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Cascaded Multilevel PV Inverter with Improved Harmonic Performance During Power Imbalance Between Power Cells

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Abstract:

The difference in power cell irradiances in cascaded multilevel converters results in different duty cycles among those cells when maintaining the maximum power point tracking (MPPT). However, the difference in cell duty cycles is undesired since it is proportional to the output voltage and current distortions. To this regard, a multilevel topology for photovoltaic (PV) applications is proposed, where an H6 bridge power cell is used instead of an H-bridge one. In case of solar irradiance mismatch among the power cells, the proposed converter injects power with lower voltage from the shaded cells without altering the PV voltage; hence maintaining the MPPT operation. This modification allows us to retain an equal duty cycle in all the power cells whatever the meteorological conditions are present; consequently, maintaining good output voltage and current waveform qualities. To test the effectiveness of the proposed solution, a detailed simulation model as well as an experimental prototype is built. The obtained results show that the proposed topology provides significantly improved output voltage and current qualities compared to the cascaded H-bridge one. The performance of the proposed topology compared to one offering improved harmonics performance, according to the European efficiency, has been also compared, where an enhancement of 2.64% has been registered.

Introduction:

MULTILEVEL converters (MLCs) are very promising candidate power electronic converters since they offer a robust, efficient, and fault-tolerant features [1]–[3]. These power converter topologies are able to output high-quality voltage waveforms with power switches operating at even the fundamental frequency when the number of levels is high enough. One the other hand, the high-quality voltage allows the use of less sizable output filter [4]. Among them is the cascaded H-bridge (CHB) converter topology [5], which consists of series-connected Hbridges, each of which is fed by a separate dc voltage source. This characteristic makes it possible to connect PV panels in each H-bridge; thus, achieving independent maximum power point tracking (MPPT), which in turn, improves the efficiency of the overall system and increases the energy injected to the grid [6].

The commonly used pulsewidth modulation (PWM) strategy in MLCs is the phase shifted PWM (PS-PWM) [7]. The PSPWM in CHB application is described as multi-unipolar carriers, one carrier designated for each H-bridge, where these carriers are shifted by Ts/n with respect to one another. Here, Ts is the carriers period, and n is the number of H-bridges. Equal power distribution and equal power losses among the power cells, as well as multiplicative effect (2nmf) in the converter output voltage switching frequency, are offered when using this modulation technique [7].

However, in case the power cells are subjected to uneven solar irradiance due to dust on the PV panels or partial shading, the system would be unbalanced. This imbalance can be grouped into two categories, interphase imbalance and intra phase imbalance. The former is believed to be an old existing problem, which is similar to any interphase imbalance issue, for which there are hundreds of solutions in the literature [8]. Nevertheless, there have been new solutions introduced, where MLCs is their application [9], [10]. The intra phase imbalance, however, is a contemporary problem that came as a challenge with MLCs.

The main causes of the harmonics generated in the converter output signals when the solar irradiation is not equal over the power cells are the difference in cell duty cycles and dc-link voltages. The controller limits the duty cycle in the shaded power cell in order to match its new MPP current when the solar irradiance decreases; consequently, the modulator receives different duty cycles. In this case, the shaded power cell starts injecting power by some delay (TD) and stops injecting it before the supposed time by TD. However, in MLCs, the cells are grouped together to form the converter output signals (output current and voltage), and the timing is a critical parameter, i.e., any advanced or delayed operation of any power cell compared to the supposed timing may deteriorate the output signals.

