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Impedance Matching In Photovoltaic Systems Using Sliding-Mode Control and Cascaded Boost Converters

K.Kalyani [1], R.Balasubramanian[2], G.Yoga[3], M.Marimuthu[4]

PG Scholar, Department of EEE, Saranathan College of Engineering, Trichy, India[1,3]
Associate Professor, Department of EEE, Saranathan College of Engineering, Trichy, India[2]
Assistant Professor, Department of EEE, Saranathan College of Engineering, Trichy, India[4]

Abstract: The maximum power point tracking (MPPT) of photovoltaic systems must be as fast and accurate as possible to increase the power production, which eventually increases the PV system profitability. This paper proposes sliding-mode controller to provide a fast and accurate maximum power point tracking in grid-connected photovoltaic systems using a single control stage. In this paper, a system connected to a PV panel consisting of two cascaded dc–dc boost converters under sliding-mode control and working as loss free resistors is studied. First, an ideal reduced-order sliding-mode dynamics model is derived from the full-order switched model taking into account the sliding constraints, the nonlinear characteristic of the PV module, and the dynamics of the MPPT controller. For this model, a design-oriented averaged model is obtained and its dynamic behavior is analyzed showing that the system is asymptotically globally stable. Moreover, the proposed system can achieve a high conversion ratio with efficiency close to 95% for a wide range of working power. Experimental results corroborate the theoretical analysis and illustrate the advantages of this architecture in PV systems.

Keywords: MPPT, sliding mode control, cascaded boost converter, PV system.

I. Introduction

The world energy demand is projected to more than double by 2050, and more than triple by the end of the century. Incremental improvements in existing energy networks will not be adequate to supply this demand in a sustainable way. Hence, it is necessary to find sources of clean energy with a wide distribution around the world. The energy generation with photovoltaic (PV) systems is inexhaustible; hence it is a suitable candidate for a long-term, reliable and environmentally friendly source of electricity. However, PV systems require specialized control algorithms to guarantee the extraction of the maximum power available; otherwise the system could be unsustainable.

To provide a high power production, the PV system includes a DC/DC converter to isolate the operating point of the generator (voltage and current) from the load, where such a power converter is regulated by an algorithm that searches, online, the maximum power point (MPP, i.e., the optimal operation condition) known as Maximum Power Point Tracking (MPPT) algorithm. The classical structure of a grid-connected photovoltaic system is presented in Figure, in which the PV generator interacts with a DC/DC converter controlled by a MPPT algorithm. Such a structure enables the PV system to modify the operation conditions in agreement with the environmental circumstances so that a maximum power production is achieved. Figure also illustrates the gird-connection side of the PV system, which is formed by a DC-link (capacitor Cb) and a DC/AC converter (inverter).

The inverter is controlled to follow a required power factor, provide synchronization and protect against islanding, among others. Moreover, the inverter must to regulate the DC-link voltage at the bulk capacitor Cb , where two cases are possible: first, the inverter regulates the DC component of Cb voltage, but due to the sinusoidal power injection into the grid, Cb voltage experiments a sinusoidal perturbation at twice the grid frequency and with a magnitude inversely proportional to the capacitance . In the second case, the DC component of Cb voltage is not properly regulated, which produces multiple harmonic components with amplitude inversely proportional to the capacitance. In both cases, the DC/DC converter output terminals are exposed to voltage perturbations that could be transferred to the PV generator terminals, thus degrading the MPP tracking process. Concerning the DC/DC power

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converter, the boost topology is the most widely used due to the low voltage levels exhibited by commercial PV modules.

II. PROPOSED SYSTEM

We propose the use of a two-stage approach based on a cascade connection of two boost converters. While this provides large conversion ratios and continuous input current, the expected efficiency is low. We overcome these two problems as follows. First, we will show that, although, conversion efficiencies are lower than those presented, this structure can provide efficiencies well above 90% for an output voltage of 380 V. This structure can take advantage of novel silicon carbide (SiC) diodes with breakdown voltages above 400 V, effectively reducing the reverse recovery losses of the second stage. Second, the dynamic stability is ensured with the use of a sliding-mode control approach based on the loss-free resistor (LFR) concept, which was proven to be particularly advantageous in terms of robustness and performance. This method allows us to avoid the classical frequency response approach, which is only valid around the operating point of the analysis. The sliding-mode approach provides a stable regulation regardless of uncertainty and the inherent nonlinearities of the dynamics of switching dc–dc converters.

