DESIGN OF PHOTOVOLTAIC CSI FOR STAIR CASE WAVEFORM GENERATION BY USING INDUCTOR CELLS

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Abstract— The current-source inverter (CSI) has the potential of becoming a preferred topology for interfacing a PV system to the ac power grid. Multi level inverters have the capability to deliver higher output power with lower \(dv/dt\) or lower \(di/dt\) and with less distorted output waveform. This paper presents a new topology for single phase multi level current source inverter. Here H-bridge coordination with inductor cell provides the multilevel waveform generation. The inductor cell is a combination of four unidirectional power electronic switches with an inductor connected across cell circuit. Inductor cell operation causes the intermediate levels of current waveform without any additional dc power sources by using charging and discharging modes. A chopper circuit is used to provide the continuous smoothing current to the input side inductor. To control the intermediate level operation PI controller is used. In this paper MATLAB simulation of 5 level and 9 levels are implemented. The results show that the circuit configuration woks properly to give low output harmonics with small size of inductors which proves the feasibility of the proposed strategy.

Index Terms—Current-source inverter (CSI), H-bridge, inductor cell, multilevel

I. INTRODUCTION

In recent years, photovoltaic (PV) systems have received unprecedented attention due to the concerns about adverse effects of extensive use of fossil fuels on the environment and energy security. Despite this high interest, grid-connected PV systems are still outnumbered by the power generation schemes based on oil, natural gas, coal, nuclear, hydro, and wind. So far, PV systems of capacities on the order of tens of megawatts have been installed and interfaced to the grid mainly at the primary distribution level. PV system installations at the secondary distribution level are dominated by rooftop units with capacities on the order of a few kilowatts with no significant impact on the existing power systems. With the growing interest in solar energy and adoption of national policies in favor of green energy, a significant increase in the number of large-size PV plants, with significant impact on the existing power grid is expected. The two main components of a PV system with potential for improvement are PV modules and power electronic inverters. PV modules contribute to the overall cost of PV systems in a big way.

The current-source inverter (CSI) has the potential of becoming a preferred topology for interfacing a PV system to the ac power grid for the following reasons. 1) CSI provides a smooth dc-side current, which is a desirable feature for PV modules. 2) The energy storage element of a CSI has a longer lifetime than that of a VSI. 3) CSI has an inherent voltage boosting capability, which allows integration of PV panels of lower output voltages and reduces the requirements of the step-up interface transformer. 4) With the evolution of reverse-blocking (RB) IGBT switches, the series diodes will be eliminated, resulting in a considerable reduction in the cost and conduction losses. 5) The recent advancements in superconductor technology, which has led to the development of superconducting magnetic energy storage (SMES) systems, can considerably reduce the losses in the energy storage element of the CSI.

Recent development of high-performance semiconductor power switches such as MOSFETs and insulated-gate bipolar transistors (IGBTs) increases the research interest in high-power converters, such as multilevel voltage-source inverters (VSIs) and its dual, multilevel current-source inverters (CSIs). Multilevel inverters have the capability to deliver higher output power with lower \(dv/dt\) or lower \(di/dt\) and with less-distorted output waveforms, resulting in reduction of electromagnetic interference (EMI) noise and size of an output filter [2]–[4]. In distributed-power-generation application, as most renewable energy sources, such as photovoltaic systems, deliver dc power; the generated power must be converted to ac power and is fed into the grid through grid-connected inverters [7]–[9]. Multilevel CSI is one of the effective solutions to tackle such problems. Control of the grid connected...
CSI is comparatively simpler than its counterpart, VSI. A grid-connected CSI can buffer the output current from the grid-voltage fluctuation, generates a predetermined current to the power grid without current-feedback loops, and can achieve a high-power-factor operation. Its output current is less affected by a grid voltage, and the CSI has inherent short-circuit protection abilities [8], [9]. Moreover, the discrete diodes connected in series with the power switches to obtain unidirectional power switches in the CSI will be unnecessary because new IGBTs with reverse-blocking capability (reverse-blocking IGBTs) are emerging [5], [6].

