A Novel Control Technique Using Seven Level Converter Topology For Single-Phase Transformerless Pv Systems

Ajay M. Mendhe , Dr. R.P.Singh

Abstract: This paper introduces a new control technique for a seven-level converter topology for single phase transformerless pv systems. The proposed control mechanism has been implemented for a cascaded full bridge operating on one bridge being fed from dc source and the other from a flying capacitor. This scheme utilizes the redundant switching states of the cascaded full bridge. The proposed scheme works upon maintaining the capacitor voltage constant, which helps in maintaining the inverter output. Simulation results have been presented to substantiate the validity of the proposed mechanism.

Index Terms: Leakage current, multilevel systems, photovoltaic (PV) systems, cascaded full bridge, sinusoidal pulse width modulation.

1. INTRODUCTION

Grid connected Photo Voltaic convertors have been used quite abundantly in residential renewable energy solutions. These convertors conventionally comprise of a heavy and expensive grid frequency transformer which works as an interface between the grid and the convertor. Transformerless systems have been researched upon and have shown to be suitably effective in terms of efficiency, cost and weight but weigh down in terms of the quality of the output power, infesting the grid with dc current [1], [2] and causing an increase in the ground leakage current [3], [4]. The module and the frame along with the connection between neutral wire and ground leads to parasitic capacitance allowing AC leakage current [3]. Apart from ground leakage current disturbing the power quality it also leads to electromagnetic interferences compromising the safety of the system. International regulations pose strict limit to this. Thus systems need to take care about this issue irrespective of the architecture on which they are built upon. The common mode voltage existing in full-bridge-based topologies leads to development of the ground leakage current, basically due to the frequency variation of the common mode voltage observed across the output [4]. Lots of solutions have been proposed over the years regarding the mitigation of the harmonic content present in the common-mode voltage [5]–[7]. With the grid-frequency transformer out of the system, the only bulky part that remains is the filter which filters the output from high frequency switching components. Any reduction in the size of the filter leads to considerable reduction in cost and weight and leads to improvement in efficiency too. Multilevel invertors focus on this aspect and have found way into the recent commercial PV convertors. Multilevel convertors capable of synthesizing the output voltage using more number of levels score over the conventional two- and three-level convertors in terms of reduction in harmonic distortion and they also present an advantage of efficient device utility on account of its ability to sub divide the input voltage among several power devices. Better quality of the output voltage waveform of the multilevel converter aids in the reduction of the filter size, with a consequent reduction in the cost and weight of the inverter and corresponding improvement in the efficiency of the system. Multilevel converters were initially used in high-voltage industrial applications, as well as power train applications. Gradually they were employed in renewable energy convertors and are still widely used for these applications [9]–[13]. Of late they have been able to find their way in residential-scale single-phase PV convertors, providing lots of opportunity to researchers to work upon improving the systems employing multilevel convertors [14]–[29].

Cascaded Full Bridge (CFB) convertors have been popularly used for stand-alone applications [17], [22]. CFBs allows host of control strategies like sequential permutation supplemented with phase shifting [19], predictive control [23] and artificial neural networks [24] to be used to mitigate harmonic distortion and achieve maximum power point tracking (MPPT). A n full bridge based CFB which has at least 4n power switches is capable of synthesizing 2n + 1 voltage levels for same level of supply voltage for each bridge. Architectures can be customized to work with different control strategies and allows reduction in the number of switches [25]–[29]. It is possible to reduce the switches-per-outputvoltage-level ratio employing different supply voltages for each bridge (asymmetrical CFBs) [32], [33]. This work discusses a topology in which two asymmetrical CFBs are used, generating seven output voltage levels. For this convertor, one bridge is powered by a dc voltage source while the other bridge is powered by a flying capacitor. Balancing the ratio between two voltages allows different set of output voltages. With flying capacitor working as a secondary source, it allows limited voltage boosting and the output is comparable to various other custom architectures. PV applications face the problem of variation in solar radiation resulting in variable DC voltage being fed into the system and need to employ strategies which are able to control the output voltage. This problem was studied in [34]–[36], and it focused on measurement of the separate full-bridge voltages and online computation of duty cycles needed to balance the voltages and to analyze the power balance between different cells. This paper deals with the capacitor voltage balancing of the discussed...
Converter when used a seven-level CFB converter. The technique is simple and much easier to use, and it achieves the desired results. Simulation results are presented to validate the proposed technique.