A. Block Diagram

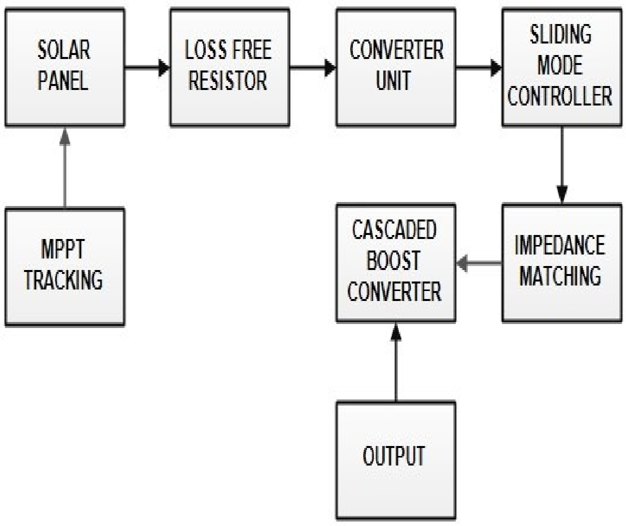

Fig 1. Block diagram of proposed diagram

B. Process Diagram

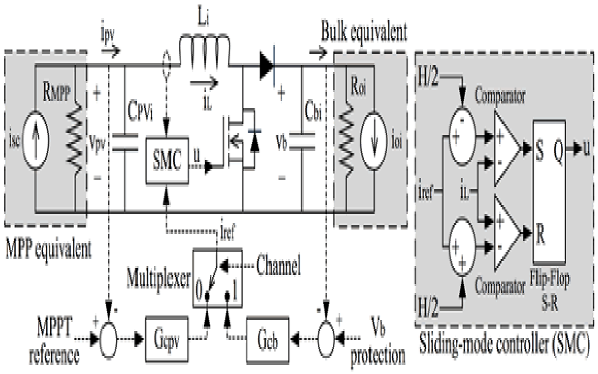

Fig 2. Equivalent circuit of PV Impedance matching and sliding mode controller

C. Structure Of Photovoltaic System

Basically, PV cell is a P-N junction. When light incident on the PN junction of the solar cell, electron hole pair is generated in the depletion layer of solar cell. So if a load is connected to the terminal of solar cell, the excess charges i.e. a current flow through the load. A solar cell can be represented by a current source parallel with a diode, a high resistance and series with a small resistance as shown.

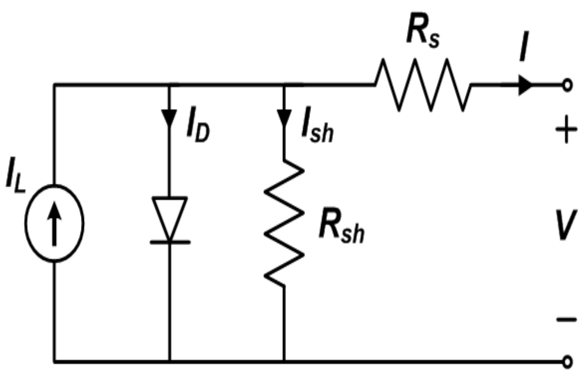

Fig 3. Equivalent circuit of PV cell

The model contains a current source, one diode, internal shunt resistance and a series resistance which represents the resistance inside each cell. The net current is the difference between the photo current and the normal diode current. The characteristics of this module shows the current vs. voltage curve for a PV module at different irradiance show the power vs. voltage curve for a PV module at different irradiance.

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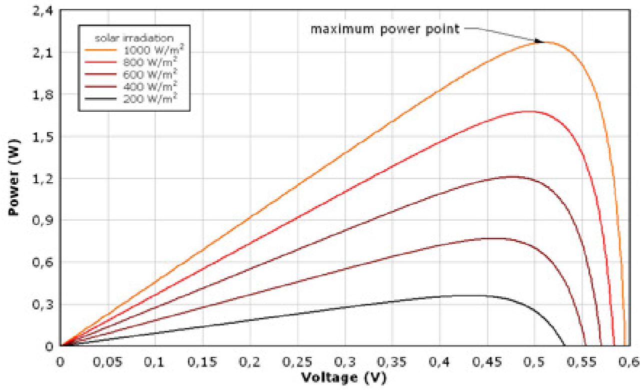

Fig 4. PV characteristics of photovoltaic system

D. PV Based PWM Cascaded Control

When the voltage regulator is implemented using conventional linear control techniques it is necessary to linearize the system model around a given operation point, which is usually the MPP at some irradiance condition. However, due to the nonlinear nature of the PV module and DC/DC converter, the performance (and even stability) of the linear controller is limited to the neighbourhood around the MPP. This constraint puts at risk the system performance since the operating point changes with the unpredictable and unavoidable environmental perturbations. To address this problem, the work in uses a sliding mode controller (SMC) to regulate the inductor current of a boost converter associated to the PV module, which enables to guarantee global system stability at any operating point.