Few topologies of the multilevel CSIs have been proposed by researchers and engineers. A conventional method to generate the multilevel current waveform is by paralleling H-bridge CSIs [10]–[12]. This topology is a dual circuit of a cascade multilevel VSI [10]. However, the requirement of many isolated dc-current sources with their complex, bulky, and costly isolation transformers and inductors is a problem introduced by this configuration. Another topology of the multilevel CSI is obtained by applying a multicell topology of the CSI (or multirating inductor multilevel CSI [10]), which is a dual converter of a flying-capacitor-based full bridge multilevel VSI [13]–[15]. However, this topology has a drawback with its bulky intermediate inductors and complexity for balancing control of the intermediate-level currents. Some control methods have been proposed for balancing control of the intermediate-level currents in [14] and [15], but very large in size of the intermediate inductors (100mH) are still used. These cumbersome inductors will be costly and limit the application of the inverter. Bai and Zhang [10] presented the configuration of a single-rating inductor multilevel CSI that is the dual structure of an improved diode-clamped multilevel VSI. Noguchi and Suros [16], [17] presented a common-emitter configuration of the multilevel CSI obtained by connecting two-level CSI modules in parallel with the three-level common-emitter CSI. This configuration has a great advantage over conventional approaches because all of the power switches are connected at a common-emitter point or an identical potential line. This topology needs only a single isolated gate-drive circuit to drive all power switches of the inverter; hence, the complexity of the gate drive circuits can be moderated. Unfortunately, the requirement of many split dc-current sources is an apparent disadvantage of this topology.

This paper checks the performance of a hybrid configuration of the multilevel CSI. In this hybrid topology, a basic H-bridge CSI, working as a main inverter circuit, is connected in parallel with inductor cells working as auxiliary circuits. The inductor connected H-bridge cells generate the intermediate levels of the multilevel output-current waveform, with no additional external dc-power sources. The operating performance of the proposed multilevel CSI of different level circuits is examined and is tested through MATLAB/simulink simulations.

![Fig 1: single H-bridge cell with inductor](image)

Fig. 1 shows a configuration of inductor based H-bridge cell circuit composed by four unidirectional power switches QC1, QC2, QC3 and QC4 and an inductor LC connected across the cell circuit. The hybrid multilevel CSI configuration can be obtained by connecting the H-bridge CSI in parallel with a single or more inductor cells, as shown in a schematic diagram of the proposed multilevel CSI in Fig. 2.

A five-level CSI configuration is obtained by connecting a single inductor cell, a nine-level CSI configuration is achieved by connecting two inductor cells in parallel with the main three-level H-bridge CSI, and so forth. The relation between the level number of the output-current waveform (M) and the number of the inductor cells (N) can be formulated as follows:

\[ M = 2^{N+1} + 1 \]  

(1)

**II. CHARACTERISTICS OF PV ARRAY**

The PV array – characteristic is described by the following [9]:

\[ i_{pv} = n_p i_{ph} - n_p i_{rs} \left( \exp \left( \frac{q}{kT_A} \frac{v_{pv}}{n_s} \right) - 1 \right) \]  

(2)
In (2), q is the unit charge, k the Boltzman’s constant, the p-n junction ideality factor, and \( T_c \) the cell temperature. Current \( i_{rs} \) is the cell reverse saturation current, which varies with temperature according to

\[
i_{rs} = i_{rr} \left( \frac{T_r}{T_{ref}} \right)^3 \exp \left( \frac{qE_G}{kT_c} \left( \frac{1}{T_{ref}} - \frac{1}{T_c} \right) \right)
\]  

In (3), \( T_{ref} \) is the cell reference temperature, the reverse saturation current at \( T_{ref} \), and \( E_G \) the band-gap energy of the cell. The PV current \( i_{pv} \) depends on the insolation level and the cell temperature according to

\[
i_{ph} = 0.01 \left[ i_{scr} + K_v(T_c - T_{ref}) \right] S
\]  

In (4), \( i_{scr} \) is the cell short-circuit current at the reference temperature and radiation, \( K_v \) a temperature coefficient, and the insolation level in kW/m\. The power delivered by the PV array is calculated by multiplying both sides of (2) by \( v_{pp} \).

\[
P_{pv} = n_p i_{ph} v_{pp} - n_p i_{rs} v_{pp} \left[ \exp \left( \frac{q}{kT_c} \frac{v_{pp}}{n_s} \right) - 1 \right]
\]  