Several attempts to mitigate this problem are reported in the literature [11]–[15]. In [11], variable switching angles is the main operation principle, where this strategy offers a cheap solution; however, it is valid only when n = 3 due to the complex computation required. Furthermore, during sever partial shadings, changing the carrier shift angles does not improve the output signals quality to an acceptable level. Marquez et al. [12] proposed the employment of an extra battery-fed power cell to overcome this problem in case n = 2. A dc–dc boost converter has been added into each power cell in [13], as shown in Fig. 1 (referred to as CHBB thereafter), where a modified modulation strategy is proposed to keep the energy among the dc-link capacitors at a similar level; hence, operating all the cells at similar duty cycles. Modular cascaded multilevel quasi-Z-source inverter offers flexibility in the power quality matter as the H-bridges' voltages are independent on the PV voltages—only some changes on its modulation and control are required, as elaborated in [14]. The operation of a solid-state transformerbased power cell in a star-connected CHB in the presence of both interphase and intra phase imbalances is studied in [15]. The previously mentioned topology-based solutions incorporate a lot of active and passive components—especially inductors—in the power cells, and in some cases, higher switching frequency is required, which not only increases the size, weight, and cost of the converter, but also degrades the system's overall efficiency.

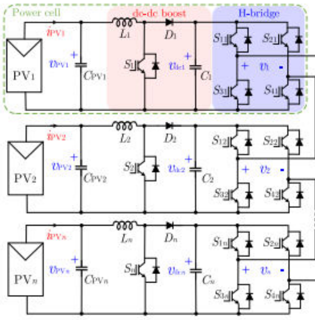


Fig. 1. Classical dc–dc boost + H-bridge-based power cell MLC (CHBB).

II. ANALYSIS OF THE PARTIAL SHADING IN THE CONVENTIONAL CHB TOPOLOGY

Fourier expansion is one of the most straightforward and sufficiently accurate tools in signal processing [17], which is thus, going to be used in this article to analyze the converters' output signals quality. According to the Fourier hypothesis, any periodic function f(t) can be expressed as a dc offset plus a sum of sines and cosines as the following:

$$f(t) = c_0 + \sum_{h=1}^{\infty} \left[a_h \cos(h\omega t) + b_h \sin(h\omega t)\right]$$

where ω is the smallest angular frequency to be evaluated. The coefficients ah and bh are defined as follows:

$$a_h = \frac{1}{\pi}\int_0^{2\pi} f(t)\cos(h\omega t)\, d(h\omega t)$$
$$b_h = \frac{1}{\pi}\int_0^{2\pi} f(t)\sin(h\omega t)\, d(h\omega t).$$

In this article, the function to be analyzed is the converter's output voltage, which is the sum of all power cell voltages. The ith power cell output voltage is considered as a square pulse train with a variable duty cycle, which can be expressed as

$$v_i(t) = v_{\mathrm{dc}i} D_i, \quad \text{where } i = 1, \ldots, n$$

such as Di and vdci are the duty cycle and voltage in the ith power cell. Fourier expansion of each power cell's output voltage can be then expressed as follows:

$$v_i(t) = c_{0i} + \sum_{h=1}^{\infty} \left[a_{hi} \cos(h\omega_c t) + b_{hi} \sin(h\omega_c t)\right]$$

where ωc is the carrier angular frequency.

The solution can be simplified by nulling bhi on the assumption that the time origin is chosen in a way the function vi(t) shows an even symmetry. In this way, Fourier coefficients can be found as follows:

$$c_{hi} = \frac{1}{\pi}\int_0^{D_i\pi} v_i(t)\, d(\omega_c t) = v_{\mathrm{dc}i} D_i$$
$$a_{hi} = \frac{2}{\pi}\int_0^{D_i\pi} v_i(t)\cos(h\omega_c t)\, d(\omega_c t) = \frac{2v_{\mathrm{dc}i}}{h\pi}\sin(h\pi D_i).$$

The output voltage of the ith power cell in Fourier expansion form can be then written as follows:

$$v_i(t) = v_{\mathrm{dc}i} D_i + \sum_{h=1}^{\infty} \frac{2v_{\mathrm{dc}i}}{h\pi}\sin(h\pi D_i)\cos(h\omega_c t)$$

