A NINE LEVEL CONVERTER TOPOLOGY FOR SINGLE-PHASE TRANSFORMERLESS PV SYSTEM

[1] RASHMI MORE, [2] PROF.SANDEEPMAHAJAN

1 Student M.Tech., Department of Electrical Engineering, G.H. Raisoni Institute of Engineering and Technology for Women, Nagpur
2 Prof, Department of Electrical Engineering, G.H. Raisoni Institute of Engineering and Technology for Women, Nagpur

rashmimore5@gmail.com, sandeep.mahajan@raisoni.net

ABSTRACT *– This paper presents a single-phase transformerless load connected photovoltaic converter based on two cascaded full bridges with different dc-link voltages. The converter can synthesize upto nine voltage levels with a single dc bus, since one of the full bridges is supplied by a flying capacitor. The multilevel output reduces harmonic distortion and electromagnetic interference. A suitable switching strategy is employed to regulate the flying-capacitor voltage, improve the efficiency and minimize the common-mode leakage current with the help of a novel dedicated circuit (transient circuit).*

Index Terms - Leakage Current, Multilevel Inverter, Photovoltaic(PV) Systems, Pulsewidth Modulation (PWM) Inverter, Power Switches.

I. INTRODUCTION

Load connected photovoltaic (PV) converters represent the most widespread solution for residential renewable energy generation. While classical designs of PV converters feature a load frequency transformer, which is a typically heavy and costly component, at the interface between the converter and the electrical Load, researchers are now considering transformerless architectures in order to reduce costs and weight and improve efficiency. Removing the load frequency transformer entails all the benefits above but worsens the output power quality, allowing the injection of dc current into the load and giving rise to the problem of ground leakage current [4].

Although the active parts of PV modules might be electrically insulated from the ground-connected mounting frame, a path for ac ground leakage currents generally exists due to a parasitic capacitance between the modules and the frame and to the connection between the neutral wire and the ground, usually realized at the low-voltage/medium-voltage (LV/MV) transformer [4]. In addition to deteriorating power quality, the ground leakage current increases the generation of electromagnetic interference and can represent a safety hazard, so that international regulations pose strict limits to its magnitude. This issue must be confronted in all transformerless PV converters, regardless of architecture. In particular, in full-bridge-based topologies, the ground leakage current is mainly due to highfrequency variations of the common-mode voltage at the output of the power converter [5].

Once the load frequency transformer is removed from a PV converter, the bulkiest wound and reactive components that remain are those that form the output filter used to clean the output voltage and current from high frequency switching components. Further reduction in cost and weight and improvement in efficiency can be achieved by reducing the filter size, and this is the goal of multilevel converters.

Multilevel converters have been investigated for years but only recently have the results of such researches found their way to commercial PV converters. Since they can synthesize the output voltages using more levels, multilevel converters outperform conventional two- and three-level converters in terms of harmonic distortion. Moreover, multilevel converters subdivide the input voltage among several power devices, allowing for the use of more efficient devices. Multilevel converters were initially employed in high-voltage industrial and power train applications. They were first introduced in renewable energy converters inside utility-scale plants, in which they are still largely employed. Recently, they have found their way to residential-scale single-phase PV converters, where they currently represent a hot research topic [11].

CFBs give developers many degrees of freedom for the control strategy. A CFB made up of n full bridges (and at least $4n$ power switches) can synthesize $2n + 1$ voltage levels when the supply voltage is the same for each full bridge. Reduction in the switches-per-output voltage- level ratio can be achieved in CFB structures if different supply voltages are chosen for each full bridge (asymmetrical CFBs).

The topology proposed in this paper consists of two asymmetrical CFBs, generating nine output voltage levels. In the proposed converter, the dc voltage source supplies one of the full bridges, whereas a flying capacitor supplies the other one. By suitably controlling the ratio between the two voltages, different sets of output levels can be obtained.

Moreover, the flying capacitor used as a secondary energy source allows for limited voltage boosting. The number of output levels per switch (eight switches, nine levels) is comparable to what can be achieved using custom architectures. In final topology two additional very low power switches and a line frequency switching device [transient circuit (TC)] were included in order to reduce the ground leakage current. Finally, it is important to put in evidence that the proposed converter can work at any power factor as reported in Section III.

This paper is organized as follows: Section II presents the power converter topology and the PWM control strategy chosen in order to maximize the performance with the use of a low-cost digital signal processor (DSP). Section III describes the regulation of the flying capacitor used to supply the second full bridge of the CFB topology. Section IV describes the principle of operation of the additional components able to reduce the ground leakage current. Sections V reports the concluding remarks.