Substituting \( i_{ph} \) from (3) in (4), \( P_{pv} \) becomes

\[
P_{pv} = 0.01 n_p \left[ i_{scr} + K_v(T_c - T_{ref}) \right] S v_{pp} - n_p i_{rs} v_{pp} \left[ \exp \left( \frac{q}{kT_c} \frac{v_{pp}}{n_s} \right) - 1 \right]
\]  

Based on (6), it is evident that the power delivered by the PV array is a function of insolation level at any given temperature. Since the inverter employed in the PV system of this paper is of current-source type, the power-versus-current characteristic of the PV array has to be examined. Fig. 2 illustrates the power-versus-current characteristic of the PV array based on the parameters listed in the Appendix for insolation levels of 0.25, 0.5, and 1 kW/m\. Fig. 2 shows that can be maximized by control of \( i_{pv} \) based on an MPPT strategy [9].

III. HYBRID MULTI LEVEL CSI TOPOLOGY DESCRIPTION

Fig 3 show the configurations of 5-level and 9-level CSIs using the proposed strategy, respectively. For \( M \)-level CSI, if the dc-current source of the main H-bridge CSI is assumed to have an amplitude \( I \), the current flowing through the \( N \)th inductor cell \( ILc(i) \) is expressed as follows:

\[
ILc(i) = I \cdot 2i, \text{ where } i = 1, 2, 3, \ldots, N. \quad (7)
\]

The output-current levels of the five-level CSI are \(+I, +I/2, 0, -I/2, \text{ and } -I\). For the nine-level CSI, the output waveform has \(+I, +3I/4, +I/2, +I/4, 0, -I/4, -I/2, -3I/4, \text{ and } -I\) current levels.

A. Operating modes of inductor connected H-bridge cell:

The inductor cells generate intermediate-level currents of the multilevel output waveform from the basic three-level current of the H-bridge CSI. It utilizes the charging and the discharging operation modes of the inductor.

The charging operation mode of the inductor \( Lc \) is conducted when the switches QC 1 and QC 3 are turned on, while the switches QC 2 and QC 4 are turned off. A current \( ILc = I/2 \) flows through the power switches QC 1 and QC 3 that energizes the inductor \( Lc \). The discharging operation mode is
achieved by turning on the switches QC2 and QC4 and by turning off QC1 and QC3. The stored energy in the inductor is discharged to the load as a current \(I/2\). The circulating current modes occur when the inductor cell deliver a null current to keep a constant current in the inductor cell. Similar operation modes occurred for the negative cycle of the output-current waveform.

Table 2 lists the switch states of the 5-level CSI. Power device utility and average switching frequency between QC1, QC2 and QC3, QC4 in the circulating modes of the inductor cell current is one of the considerations to use redundant switching states for \(I\), 0, and \(-I\) output-current generation. It is also related to the heat distribution among the power switches QC1, QC2, QC3, and QC4 caused by the switching and conduction losses.

**B. Current ripple reduction in source current:**

In the proposed multilevel CSI, the dc-current source is indispensable. In order to test the proposed multilevel CSI, the dc-current source is obtained by employing a chopper with a smoothing inductor \((L_i)\) connected with the H-bridge CSI. The chopper consists of a controlled switch \((Q_C)\) that regulates the dc current flowing through the smoothing inductor as the dc input current \(I_L i\). A free-wheeling diode \((DF)\) is used to keep continuous current flowing through the smoothing inductor. The chopper works as a regulated dc-current source. Fig. 4 shows the five-level CSI configuration with the chopper-based dc-current source. The power source \((V_{in})\) can be constant voltage source like batteries system or a rectifier.

**C. Harmonics reduction:**

It is necessary to connect a capacitor across the load, because the inverter works as a current source and the load usually has an inductive component. The capacitor also functions to filter the harmonic components, e.g., switching harmonic components, of the PWM multilevel output current \([18]\). The harmonic components of the PWM current will flow through the filter capacitor \(C_f\).

In general, using a higher switching frequency with its constraints, and using the higher level number of the output current, a smaller size of filter capacitor can be achieved. A proper choice of the filter capacitor is also important to minimize the heat in the filter, such as capacitors having small equivalent series resistance (ESR).

