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Control of a Three-Phase Cascaded H-Bridge Multilevel Inverter for Stand-alone PV System

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Abstract- **This paper presents a three-phase cascaded H-bridge converter for a stand-alone photovoltaic (PV) application. The multilevel topology consists of several H-bridge cells connected in series, each one connected to a string of PV modules. The adopted control scheme permits the independent control of each dc-link voltage, enabling, in this way, the tracking of the maximum power point for each string of PV panels. Additionally, low ripple sinusoidal-current waveforms are generated with almost unity power factor. The topology offers other advantages such as the operation at lower switching frequency or lower current ripple compared to standard two-level topologies. Simulation and experimental results are presented for different operating conditions.**

Index Terms**—Multilevel inverters, photovoltaic (PV) power systems, power conversion.**

INTRODUCTION

Stand-alone Three-phase photovoltaic (PV) systems are nowadays recognized for their contribution to clean power generation. A primary goal of these systems is to increase the energy injected to the grid by keeping track of the maximum power point (MPP) of the panel, by reducing the switching frequency, and by providing high reliability. In addition, the cost of the power converter is also becoming a decisive factor, as the price of the PV panels is being decreased [1]. This has given rise to a big diversity of innovative converter configurations for interfacing the PV modules with the grid. Currently, the state-of-the-art technology is the two-level multi string converter. This converter consists of several PV strings that are connected with dc–dc converters to a common dc–ac converter [2], [3]. This topology features several advantages such as the independent tracking of the MPP of each string to the existing plant. This converter topology can reach peak efficiencies up to 96% [4]. In the last years, multilevel converter topologies have been also considered in PV applications [5]. These converter topologies can generate high-quality voltage waveforms with power semiconductor switches operating at a frequency near the fundamental [6]. Although, in low-power applications, the switching frequency of the power switches is not restricted, a low switching frequency can increase the efficiency of the converter [7]. Additionally, multilevel converters feature several dc links, making possible the independent voltage control and the tracking of the MPP in each string. This characteristic can increase the efficiency of the PV system in case of mismatch in the strings, due to unequal solar radiation, aging of the PV panels, and different type of the cells or accumulation of dust in the surface of the panels [8]. and the possibility to scale the system by plugging more strings

Among the available multilevel converter topologies, the cascaded multilevel converter constitutes a promising alternative, providing a modular design that can be extended to allow a transformerless connection to the grid [9], [10]. Additionally, this topology features power semiconductors with a lower rating than the standard two-level configurations, allowing cost savings [5]. Last but not the least, multilevel topologies feature several freedom degrees that make possible the operation of the converter even under faulty conditions, increasing, in this way, the reliability of this system. In spite of all these characteristics, the cascaded multilevel topology has also disadvantages, as the strings of PV panels are not grounded and extra measures have to be taken in order to avoid currents due to stray capacitances between the panel and the earth [9].

In order to properly operate a cascaded converter with n cells, the independent control of the dc-link voltages and the control of the grid current i_S (Fig. 1) are necessary. This task must be accomplished by using the n available actuation signals corresponding to the modulation units of each cell. Several methods have been proposed to the control of this configuration. In [12]–[14], the reference signals for the modulation units of each cell are multiplied by a factor that depends on the voltage in each dc link and the power that the corresponding string of PV panels is delivering. Unfortunately, no experimental results are given. Other approaches operate only under equal dc-link voltages [15], which is not adequate for the tracking of the MPP in each string. In [16] control methods based on passivity controllers have been presented. The experimental results show that independent control of the dc-link voltages is possible.
However, the equations for the controller are not explicitly described, and high-performance control platforms are required for real-time implementation of the proposed control schemes
In this paper, a simple scheme based on the algorithm presented in [16] is applied for the control of a PV cascaded converter system. The control scheme is enhanced with MPP tracking (MPPT) algorithms that independently adjust

the reference of the dc-link voltages in order to maximize the generated energy

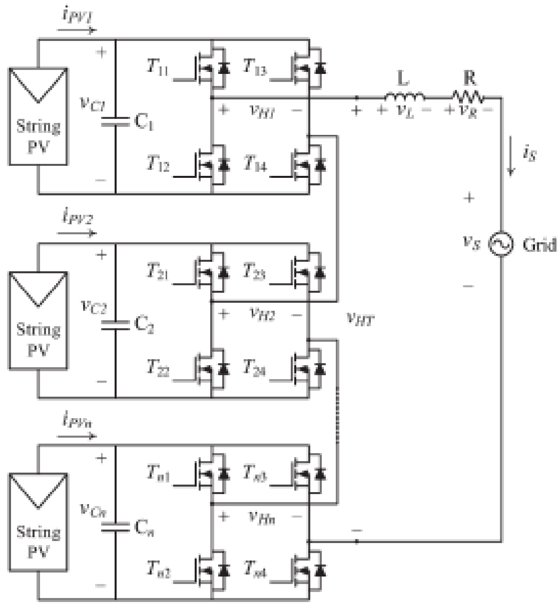

Fig. 1. Topology for grid connection.