Thus, the total output voltage can be described as

$$v_{\mathrm{out}}(t) = \sum_{i=1}^{n}\left(v_{\mathrm{dc}i} D_i + \sum_{h=1}^{\infty} \frac{2v_{\mathrm{dc}i}}{h\pi}\sin(h\pi D_i)\cos(h\omega_c t + \theta_i)\right)$$

where θi is the ith carrier shift angle, which is estimated as

$$\theta_i = \frac{2\pi}{n}(i-1).$$

As it can be seen from equation, the hth harmonic content at the total output voltage is expressed as follows:

$$v^h = \sum_{i=1}^{n} \frac{2v_{\mathrm{dc}i}}{h\pi} \sin(h\pi D_i)\cos(h\omega_c t + \theta_i).$$

If the converter is assumed to have three power cells, the hth harmonic content would be written as in the following:

$$\begin{aligned} v^h = {} & \frac{2v_{\mathrm{dc}1}}{h\pi}\sin(h\pi D_1)\cos(h\omega_c t) \\ & + \frac{2v_{\mathrm{dc}2}}{h\pi}\sin(h\pi D_2)\cos\left(h\omega_c t + \frac{2\pi}{3}\right) \\ & + \frac{2v_{\mathrm{dc}3}}{h\pi}\sin(h\pi D_3)\cos\left(h\omega_c t + \frac{4\pi}{3}\right). \end{aligned}$$

From above equation , in order for the hth harmonic content to be eliminated in the total output voltage, the dc-link voltages, as well as the duty cycles have to be equal. In case of partial shading, the control would decrease the duty cycle of the shaded power cell in order for its current to be limited to a lower level according to the partial shading severity. An illustrative example has been performed and is shown in this article to further clarify the mathematical derivations' outcome. Fig. 2 shows test cases of balanced and unbalanced CHB operations. As it can be seen from plot (cz) of this figure, as the third cell get shaded, its duty cycle decreases causing the cell to start injecting power with a delay TD with respect to the supposed time, and stopping before the supposed time by a TD. This duty cycle decrease causes some pulses to be thinner or even completely absent from the total output voltage, yielding into a distortion in the latter, as highlighted in the zoomed-in view [see plot (dz)]. It is also noteworthy that the effective switching frequency reduces due to those absent pulses as shown in Fig. 2(d2).

III. PROPOSED MULTILEVEL TOPOLOGY

As described by (10), an alternative to eliminate the hth harmonic content during partial shading is either by equalizing all cells duty cycles and voltages or by increasing all cells duty cycle peaks to be close to unity. In order to rise the duty cycle of the shaded power cell back to a value that is close to the unity, the cell output voltage has to be decreased; however, the point

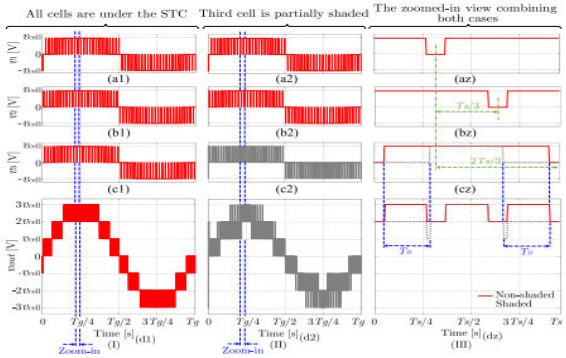


Fig. 2. Each power cell's output voltage in addition to the resulted total output voltage, in both cases, balanced, and unbalanced solar irradiance among the cells.

