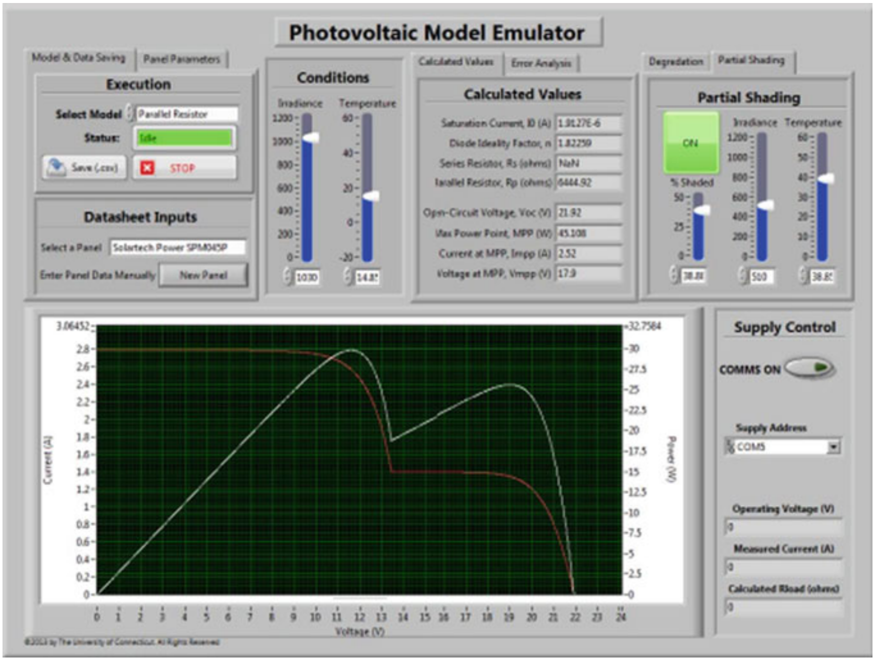


Fig. 10 Front panel of the emulator [33]

high enabling a reduction in the size of the converter. In [34], an analog model of the solar panel is created using the framework of Mentor Graphics. The temperature and irradiance are fed as inputs, and open-circuit voltage and short-circuit current values of the PV panels are generated. Using these values, an artificial neural network is trained in MATLAB and its optimised output is implemented with FPGA. Ickilli et al. [35] use an Altera Cyclone-III FPGA board, the reference signal from which drives a buck converter to generate the physical output of the emulator. In [37], the PV

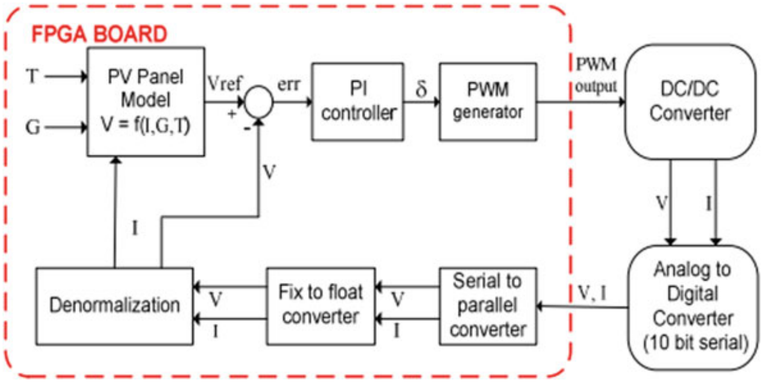


Fig. 11 Control schematic of emulator in [35]

characteristics are modelled with the Xilinx System Generator (XSG) platform based on FPGA, which has the advantage that the VHDL code is automatically generated using HDL co-simulation. Jin and Zhang [38] propose a FPGA-based space solar array simulator in combination with a linear power regulator for fast response. A control schematic of the emulator in [35] is shown in Fig. 11.

5.3 Dual Mode Controls

Escobar et al. [39] propose a controller which is a combination of a proportional-derivative voltage mode controller (VMC) and a passivity-based current mode controller (CMC). By introducing an additional variable, the location of the operating point is determined, and the appropriate mode of control is chosen with some hysteresis. A dual-mode control has also been suggested in [40] to avoid the stability problems in the constant current zone or constant voltage zone. A hysteresis-based controller based on dsPIC33F is proposed for stable operation. Since the PV controller normally operates at maximum power point, small disturbances can make it oscillate between the modes which are avoided by the hysteresis. The hysteresis controller takes the difference between the actual PV voltage and the voltage at maximum power point and decides the switch between voltage mode and current mode vide Fig. 12.