2 CASCADED FULL BRIDGE CONVERTER WITH A FLYING CAPACITOR

Fig. 1 shows a cascaded full bridge converter with a flying capacitor for single-phase transformerless PV applications [38]. The converter uses two full bridges in cascade. One full bridge is fed from a dc source, while the other bridge is fed from a flying capacitor. The number of voltage levels available at the output of the converter depends on the voltage ratio maintained between the dc voltage \( V_{DC} \) and the flying capacitor voltage \( V_c \). If the ratio is kept at 2:1, the inverter works as a seven-level CFB converter. If the ratio is maintained at 3:1, the number of output voltage levels obtained is nine. For the present study, the inverter is operated as a seven-level CFB converter. Hence the capacitor voltage magnitude should be kept at half of the dc supply voltage. The advantage of supplying one bridge with a flying capacitor is that only one dc supply is required for the inverter. This is an advantage over the conventional CFB converter which would require two isolated dc power sources for each phase. However, the topology discussed here presents a challenge, in that, it is not easy to maintain the capacitor voltage constant. Even if the capacitor is initially charged, it has a propensity to discharge as the circuit operates. As the capacitor discharges, the output voltage waveform deteriorates and the purpose of the circuit fails. The successful functioning of the circuit as a seven-level CFB converter, absolutely essentially requires that the capacitor voltage be held constant at a level that is half of the dc supply voltage. [38] presents a method to maintain the capacitor voltage constant; however, the method is quite complex. Here a simpler control technique is presented to control the capacitor voltage and maintain it at its desired value, so that the desired output voltage waveform is obtained.

2.1 Proposed Control Scheme

A number of control techniques are available for multilevel CFB converters. These include the Sinusoidal Pulse width modulation (PWM) technique, the Space Vector PWM technique, the Selective Harmonic Elimination PWM technique, and so on. Out of these, the two most prominently used techniques are the sinusoidal PWM and the space vector PWM technique. However, the space vector PWM technique cannot be used for single phase converters. As such, the sinusoidal PWM technique will be considered in this work.

Among the sinusoidal PWM techniques available for multilevel converters, the level-shifted PWM (LSPWM) technique is the simplest. Hence this work uses the LSPWM technique to modulate the CFB converter. This technique uses a single modulating wave for the single phase converter and six level-shifted carrier waves to obtain a seven-level output, as shown in Fig 2.

![Fig.2 Modulating and Carrier Waves for the Seven-Level CFB converter](image)

The carrier waves can be labeled from top to bottom as \( v_{cr1+}, v_{cr2+}, v_{cr1-}, v_{cr2-}, v_{cr3+} \) and \( v_{cr3-} \); whereas the modulating wave can be labeled as \( v_m \). When \( v_m \) is greater than \( v_{cr3+} \), those switches of the converter are turned on which give an output voltage equal to 3E. Here 2E is the dc supply voltage whereas E is the voltage across the flying capacitor. When \( v_m \) is greater than \( v_{cr2+} \), the switches of the converter which give an output voltage of 2E are turned on, and so on. The switching states for the seven-level asymmetrical CFB converter modulated using LSPWM technique are listed in Table 1.

**Table 1**

<table>
<thead>
<tr>
<th>Switches in ON state</th>
<th>Capacitor status</th>
<th>Output voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2, 5, 6</td>
<td>Discharging</td>
<td>2E + E = 3E</td>
</tr>
<tr>
<td>1, 2, 5, 7</td>
<td>Floating</td>
<td>2E + 0 = 2E</td>
</tr>
<tr>
<td>1, 2, 7, 8</td>
<td>Charging</td>
<td>2E - E = E</td>
</tr>
<tr>
<td>1, 3, 5, 6</td>
<td>Discharging</td>
<td>0 + E = E</td>
</tr>
<tr>
<td>1, 3, 5, 7</td>
<td>Floating</td>
<td>0 + 0 = 0</td>
</tr>
<tr>
<td>1, 3, 7, 8</td>
<td>Charging</td>
<td>0 - E = -E</td>
</tr>
<tr>
<td>3, 4, 5, 6</td>
<td>Discharging</td>
<td>-2E + E = -E</td>
</tr>
<tr>
<td>3, 4, 5, 7</td>
<td>Floating</td>
<td>-2E + 0 = -2E</td>
</tr>
<tr>
<td>3, 4, 7, 8</td>
<td>Charging</td>
<td>-2E - E = -3E</td>
</tr>
</tbody>
</table>

For the output voltage levels of 3E, 2E, 0, -2E and -3E, there is only one possible combination of switches. However, for the voltage level E and -E, the CFB converter offers redundant switching states. The redundancy of switching states is an important advantage in case of multilevel converters, and can be put to good and effective use. The capacitor status during each switching state of the