II. NINE-LEVEL CONVERTER AND PWM CONTROL STRATEGY

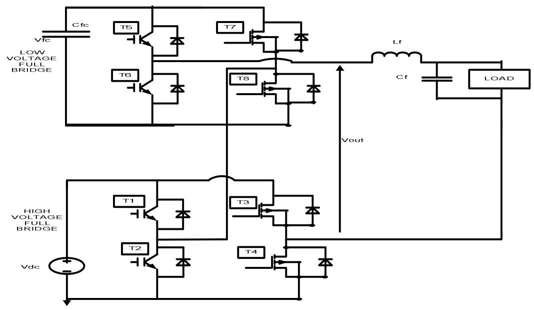


Fig. 1. CFB with a flying capacitor.

The proposed converter is composed of two CFBs, one of which is supplied by a flying capacitor (Fig. 1). The PWM strategy alone is not sufficient to maintain a low ground leakage current, other components were added as described in Section IV. The proposed PWM strategy stretches the efficiency by using the two legs where PWM frequency switching does not occur, devices with extremely low voltage drop, such as MOSFETs lacking a fast recovery diode. In fact, the low commutation frequency of those two legs allows, even in a reverse conduction state, the conduction in the channel instead of the body diode (i.e., active rectification). Insulated-gate bipolar transistors (IGBTs) with fast antiparallel diodes are required in the legs where high-frequency hard-switching commutations occur. In load-connected operation, one full-bridge leg is directly connected to the load neutral wire, whereas the phase wire is connected to the converter through an *LC* filter. As it will be described and justified in the following section, flying-capacitor voltage *Vfc* is kept lower, at steady state, than dc-link voltage *VDC*. Accordingly, the full bridge supplied by the dc link is called the high-voltage full bridge (HVFB), whereas the one with the flying capacitor is the low-voltage full-bridge (LVFB).

The CFB topology allows certain degrees of freedom in the control, so that different PWM schemes can be considered; however, the chosen solution needs to satisfy the following requirements.

1) Most commutations must take place in the LVFB to limit the switching losses.

2) The neutral-connected leg of the HVFB needs to switch at load frequency to reduce the ground leakage current.

3) The redundant states of the converter must be properly used to control the flying-capacitor voltage.

4) The driving signals must be obtained from a single carrier for a low-cost DSP to be used as a controller.

TABLE I

DESCRIPTION OF THE CONVERTER OPERATING ZONES

Zone	Output Voltage	On Devices	Off Devices	Switching Devices
Zone3B	$-V_{DC} - V_{fc}=-V_{DC}$	T2, T3,T7	T1, T4, T8	T5, T6
Zone3A	$-V_{DC}=-V_{DC}+V_{fc}$	T2, T3,T8	T1, T4, T7	T5, T6
Zone2A	$-V_{DC} + V_{fc} = 0$	T3, T7	T4, T8	T1, T2, T5,T6
Zone2B	$-V_{DC} = -V_{fc}$	T3, T7	T4, T8	T1, T2, T5,T6
Zone1B	$-V_{fc} = 0$	T1, T3,T7	T2, T4, T8	T5, T6
Zone1A	$0 = V_{fc}$	T2, T4,T8	T1, T3, T7	T5, T6
Zone2A	$V_{fc} = V_{DC}$	T4, T8	T3, T7	T1, T2, T5,T6
Zone2B	$0 = V_{DC} - V_{fc}$	T4, T7	T3, T7	T1, T2, T5,T6
Zone3B	$V_{DC} - V_{fc} = V_{DC}$	T1, T4,T7	T2, T3, T8	T5, T6