In addition, the quality of the grid currents is improved by using, for the measurement of the dc voltages, a digital 100-Hz band reject filter

This paper is organized as follows. First, the converter topology is presented in Section II. Then, the control principle is explained in Section III. The model necessary for the design of the controllers is described in Section IV. The last section shows the simulation and experimental results that validate the proper operation of the converter. The results demonstrate that this topology can inject to the grid sinusoidal input currents with unity power factor, even under conditions of unequal solar radiation of the string of PV cells.

$$\frac{di_S}{dt}=\frac{1}{L}\left(\sum_{j=1}^{n}(S_j v_{Cj})-Ri_S-v_s\right) \qquad (2)$$

$$\frac{dv_{Cj}}{dt}=\frac{1}{C_j}(i_{PVj}-S_j i_S), \qquad (3)$$

III. CONTROL SCHEME

The control strategy is based in the classical scheme for the control of a single H-bridge converter connected to the grid. In [12]–[16], this idea has been extended for the case of n cells connected in series for the control of an active rectifier. From these different control schemes, only [16] seems to be suited for this application because they are able to operate with different dc-link voltages. In this paper, the control scheme proposed in [16] is used for this application by adding MPPT controllers in the voltage reference.

The scheme in Fig. 2 includes $n+1$ control loops: n of them are used to adjust the capacitor voltage in each dc link, and the other one is necessary for the generation of a sinusoidal input current with unity power factor. As shown in Fig. 2, the sum of the dc-link voltages V_{C1} to V_{Cn} is controlled through

a PI that determines the amplitude of the input current $\hat{i}_s$. By multiplying the output of this controller with a normalized sinusoidal signal in phase with the voltage grid, a suitable reference for the current loop is obtained

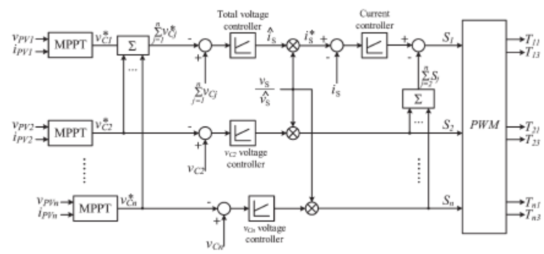

Fig. 2. Proposed control scheme.

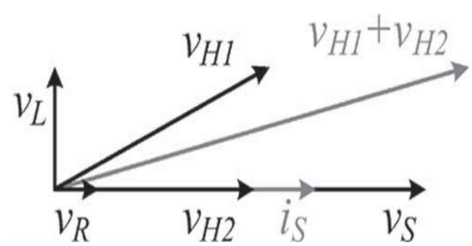

Fig. 3. Phasor diagram.

IV. SYSTEM MODELING AND CONTROLLER DESIGN

In this section, the tuning procedure for the three control loops in Fig. 4 is described. The design of the filter for the mitigation of the 100-Hz harmonic component in the input current i_S is also addressed.

A.Current Loop

Since the dynamic of the current loop is much faster than the dynamic of the voltage loop, the design for the controller will mainly consider this dynamic and the delay time of the converter and the modulator. The plant is given by

$$G_i(s)=\frac{I_s(s)}{V_{HT}(S)}=\frac{I_s(s)}{V_{HT}(s)+V_{H2}(s)}=\frac{1}{L_s+R} \qquad (4)$$

The simplified control scheme of the current control loop is shown in Fig. 4(a). The design of the current controller assumes that grid voltage v_S is a slowly variant disturbance for the current loop. For this reason, it will not be considered.

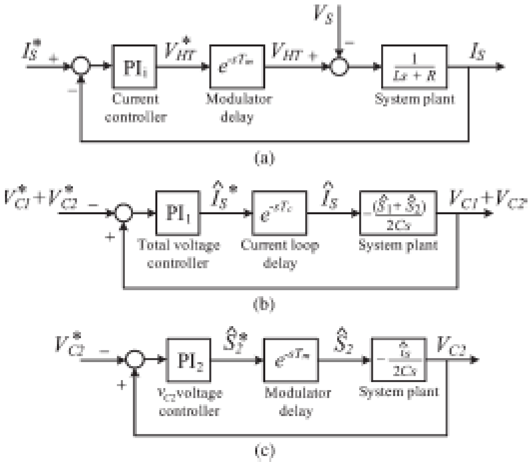

Fig. 4. (a) Current loop. (b) Total voltage loop. (c) Second cell voltage loop

B. Voltage Loop

Two PI controllers are necessary for the independent control of each dc-link voltage. In order to design the controllers, suitable transfer functions are obtained by the linearization of (3) with *j* = 1, 2 around the nominal operating point. In this case, it will be considered that the system operates at a nominal radiation of 1 kW/m2 and at 25 ◦C. As a first step, the transfer function of the loop that considers the total dc-link voltage will be calculated. The derivation of this expression is documented reproduced here for the sake of completeness.