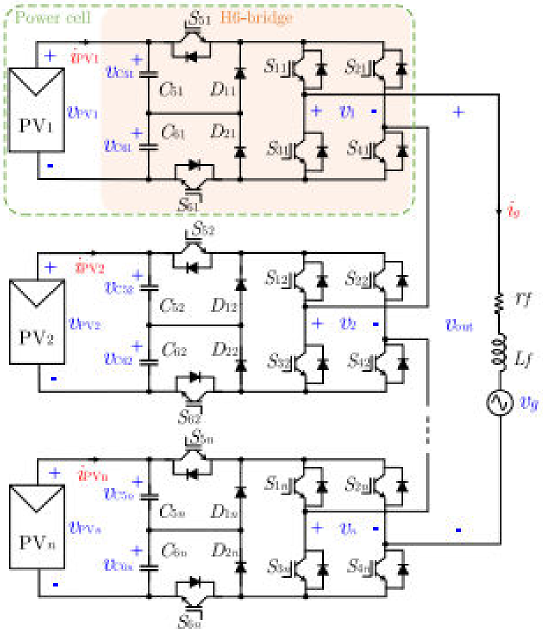


Fig. 3. Proposed cascaded multilevel topology for PV systems.

is to not alter the PV voltage and MPPT. A dc–dc stage can be employed between each H-bridge and PV string, ensuring a decoupled voltage between the H-bridge's dc link and PV string. The dc–dc converter can be a boost [13] (see Fig. 1), buck—boost [18], or flyback [19]. However, this solution adds more inductors; consequently, the hardware is more expensive and sizable. Furthermore, the dc–dc stages operate at higher switching frequency, affecting the efficiency of the system negatively. For this purpose, it is proposed in this article to replace the H-bridge in each power cell by an H6 one, where the dc-link capacitor is substituted by a split one, and only two active semiconductor devices and two diodes are added. The overall schematic diagram of the proposed MLC for PV applications, where n cells are regarded, is depicted in Fig. 3. The proposed concept comprises injecting power from the shaded power cell with less voltage, without altering the PV string voltage (see Fig. 4); hence, retaining the MPPT. Each cell's output voltage can be determined as the follows:

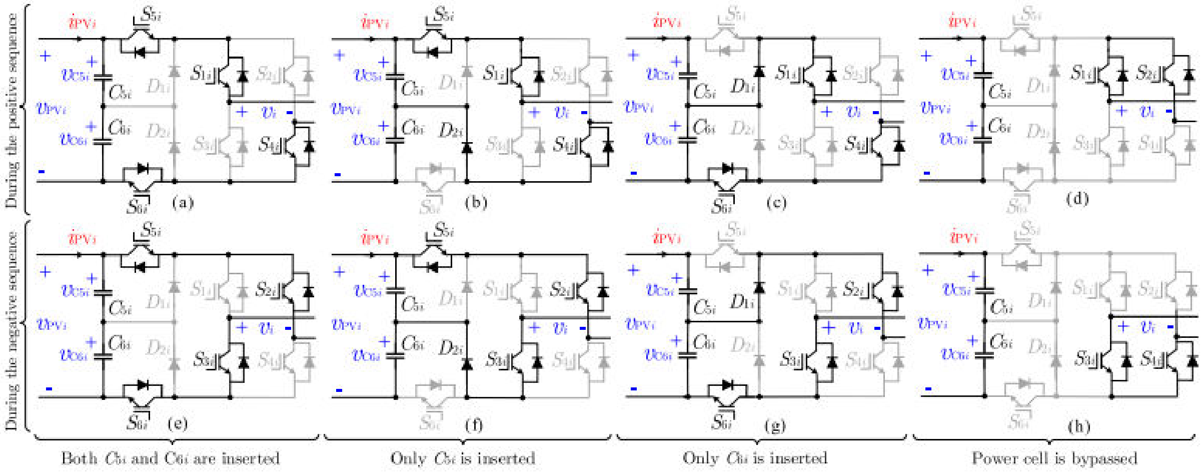


Fig. 4. Operation states in the proposed power cell

$$v_i = (S_{1i} - S_{2i})\,(S_{5i}v_{C5i} + S_{6i}v_{C6i}) \tag{11}$$

where Sxi is the xi active semiconductor state, which could be either ON or OFF. According to Fig. 3, i refers to the cell's index and x refers to the semiconductor number in that cell. The variables vi, vC5i, and vC6i are, respectively, the output voltage, the voltage at the terminals of capacitor C5, and the voltage at the terminals of capacitor C6 of the ith cell. If the capacitors charge in each power cell is well balanced, the cell's output voltage can be expressed as

$$v_i = v_{\mathrm{PV}i}\left(S_{1i} - S_{2i}\right)\left(\frac{S_{5i} + S_{6i}}{2}\right)$$

such as vPVi is the voltage at the terminals of the ith PV string. The dynamic behavior of each power cell can be described by the following differential equation:

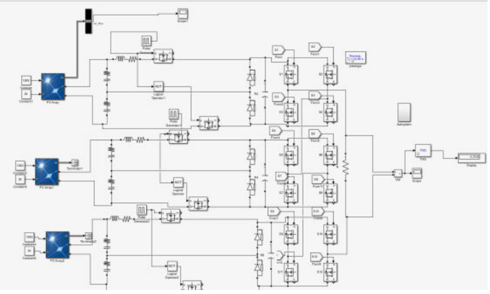
$$C_{\{5,6\}i}\frac{dv_{C\{5,6\}i}}{dt} = \left(i_{\mathrm{PV}i} - \left(S_{1i} - S_{2i}\right) S_{\{5,6\}i}\, i_g\right). \qquad (13)$$

Thus, according to Kirchhoff's voltage law, the overall system's dynamic behavior can be assessed as in the following equation

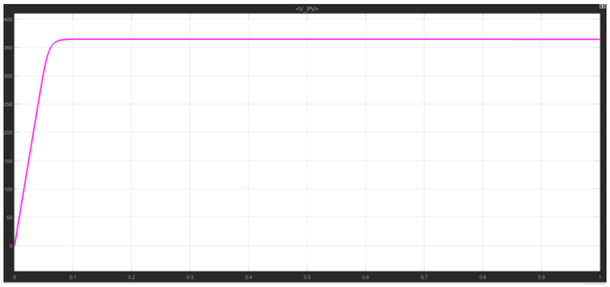
$$L_f\frac{di_g}{dt} = \sum_{i=1}^{n}\left(\left(S_{1i} - S_{2i}\right)\left(\frac{S_{5i} + S_{6i}}{2}\right) v_{\mathrm{PV}i}\right) - r_f\, i_g$$

where ig, vg, Lf , and rf are, respectively, the grid current, grid voltage, filter inductance, and filter internal resistor

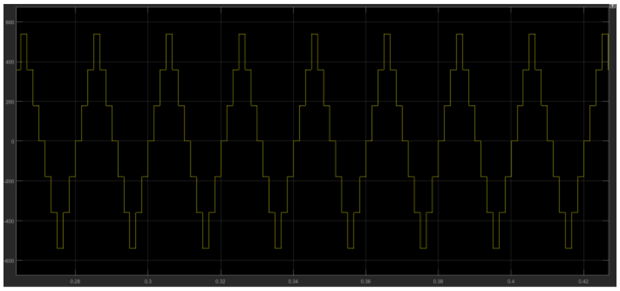
Simulation results



Simulation Main circuit diagram



Solar voltage



Inverter output voltage

Conclusion

Their voltages were the main factors in the distortion of these output signals. Moreover, the difference in cell voltages could have a less effect, in this matter, if the cell duty cycles were close the unity. Accordingly, a cascaded MLC was proposed, where the cells were able to provide less voltage than the total cell one, which, in turn, allows the cell duty cycle to be raised back to unity after it decreases in case of partial shading. The proposal was cost effective, lighter, and less sizable since it did not require extra passive elements with respect to its counterparts. Only some active components were added. The proposed converter was tested under both simulation and experiment, and it was shown that it provided a significantly improved output voltage and current qualities in case of partial shading, where the THD according to 50th harmonic orders–as included in the EN50160 standard–was decreased from 15.23% to 10.75% in the voltage. Furthermore, a loss and efficiency comparison with respect to its counterpart CHBB was included in this article. Due to the employment of the same switching frequency as in the CHB in the proposed converter

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