Zone3A	$V_{DC} = V_{DC} + V_{fc}$	T1, T4,T8	T2, T3, T7	T5, T6

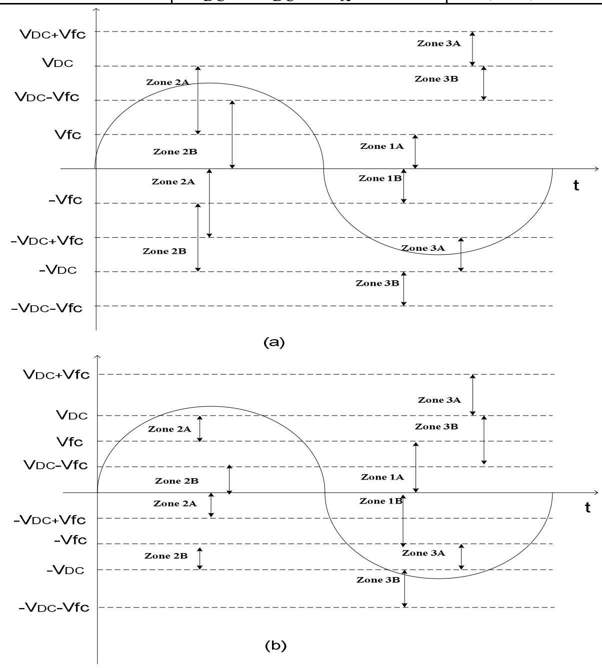


Fig. 2. Operating zones under different *V*fc ranges. (a) *V*fc < 0.5*V*DC. (b) *V*fc > 0.5*V*DC.

The switching pattern described in Table I was developed starting from the above requirements. Capacitive coupling renders the common-mode current inversely proportional to the switching frequency of the neutral-connected leg.

The converter can operate in different output voltage zones, where the output voltage switches between two specific levels. The operating zone boundaries vary according to the dc-link and flying-capacitor voltages, and adjacent zones can overlap (Fig. 2).

In zones labeled A, the contribution of the flying-capacitor voltage to the converter output voltage is positive, whereas it is negative in B zones. Constructive cascading of the two full bridges can, therefore, result in limited output voltage boosting. Depending on the *V*fc/*VDC* ratio, one of the (a) or (b) situations in Fig. 2 can ensue; nevertheless, the operation of the converter does not differ much in the two cases. If two overlapping operating zones can supply the same output voltage, the operating zone to be used is determined taking into account the regulation of *V*fc, as will be described in Section III.

The switching pattern depends on the instantaneous fundamental component of output voltage *Vout* and on the measured values of *V*fc and *VDC*. If *V*fc = *VDC*/3, the converter can synthesize nine equally spaced output voltage levels. One leg of the HVFB operates at load frequency and one leg of the LVFB at five times the load frequency.

Moreover, apart from zone 2, no high-frequency commutations occur in the whole HVFB (Fig. 2). Since the voltage regulation of the flying capacitor takes place in zone 2, the zone-2 behavior is more articulated and will be described in detail in the following section.

III. FLYING-CAPACITOR VOLTAGE REGULATION

Since the main task facing a load-connected PV converter is the transfer of active power to the electrical load, controlling the voltage of the flying capacitor is critical.

Flying-capacitor voltage *V*fc is regulated by suitably choosing the operating zone of the converter depending on the instantaneous output voltage request. Depending on the operating zone of the converter (Fig. 2), *V*fc can be added to (A zones) or subtracted from (B zones) the HVFB output voltage, charging or discharging the flying capacitor. In particular, considering a positive value of the current injected into the load, the flying capacitor is discharged in A zones and charged in B zones. Since a number of redundant switch configurations can be used to synthesize the same output voltage waveform, it is possible to control the voltage of the flying capacitor, forcing the converter to operate more in A zones when the flying-capacitor voltage is higher than a reference value or more in B zones when it is lower than a reference value. Similar considerations hold in case of a negative injected current.

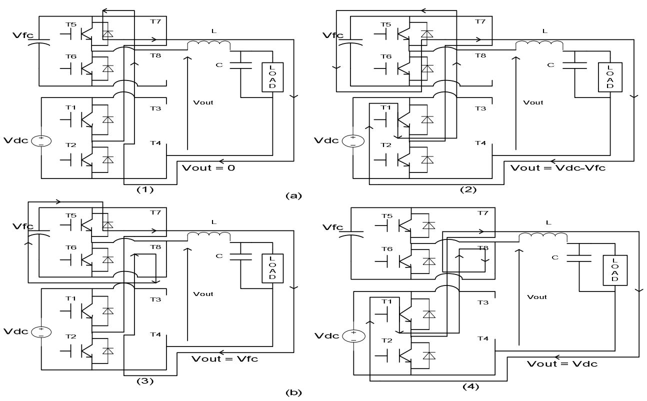


Fig. 3. Converter configurations for the regulation of the flying capacitor. (a) Flying-capacitor charge. (b) Flying-capacitor discharge.

In each case, some commutations between nonadjacent output levels must inevitably occur (level skipping), with the drawback of a certain increase in the output current ripple. The voltage control of the flying capacitor (which determines the zone-A or zone-B operation) is realized by a simple hysteresis control.