![Fig.1 CFB with a flying capacitor](image)
inverter is also shown in Table 1. When a switching state causes the capacitor current to leave from its upper plate, it causes the capacitor to discharge. On the other hand, if a switching state causes the capacitor current to enter through its upper plate, it results in the charging of the capacitor. If no current flows through the capacitor during a switching state, it neither charges nor discharges, and is said to be floating. It is observed from Table 1 that there is a natural balance in the charging and discharging times of the capacitor during each cycle of the inverter output waveform. During the positive half cycle, the capacitor discharges for the output voltage level 3E and floats for 2E. For the output voltage level E, switches 1,2,7,8 can be turned on so that the capacitor charges. During the negative half cycle, the capacitor charges for the output voltage level – 3E. If the switches 3,4,5,6 are turned on for the voltage level – E, the capacitor would discharge. Thus for the equivalent voltage levels in the positive and negative half cycle (equivalent voltage levels will have equal on-times in a cycle), if the capacitor charges for a level in the positive half cycle, it discharges for the corresponding level in the negative half cycle, and vice versa. This implies that if the capacitor were lossless and was initially charged to a voltage E, the capacitor voltage would remain constant over a cycle on account of alternate charging and discharging for equal times in the cycle. However, in practice, the capacitor will have some losses. As a result, the capacitor voltage will continue to decrease as the inverter operates and the output voltage waveform will be affected. To overcome this problem, the redundant states of the seven-level inverter can be utilized. Those states which cause the capacitor to discharge can be discarded in favor of those states which result in the charging of the capacitor. As such, during the positive half cycle, the switching state +E with switches 1,2,7,8 on is chosen as it causes the capacitor to charge. Also, in the negative half cycle, the switching state – E with switches 1,3,7,8 on, which again causes charging of the capacitor is chosen. With this choice, the capacitor discharges only when the switches 1,2,5,6 are on for the switching state 3E; whereas it is either floating or charging during all the other switching states. This choice of switching states helps in maintaining the capacitor voltage at its desired value (to the one that it has been charged initially). If the capacitor still continues to lose charge, a slight negative offset can be provided in the modulating wave. This will cause the discharging time of the capacitor on account of the switching state 3E to decrease, with a corresponding increase in the charging time. This will further help in maintaining the capacitor voltage constant. It must be mentioned here that these techniques will keep the capacitor voltage constant only in case of light loads, i.e. loads that do not draw a significant amount of current. If the load current has a large value, then these techniques will not be sufficient in maintaining the capacitor voltage constant.

3 SIMULATION RESULTS
The CFB converter shown in Figure 1 is simulated using MATLAB Simulink with the proposed control technique.

Fig.3 shows the flying capacitor voltage for one cycle of the inverter operation. As seen, the capacitor voltage remains almost constant at the value to which it was initially charged.

Fig.3 shows the modulating and carrier waves for the seven-level CFB converter with a 20% negative offset in the modulating wave. This will cause the on-time of the switching state 3E to decrease, resulting in the decrease of the discharging of the capacitor. At the same time, it will increase the on-time of the switching state – 3E so as to increase the charging time of the capacitor. The dc supply voltage is selected as 200 V, while the capacitor voltage is taken as 100 V to ensure a ratio of 2:1 between the two. The frequency of the modulating wave is taken as 50 Hz to obtain a 50 Hz inverter output voltage. The frequency modulation index m is taken as 21 so that the harmonics appear across the sidebands of m1, 2m1 and so on. This ensures that the lower order harmonics are eliminated, as a result of which the size of the filter decreases. The simulation here is done without considering a filter as the focus of this research is only on the capacitor voltage balancing. A 10 kΩ resistive load is considered for the inverter so that the load current has a small value. A 20% negative offset is provided in the modulating wave to assist in keeping the capacitor voltage constant.
modulating wave to decrease the capacitor discharging time while simultaneously increasing the capacitor charging time. This results in keeping the capacitor voltage constant during inverter operation in spite of losses in the capacitor, which would otherwise have decreased the capacitor voltage and deteriorated the inverter output voltage waveform. The dc offset, however, introduces a dc component in the inverter output voltage, the magnitude of which is directly dependent on the amount of negative offset provided. Also, the technique is useful only for light loads, and not where the load draws a large current. Simulation results are presented to validate the proposed technique and prove its effectiveness in keeping the capacitor voltage constant.

REFERENCES