The solution proposed in that work considers three controllers in cascade as follows: the SMC that generates the activation signal for the MOSFET, a PI controller designed to provide the SMC reference depending on the command provided by a P & O algorithm, which is in charge of optimizing the power. However, the design of the PI controller requires a linearized model of the system around the MPP; hence it cannot guarantee the same performance in all the range of operation. In fact, a wrong design of such a PI controller could make the P & O unstable; hence both PI and P & O controllers have a circular dependency on their parameters. Similarly the work in uses a SMC to regulate the input capacitor current of the boost converter. This solution has a major advantage over the work reported the solution in does not require a linearized model since the transfer function between the capacitor current and voltage is linear and it does not depend on the irradiance or temperature conditions. Therefore, such a solution is able to guarantee the desired performance in all the operating range. However, as in the previous work, the three controllers are designed separately, which makes difficult to perform the system design: again, a wrong P & O perturbation period could lead to an unstable system operation.

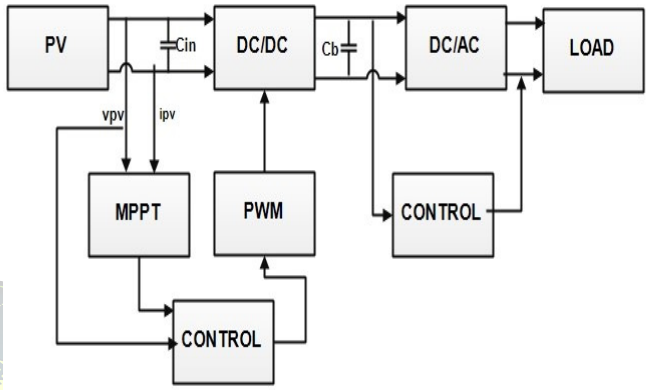

Fig 5. Block diagram of PWM cascaded control

III. MAXIMUM POWER POINT TRACKING

There are many algorithms for maximum power point tracking. Among them P & O is most widely used algorithm. It is a kind of "hill-climbing" method. In figure 4 P-V curve is shown.

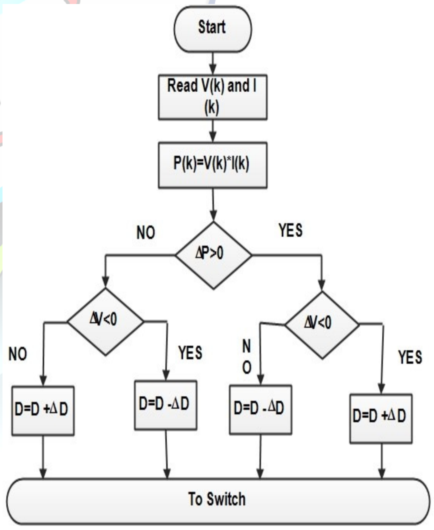

Fig 6. Flow Chart Of Perturb and Observe Algorithm

The flow chart of the implemented P & O algorithm. The algorithm works in this way. Present power P(k) is calculated using present voltage V(k) and current I(k). Then it is compared with the previous power P(k-1). If the power increases, the voltage is changed in the same direction. Otherwise the voltage direction is changed. The efficiency of a solar cell is very low. In order to increase the efficiency, methods are to be undertaken to match the

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source and load properly. One such method is the Maximum Power Point Tracking (MPPT). This is a technique used to obtain the maximum possible power from a varying source. In photovoltaic systems the I-V curve is non-linear, thereby making it difficult to be used to power a certain load. This is done by utilizing a boost converter whose duty cycle is varied by using a MPPT algorithm. There are different methods used to track the maximum power point are 1. Perturb and Observe method, 2. Incremental Conductance method, 3. Parasitic Capacitance method and 4. Constant Voltage method Among the different methods used to track the maximum power point, Perturb and Observe method is the most widely used method in PV MPPTs and is highly competitive against other MPPT methods. Perturb and Observe method is a slight perturbation is introduce system.