Adding these two equations yields

$$S_1 i_S + S_2 i_S = i_{PV1} + i_{PV2} - C_1 \frac{dv_{C1}}{dt} - C_2 \frac{dv_{C2}}{dt} \tag{5}$$

By considering only the dc component of the term $S_1 i_S + S_2 i_S$ the last equation is equivalent to

$$\frac{\hat{S}_1 \hat{i}_S + \hat{S}_2 \hat{i}_S}{2} = i_{PV1} + i_{PV2} - C_1 \frac{dv_{C1}}{dt} - C_2 \frac{dv_{C2}}{dt} \tag{6}$$

where $\hat{x}$ indicates the maximum value of *x*.

C. Mitigation of the 100-Hz Harmonic Component in the Input Currents

Using this control configuration, a harmonic component of the triple of the fundamental frequency appears in the input current i_S. In order to mitigate this harmonic component in the current, a band reject filter centered in 100 Hz has been placed between the voltage measurements v_{C1} and v_{C2} and the inputs of voltage controllers, as shown in Fig. 6. In this way, the 150-Hz harmonic component is eliminated from the current references. Note that filters between PV voltage measurements and MPPT blocks are intentionally avoided because it is necessary to assure the proper tracking of the optimum power point.

The digital filters work according to the principle shown in Fig. 5. The original signal $V(t)$ is delayed by a half cycle and then added to the original waveform to obtain the dc component of the signal. A block diagram of the complete control scheme, including the two 100-Hz filters, is shown in Fig. 6.

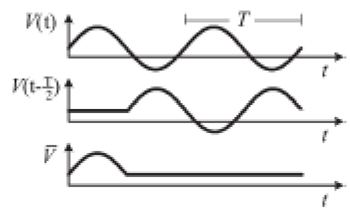

Fig. 5. Filter principle.

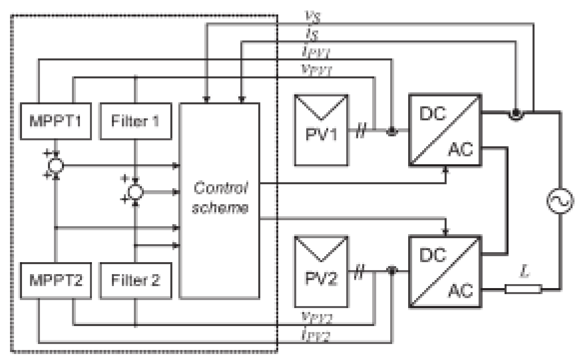

Fig. 6. Proposed control scheme with MPPT and band reject filters.

V. MATLAB/SIMULINK MODEL

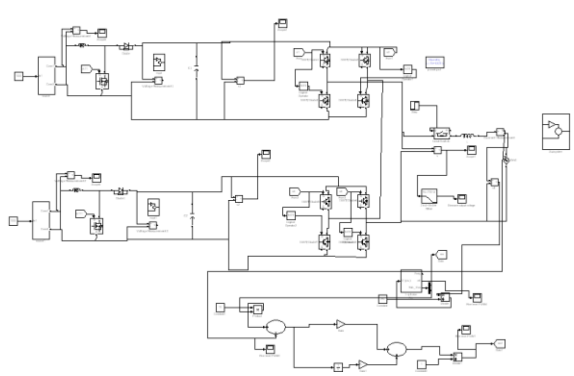

Fig.7 Matlab/Simulink Model

Fig.7 shows the Matlab /Simulink model of grid connected PV system. It consists of a PV string, DC to DC converter and inverter.