![Fig. 5. Simplified model of CSI, filter capacitor, and load.](image1)

Fig. 5 shows a circuit model of the CSI \((i)\) connected with a filter capacitor \((C_f)\) with its internal resistance \((R_{Cf})\), and the load, which is a series connection of a resistor \(R\) and an inductor \(L\). For this circuit, the resonance frequency \((\omega_0)\) is expressed as

\[
L_c = \frac{L_i R}{\omega_0^2 L_i} \quad (8)
\]

Therefore, the capacitor value that satisfies (8) should be avoided to prevent such resonance in the circuit. In addition, as in dual property with the VSI, because the inverter behaves as a current source, a capacitive load should be connected. Hence, the total impedance connected to the CSI including the filter capacitor should be a capacitive. It is another consideration in choosing the value of the filter capacitor.

**III. HYBRID MULTI-LEVEL H-BRIDGE CSI CONNECTED PV SYSTEM IN MATLAB SIMULINK**

Fig 7 shows the designed matlab circuits of 5,9-level Hybrid H-bridge cell CSI with R-L load and Table 1, gives information of power circuit
parameters. The PV Simulink model is as shown in fig 6.

**TABLE 1: System Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smoothing inductor (L_i) and inductor cell (L_c)</td>
<td>1 mH and 5 mH</td>
</tr>
<tr>
<td>Power source voltage (Vin)</td>
<td>160 V</td>
</tr>
<tr>
<td>Inverter switching frequency</td>
<td>22 KHz</td>
</tr>
<tr>
<td>Filter capacitor C_f</td>
<td>5 µF</td>
</tr>
<tr>
<td>Load</td>
<td>R=8 Ω, L=1.2 mH</td>
</tr>
<tr>
<td>Output current frequency</td>
<td>60 Hz</td>
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</table>

A. Hybrid Multilevel-H bridge cell CSI control scheme:

A simple proportional-integral (PI) regulator is applied to control the dc current flowing through the smoothing inductor, which determines the amplitude of the pulse width modulation (PWM) output-current waveform I_PWM simultaneously. Making the smoothing inductor current follows the reference current is an objective of this current regulator. The switching gate signals of the chopper switch (Q_c) is generated by comparing the error signal of the detected inductor current in the steady state and a triangular waveform after passing through the PI regulator.

In order to achieve a lower distortion of the output-current waveform, a PWM technique is applied. In this paper, a level shifted multicarrier-based sinusoidal PWM technique is employed to generate gate signals for the CSI power switches and to obtain the PWM current waveforms [19], [20]. A schematic control diagram [1], including the current controller of the chopper and the inductor cell for the 5-level CSI, is shown in Fig. 8.

The control circuit of the inductor cell functions to control the operation modes, i.e., the charging, the discharging, and the circulating modes, of the inductor cell L_c. The current flowing through the inductor cell IL_c is kept constant. It generates the intermediate-level currents based on the output-current waveform of the H-bridge CSI.

A PI regulator is applied to zero the error between the detected current flowing through the inductor cell and the reference current to obtain stable and balanced intermediate-level currents. The amplitude of the inductor cell current is half of the dc input current I_Li. The output of the PI regulator is modulated by a triangular carrier to generate the control signal i[0], determining the operation mode of the inductor cell. In case of the nine-level CSI, the control circuit of the second inductor cell is similar to the first inductor cell mentioned earlier. The difference is only the reference value of the second inductor cell current I_Lc2, which is quarter of the dc input current. Therefore, for an M-level CSI, if the dc-current source is assumed to have amplitude I, the current flowing through the Nth inductor cell I_Lc is as expressed in (7). During the maximum and zero levels of the output-current generation, there is only circulating current mode, no charging and no discharging operation modes in the inductor cell, as listed in Table 2. The frequency of the triangular carrier waveform determines the switching frequency of the inductor cell’s power switches, which also regulates the charging and the discharging modes of the inductor cell. The discharging mode means that the inductor cell injects power to the load, and during the charging mode, the main H-bridge inverter injects power to the load. In case of a resistive load, the inductor cell value can be found as

\[
\omega_0 = \frac{1}{\sqrt{ILc}} \left[ \frac{R^2C_f-L}{R^2C_f-L} \right]^{1/2}
\]

where ILc is the inductor cell current (in amperes), R is a load resistance (in ohms), fs is a switching frequency of the inductor cell circuit (in hertz), and ∆ILc is an acceptable current ripple of the inductor cell current (in amperes). The higher the switching frequency is, the higher is the frequency of the charging and discharging of the inductor cell, which results in the smaller ripple of the inductor cell current, and even a smaller size of the inductor cell can be used.
Fig. 6. PV modeling