A. MPPT For Solar System Under Sliding Mode Control

A PV power system usually includes PV panels, power converters and load. The maximum power point can be captured by tuning the controller and regulating the converter. Some MPPT control methods have also been proposed for PV generation system to eliminate the probable mismatch between solar power and its ideal maximum power under different climate.

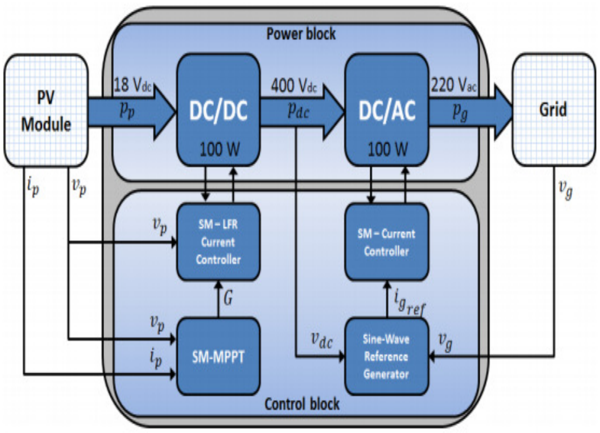

Fig 7. Block diagram of Impedance Matching

In this way, tracking MPP is quite important for solar system not only to enhance the efficiency of system but also to reduce the cost of energy. In this work, we propose a two-stage method by using cascaded boost converters due to its high conversion ratios. However, the cascaded configuration has some inherent drawbacks regarding on the controller design and system dynamic stability, which can be seen with the impedance ratio criteria. MPPT searches the operating voltage close to the maximum power point (MPP) in various environmental conditions. As we know, the electrical circuit of power converters can be represented and analyzed by using the ideal canonical elements, such as LFR which belongs to a range of circuits named POPI (power input equals to the power output). Thus, the input port can absorb the power and then transfer it to the output without losses. The architecture of PV system connecting to boost-boost converter with a DC load is illustrated in Figure. The output power can be obtained by the following function of the LFR conductance g1=1/r1

B. Sliding Mode Conditions

By imposing the existence conditions given by the sliding domain in the parameter and in the state spaces can be obtained. For instance, in the plane (vc2, vc1) and based on the sliding mode regime will exist provided that Vg < vc1 < vc1L where the critical value vc1L is given by

$$v_{c1L}=v_d+v_m \tag{1}$$

$$v_{c1L}=\frac{V_{dc}+\sqrt{V_{dc}^{2}+4\alpha_2 g_1 v_p(1-\alpha_2 G_2)(v_d+v_m)}}{2(1-\alpha_2 G_2)} \tag{2}$$

Other boundaries also exist but the ones expressed are the most restrictive. The equivalent control variables *u*eq1 (**x**) and *u*eq2 (**x**) depend on *g*1 , which is the output of the MPPT algorithm. Considering result in the following reduced-order model for the ideal sliding-mode dynamics

$$\frac{dv_p}{dt}=\frac{i_p}{C_p}-\frac{g_1 v_p}{C_p} \tag{3}$$

$$\frac{d_{vc1}}{dt}=\frac{g_1 v^2{}_p}{C_1 v_{c1}}\beta_2-\frac{\alpha_1 g_1 v_p}{C_1}\left(g_1 v_p-i_p\right)-\frac{G_2 v_{c1}}{C_1} \tag{4}$$

$$\frac{d_{vc1}}{d_t}=\frac{i_{L1}}{dt}(1-u_1)-\frac{i_{L2}}{C_1}=0 \tag{5}$$

C. Control Stratergy

Pulse-width modulation (PWM) technique is used here. The average value of voltage (and current) fed to the load is controlled by turning the switch between supply and load on and off at a fast pace. The longer the switch is on compared to the off periods, the higher the power supplied to the load is. PWM is one of the two principal algorithms used in photovoltaic solar battery chargers, the other being MPPT. The main advantage of PWM is that power loss in the switching devices is very low. When a switch is off there is practically no current, and when it is on, there is

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almost no voltage drop across the switch. Power loss, being the product of voltage and current, is thus in both cases close to zero.