5.4 Other Controls

Sliding mode controllers have been proposed for control of PV emulators in [41–44]. Such controllers show a robust response to parametric variations and to disturbance

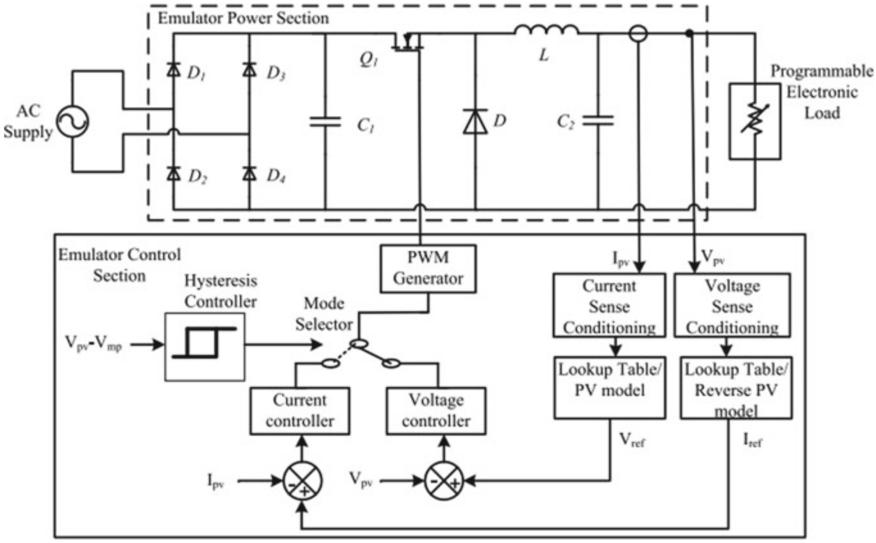


Fig. 12 Schematic of the emulator in [40]

inputs and possess a high control bandwidth. Mahmud et al. [41] use a three-phase interleaved buck converter for the power section which reduces the ripple current considerably. Mahmud and Zhao [44] use a differential mode phase current signal which helps to make the circuit more robust to errors in measurement and makes use of a current balancing algorithm. A fractional order sliding mode control which replicates the I-V characteristics of a PV array more robustly has been suggested in [45].

Cupertino et al. [46] propose a two-stage emulator connected to the grid. A front-end PWM voltage source rectifier fixes the DC voltage while ensuring a high source power factor. Grid synchronisation is done using PLL techniques, and space vector modulation is used for control. The second stage bidirectional DC-DC converter enables rapid response with stable operation down till no load. It can operate either in open-circuit control mode during unloaded conditions or in array control mode where current reference is obtained from I-V characteristics embedded in lookup tables. The control schematic is shown in Fig. 13.

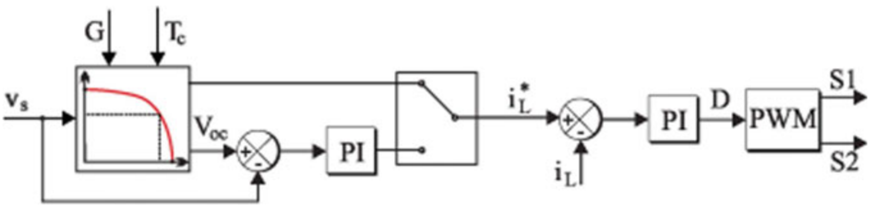


Fig. 13 A control schematic of emulator in [46]

A buck converter-based emulator with a front-end power factor controller has also been discussed in [47]. The emulator makes use of the 2D2R PV model. Chariag and Sbita [48] use an average current mode control for the current loop. [49] is proposed an emulator which is modular in nature. Any series–parallel combination of PV panels can be taken care of by one emulator, and many such emulators can again be connected in series/parallel. A DC bench power supply is made use of and control is with a DSP. The inductor current of the buck converter of each emulator is controlled based on the PV model. The emulator can also take care of partial shading due to the modular nature of the emulator. A distributed MPPT-based approach has also been described in [50] based on a dynamic boost converter and implemented with a low-cost Arduino board.

A cloud-connected virtual PV emulator has been outlined in [51]. An emulator with a combination of fractional order PID control and fuzzy control has been suggested in [52]. An emulator capable of emulating accurately even under partial shading conditions has been analysed in [53]. The emulator makes use of the lookup table principle and uses an adaptive PI controller as the control strategy. Since dynamic response is an important requirement of an emulator and since this is closely related to stability aspects, a nonlinear Lyapunov controller with a hybrid referencing technique has been proposed in [54]. The mode transitions between voltage and current modes that occur in a normal emulator are regulated by the Lyapunov controller.

A hybrid damping injection controller has been suggested in [55] which is based on the 1D2R model and makes use of a look up table generated offline. The controller takes care of the instabilities in the constant current and constant voltage regions by suitable damping. Apart from series/parallel configurations, the emulator can also take care of honeycomb, bridge-link and total-cross-tied configurations and track the I-V characteristics even under partial shading.

A PV system is vulnerable to changing climatic conditions, and the power generation can swing rapidly under passing cloud conditions. Wild variations are not acceptable to the utility authorities who prescribe an acceptable power ramping rate. This aspect has been analysed, and an emulator which can take care of such variations has been incorporated in the emulator described in [56].

6 Conclusion and Future Scope

This paper has presented a detailed summary of the different topologies and control strategies used to configure solar photovoltaic emulators. The issues involved and the relative merits have been outlined. It is foreseen that this would give an overview of the technology and push people to explore new avenues in configuring solar simulators. As a further extension of this, the optimisation techniques used in emulators can be further explored and new techniques like grey wolf optimisation and teacher–learner-based optimisation can be pursued [57, 58].

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