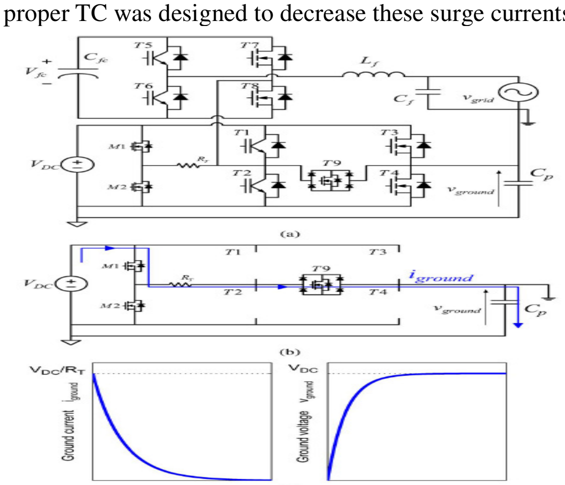
Fig.3. illustrates the regulation of Vfc supposing a positive current with Vout > 0 and Vfc < 0.5VDC. If Vfc is too low, output level Vfc can be replaced by VDC − Vfc, thus switching between the 0 and VDC − Vfc output levels [zone 2B, Fig. 3(a)]. Similarly, if Vfc is too high, VDC − Vfc can be replaced with Vfc, causing the converter to switch between the Vfc and VDC output levels [zone 2A, Fig. 4(b)]. In Fig. 4, the devices switching at low frequency are short circuited when on and not shown when off. Similar Vfc regulation strategies can be likewise developed for the case when Vfc > 0.5VDC.

If Vfc < 0.5VDC, in order to minimize the current ripple,
zone 2 is chosen only when Vfc < Vout < VDC − Vfc (zones 3 are otherwise chosen), limiting level skipping. Level skipping always occurs if Vfc > 0.5VDC; hence, any A or B zone can be chosen according to the voltage regulation algorithm.

Since the dc-link voltage can go through sudden variations due to the MPPT strategy, it is important that the converter is able to work in any [VDC, Vfc] condition. While the distortion of the output voltage is minimized through the on-line dutycycle computation, it is important to assess the capability of the converter to regulate the flying-capacitor voltage under different operating conditions.

IV. APPLICATION TO TRANSFORMERLESS PV CONVERTERS—TC

A particular feature of the commutation pattern of Table I
is that T3 and T4 switch at load frequency, commutating at every zero crossing of Vload. If the zero crossing with a negative derivative is considered, T4 opens and T3 closes, changing the neutral wire voltage (and thus the voltage across the parasitic capacitance of the PV field) from zero to VDC. For this reason, the commutation can cause a large surge of leakage current that can decrease the power quality and damage the PV modules. A proper TC was designed to decrease these surge currents.



.

Fig. 4. Ground leakage current limitation circuit topology and behavior.

(a) TC topology. (b) TC operation. (c) TC waveforms.

Fig. 4(a) shows the proposed converter topology; it is constituted of the two-cell CFB described in Fig. 1 with the addition of the TC components. In order to better understand the behavior of the TC, the distributed parasitic capacitance of the PV source was modeled with a simple equivalent parasitic capacitance, i.e., *Cp*, connected between the negative pole of the dc link and the ground.

The TC consists of two low-power MOSFETs M1 and M2, bidirectional switch T9, and resistor *RT* . When the converter enters operating zone 1, the HVFB output voltage must be zero, obtained by switching T1 and T3 or T2 and T4 on. Nevertheless, to operate the TC, when entering zone 1, T1, T2, T3, and T4 are all kept off, while T9 is on. This keeps the neutral potential floating, so that the voltage on the parasitic capacitor Vground stays constant [see Fig. 4(b)]. At this point, one of M1 and M2 is turned on (M1 if the slope of the zero crossing is negative and M2 if positive). So doing, *Cp* is charged through *RT* with a first-order transient [see Fig. 4(c)], limiting the current surge.

Whereas the TC introduces additional components, they can be selected with current ratings much lower than the devices of the CFB. Moreover, the power loss due to the added resistor is negligible. Estimating the energy lost charging and discharging a capacitor *Cp* to *V*DC averaged over a line period *T* by $P\text{tc} = CpV^2_{DC}/T$, with $Cp = 200$ nF and $V_{DC} = 300$ V, a dissipation of about 1W is obtained. The operation of the TC is not affected by the power factor because in Load-connected operation, the output voltage is always very close to the Load voltage. The correct operation of the TC requires the Load voltage instantaneous angle that can be obtained with a phase-locked loop (PLL) fed by the load voltage.

V. CONCLUSION

This paper has proposed a novel nine-level converter topology for transformerless PV converter based on a CFB topology with two full bridges, one of which is supplied by a floating capacitor.