IV. CASCADE DC TO DC BOOST CONVERTER

The multilevel cascade dc to dc boost converter is the extension topology of single level boost converter. The use of multilevel converter is to improve the conversion ratio and efficiency of the converter. The main advantage of the multilevel topology is that the voltage conversion ratio is directly enhanced by the addition of levels. The multilevel cascade dc to dc boost converter is illustrated in Fig. 1. Figure 1, the input source of boost converter is denoted as Vs. The 1th level of the dc to dc converter inductance, diode, switch and capacitor are denoted as L1, D1, S1 and C1 respectively. Then, the Nth level of the converter components are denoted as Ln, Dn, Sn and Cn respectively.

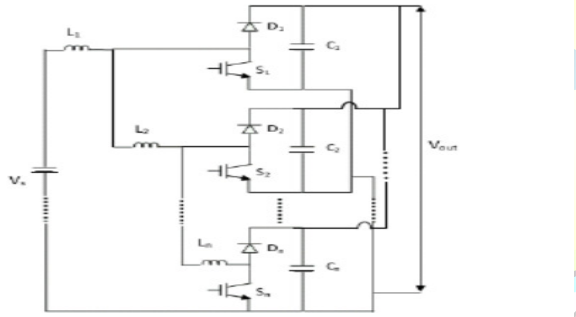

Fig 8. Equivalent circuit of multilevel cascaded boost converter.

When the switches (S1, S2…Sn) ON in Fig. 1, the inductors L1, L2,.Ln are connected to the input voltage (Vs). The output voltage of C1 is smaller than voltage through D2, Dn. At the same time, the negative level of voltages of C2 … Cn is equal to the positive level value of C1. Hence, the total voltage across C2..Cn is smaller than C1. During the turns off condition of switches, the inductor current is closed to D1 of all switched diodes. Throughout the switch off condition, the inductor current closes D1 charging C1 and the output voltage level is resulted as the converter voltage. The voltage on the C1 is equal to the summing up voltage on the input source and the voltage level of C2..Cn. Thus, it is possible to achieve high voltage gain against the duty cycle. But, when include the switched inductor circuit; the switching frequency level is limited with high gain. Therefore, the proposed converter is suitable for charging power in photovoltaic applications. Moreover, the peak current of inductor is limited by switched inductor so no additional protection circuit is required.

According to the consideration of general converter operation, these converters work in the steady state with the condition of Continuous Conduction Mode (CCM). Here, the conduction duty ratio is denoted as the switching frequency the switching period is f T1 = and the load is RL load. The input voltage and current are denoted as Vin and in NI respectively. The output voltage and current are VO and IO. During the conversion process, the conversion output without power loss is in out VI =VI The voltage transfer ratio gain is denoted as which is described as following them

$$G = \frac{V_o}{V_{in}}$$

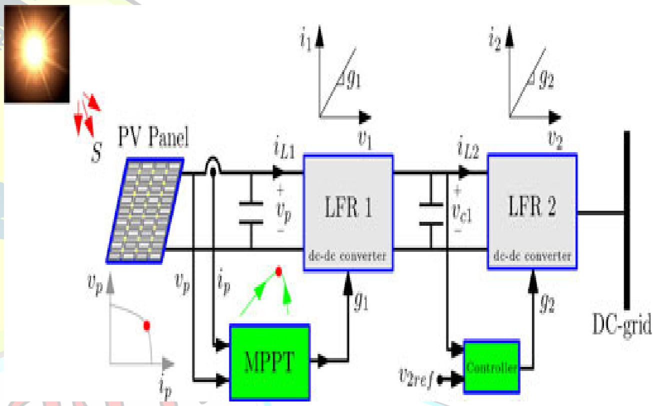

Fig 9. Overview Of Proposed System.

Table1. Parameters of the PV Module

Parameter	Value
Number of cells Ns	36 cell
Standard light intensity S_0	1000 W/m2
Ref temperature T_{ref}	25 ◦C
Series resistance *Rs*	0.008 Ω
Short-circuit current *Isc*	0.5 A
Saturation current *Is*	3.8074·10−8 A
Band energy *Eg*	1.12
Ideality factor *A*	1.2
Temperature coefficient *Ct*	0.00065 A/C
Open-circuit voltage *Vc*	22 V