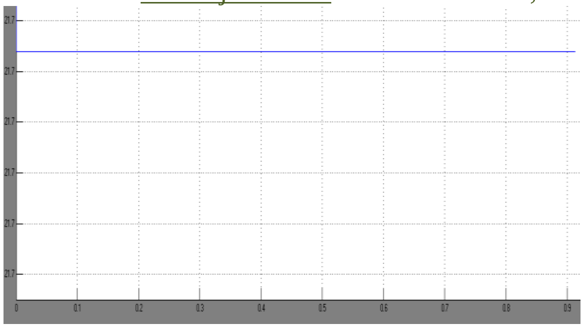

Fig.8 PV cell output

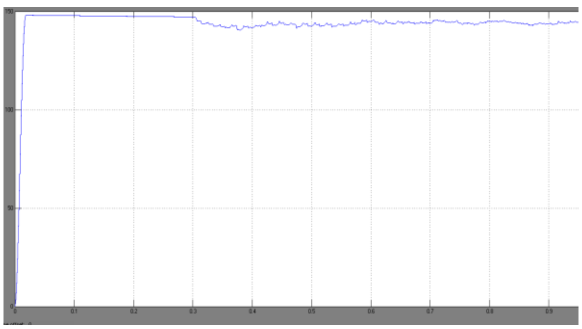

Fig.9 Inverter input voltage

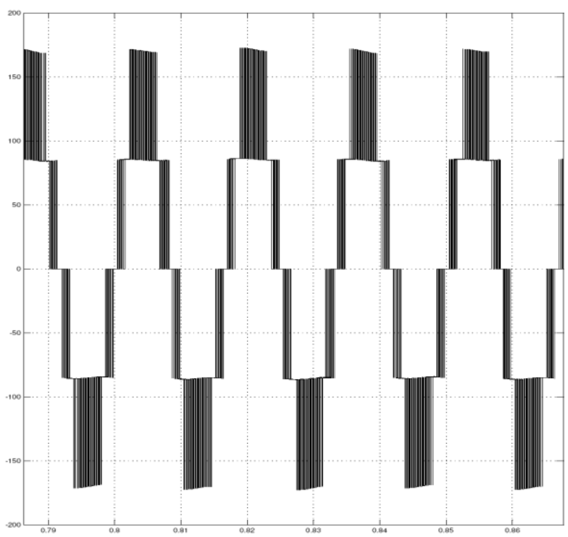

Fig.10 Five level output voltage

Fig.8 shows the PV cell output and Fig.9 shows the inverter input voltage. Fig. 10 shows Five level PWM out put voltage.

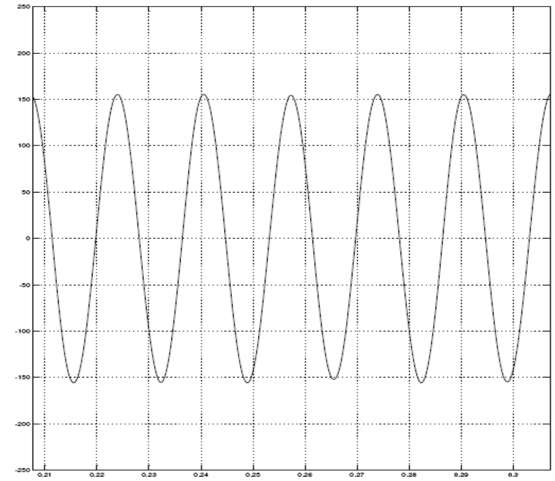

Fig.11 Filtered output voltage

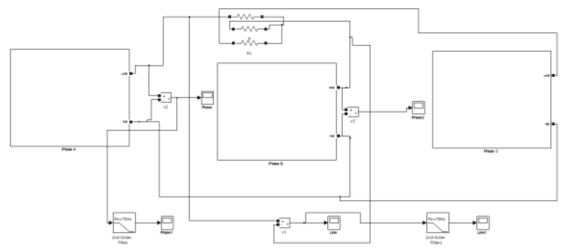

Fig.12 Three Phase Blocks

Fig.12 shows the Three phase standalone PV system with cascaded multilevel inverters. Fig. 13 shows the corresponding five level phase voltage.

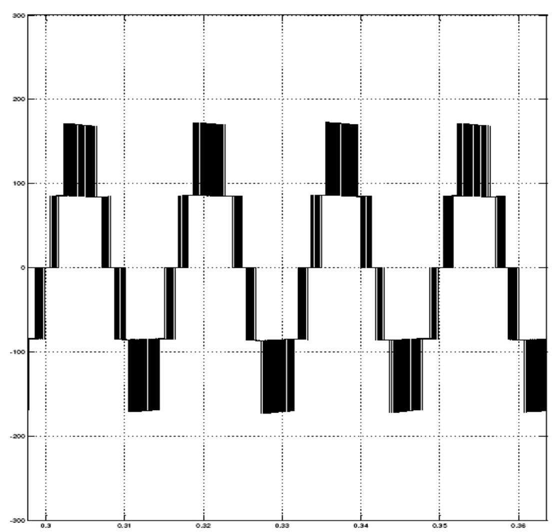

Fig.13 Output voltage

VI. CONCLUSION

In this paper, a cascaded H-bridge multilevel converter has been proposed as a feasible multistring topology for PV applications. The converter features several advantages such as the generation of high-quality currents, the capacity to operate at a lower switching frequency than a two-level converter, and the modularity that can reduce the cost of the solution. The converter is first controlled using a scheme proposed for multilevel active rectifiers and improved by adding MPPT algorithms. A three phase cascaded H-Bridge for standalone system is proposed. A Matlab/Simulink based model is developed and simulation results are presented.

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