A suitable PWM strategy was developed in order to improve efficiency and with the help of a specific TC, minimize the ground leakage current.

The proposed PWM strategy can regulate the voltage across the flying capacitor.

The proposed converter can continuously operate at arbitrary power factors, has limited boosting capability, and can produce nine output voltage levels with 11 power switches, of which three are low power switches for the TC and only four need to be controlled by PWM.

REFERENCES

[1] G. Buticchi, Davide Barater, Emilio Lorenzani, Carlo Concari "A Nine-Level Load-Connected Converter Topology for Single-Phase Transformerless PV Systems" , *IEEE Trans. Ind. Electron.*, Vol, 61, No. 8, Aug. 2014

[2] G. Buticchi, L. Consolini, and E. Lorenzani, "Active filter for the removal of the dc current component for single-phase power lines," *IEEE Trans. Ind. Electron.*, vol. 60, no. 10, pp. 4403–4414, Oct. 2013

[3] G. Buticchi and E. Lorenzani, "Detection method of the dc bias in distribution power transformers," *IEEE Trans. Ind. Electron.*, vol. 60, no. 8, pp. 3539–3549, Aug. 2013.

[4] H. Xiao and S. Xie, "Leakage current analytical model and application in single-phase transformerless photovoltaic Load-connected inverter," *IEEE Trans. Electromagn. Compat.*, vol. 52, no. 4, pp. 902–913, Nov. 2010

[5] O. Lopez, F. Freijedo, A. Yepes, P. Fernandez-Comesaa, J. Malvar, R. Teodorescu, and J. Doval-Gandoy, "Eliminating ground current in a transformerless photovoltaic application," *IEEE Trans. Energy Convers.*, vol. 25, no. 1, pp. 140–147, Mar. 2010.

[6] S. Araujo, P. Zacharias, and R. Mallwitz, "Highly efficient single-phase transformer less inverters for Load-connected photovoltaic systems," *IEEE Trans. Ind. Electron.*, vol. 57, no. 9, pp. 3118–3128, Sep. 2010.

[7] D. Barater, G. Buticchi, A. Crinto, G. Franceschini, and E. Lorenzani, "Unipolar PWM strategy for transformerless PV Load-connected converters," *IEEE Trans. Energy Convers.*, vol. 27, no. 4, pp. 835–843, Dec. 2012.

[8] T. Kerekes, R. Teodorescu, P. Rodridguez, G. Vazquez, and E. Aldabas, "A new high-efficiency single-phase transformerless PV inverter topology," *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 184–191, Jan. 2011.

[9] S. Kouro, M. Malinowski, K. Gopakumar, J. Pou, L. Franquelo, B. Wu, J. Rodriguez, M. P. Andrez, and J. Leon, "Recent advances and industrial applications of multilevel converters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 8, pp. 2553–2580, Aug. 2010.

[10] Mohammad Kazem Bakhshizadeh, Hossein Iman-Eini, Frede Blaabjerg "Selective Harmonic Elimination in Asymmetric Cascaded Multilevel Inverters Using a New Low-frequency Strategy for Photovoltaic Applications" *Electric Power Components and Systems*, Doi: 10.1080/15325008.2015.1021058

[11] G. Buticchi, E. Lorenzani, and G. Franceschini, “A five-level single-phase Load-connected converter for renewable distributed systems,” *IEEE Trans. Ind. Electron.*, vol. 60, no. 3, pp. 906–918, Mar. 2013

[12] J. Chavarria, D. Biel, F. Guinjoan, C. Meza, and J. Negroni, “Energybalance control of PV cascaded multilevel Load-connected inverters under level-shifted and phase-shifted PWMS,” *IEEE Trans. Ind. Electron.*, vol. 60, no. 1, pp. 98–111, Jan. 2013.

[13] G. Grandi, C. Rossi, D. Ostojic, and D. Casadei, “A new multilevel conversion structure for Load-connected PV applications,” *IEEE Trans. Ind. Electron.*, vol. 56, no. 11, pp. 4416–4426, Nov. 2009.S. Daher, J. Schmid, and F. Antunes, “Multilevel inverter topologies for stand-alone PV systems,” *IEEE Trans. Ind. Electron.*, vol. 55, no. 7,pp. 2703–2712, Jul. 2008.

[14] S. Daher, J. Schmid, and F. Antunes, “Multilevel inverter topologies for stand-alone PV systems,” *IEEE Trans. Ind. Electron.*, vol. 55, no. 7,pp. 2703–2712, Jul. 2008.