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HARDWARE IMPLEMENTATION

A. *Circuit Diagram*

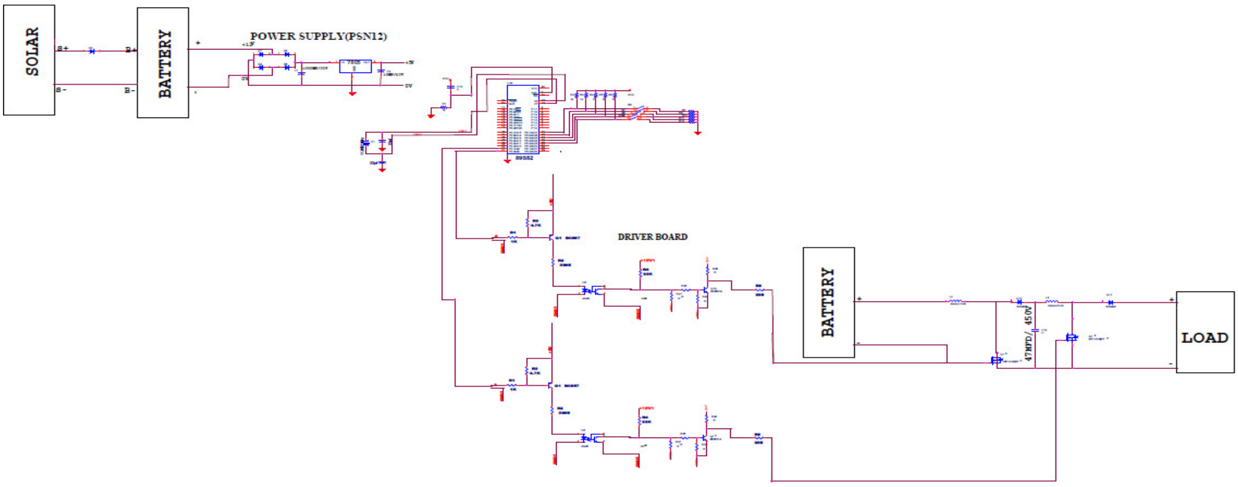
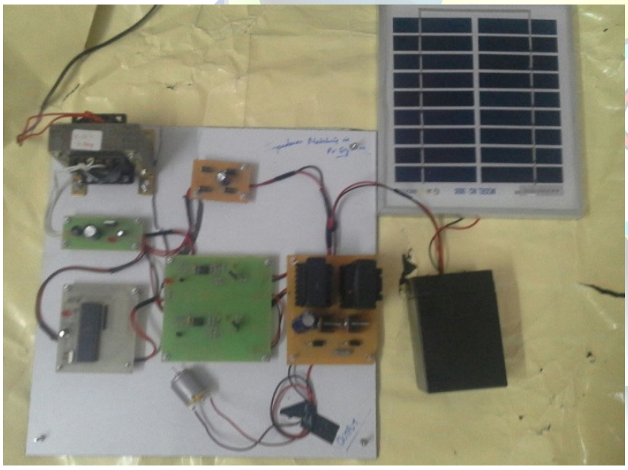


Fig 10. Equivalent Circuit Of Proposed System.

HARDWARE DESCRPTION



REQUIREMENTS

PV Panel
Battery
Processor: Dual core processor
Hard disk: 160 GB
RAM: 2 GB

CONCLUSION

High-voltage conversion ratios can be achieved by using a cascade connection of dc–dc boost converters, in order to step up the low voltage of a PV module to the dc voltage of the grid (380 V). This cascade connection can be robustly controlled with a sliding-mode scheme imposing an LFR, such that the input current is proportional to the input voltage. The operation of the circuit has been analyzed theoretically and with numerical simulations using the PV and MPPT models which are plugged in the ideal sliding-mode dynamic model. This model, which has been validated by using the full-order switched model, has the advantage of faster simulation time. Moreover, the ideal sliding-mode dynamic model allows us to develop a design oriented description which facilitates the stability analysis of the system. This stability analysis shows that the system exhibits stable LFR characteristics without any conditions. Using the LFR canonical element with SMC in the cascade connection adds simplicity for the stability analysis and the implementation. The proposed system has been compared with a coupled inductor converter reported in terms of dynamic performance, number of components, volume, and simplicity. While the coupled-inductor converter achieves slightly larger conversion efficiencies, the proposed system provides improved dynamic properties and higher

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reliability. Finally, with the proposed system, a high conversion ratio can be achieved together with very fast tracking speed, high efficiency for the converters, and high static MPPT efficiency, which allows us to obtain the maximum available energy from the PV module.

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