Fig 7(a) 5-level Hybrid H-bridge CSI.
Fig 7(b): 9-level Hybrid H-bridge CSI.

Fig. 8. Control diagram of proposed five-level CSI.
<table>
<thead>
<tr>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
<th>QC1</th>
<th>QC2</th>
<th>QC3</th>
<th>QC4</th>
<th>Output</th>
<th>operating mode of inductor connected H-cell</th>
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<td>circulating mode</td>
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In order to examine the proper transient operation of the proposed multilevel CSI topology, a 5-level and 9-level CSI configurations, as shown in Figs. 7 with chopper-based dc-current source were simulated by using Matlab software. The system parameters are listed in Table 1.

**IV. RESULTS**

Fig. 10 shows a computer simulation result of the proposed five-level CSI, where the five-level current, load current, the current flowing through the filter capacitor, the dc input current, and the inductor cell current waveforms are presented. Fig. 9 shows some transient waveforms in the start-up of the proposed five-level CSI, i.e., a five-level PWM current, a load current, a dc input current, and an inductor cell current with the same circuit parameters, as defined in Table 1. An excellent transient characteristic of the chopper and the inductor cell controllers can be confirmed, as shown Fig.8. The inductor cell current has been driven to the balanced condition of 50% of the 8-A dc input current. Fig. 11 shows 9-level simulation result.

The amplitudes of the first and the second inductor cell currents are 50% and 25% of the 8-A dc input current, respectively in 9-level CSI. Fig 12 shows the voltage developed by the photo voltaic cells.
Fig 11: Nine-level (I9-level), load current (ILoad), dc input current (ILi), and the first and second inductor cell current (ILC 1 and ILC 2) waveforms.

Fig 12: PV Voltage

The amplitudes of the first and the second inductor cell currents are 50%, 25% and 12% of the 8-A dc input current, respectively in 9-level CSI.

In the proposed multilevel CSI, the voltage stress of the power switches is given by the maximum filter-capacitor voltage, which is determined by the amplitude of the multilevel current waveform and the load. It remains the same for all level number of the multilevel CSI. If we give attention to the current rating of the inductor cell’s power switches, the more inductor cell are connected, the lower current rating of the power switches is required. In this paper, a new configuration of multilevel CSI, which employs inductor cells as auxiliary circuit, has been proposed.

V. CONCLUSION

The inductor cells are connected in parallel with the main H-bridge CSI to generate multilevel output-current waveforms without additional external dc-power sources. The following are some advantages that can be obtained using the proposed multilevel CSI topology connected to the PV system compared with other topologies.

1) Compared with the conventional two-level power converter, the proposed multilevel CSI can generate multilevel output-current waveform with less distortion by connecting a single or more inductor cells across the H-bridge CSI. It results in a smaller \( \frac{dI}{dt} \) produced by the circuit. Furthermore, a smaller size of the output capacitor filter can be used to filter the harmonic components of the output current.

2) In conventional parallel multilevel CSI topology, it needs many isolated dc-current sources with its complex, bulky, and costly isolation transformers and inductors. Using the proposed multilevel CSI, multilevel output waveform can be synthesized using only a single dc-power source without any additional dc-power sources.

3) The control circuit of the intermediate-level current is simple, resulting in small size of the inductors. In conventional multilevel CSI, especially multicell multilevel CSI topology and single-rating inductor multilevel CSI, they need bulky intermediate inductors with their control complexity to generate intermediate-level currents. The validity of the proposed topology has been verified through both computer simulations and experimental tests. Future works include an application of the proposed multilevel CSI for a grid-connected interactive system, and the development of the multiphase inverter circuit configuration.

REFERENCES


