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Paper

Cascaded Multilevel Embedded Type Switched Boost Inverter

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Interfacing renewable resources with the grid requires a power inverter that meets with the increasing demand of power and its quality related to reduced harmonic distortion. In relation to which multilevel inverters (MLI) have been gaining more consideration for medium voltage high power applications. In this work, a MLI using an embedded type switched boost inverter is studied with their basic performance parameters derived from its basic topology. The model is then simulated using a multicarrier modulation in MATLAB to prove its advantage over the existing topologies. © 2022 Institute of Electrical Engineers of Japan. Published by Wiley Periodicals LLC.

Keywords: boost inverter; multilevel; multicarrier

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1. Introduction

Owing to the rapidly increasing energy demand leading to subsequent decrease in conventional energy resources, the energy conversion through renewable resources have been a priority in every country. Existing PV modules exhibits lower and varying output-range, therefore, needs a power conditioner (PC) intended for further use based on specific applications. Also the requirement of reduction in the size and cost of the devices compel us to lessen the number of stages in PC. As a result, Z source inverters (ZSI) proved a break-through by providing single stage power conversion for renewable energy interfaces by combining both boosting and dc-ac conversion [1,2]. With the evolution of power electronics, ZSI have paved path for many new inverter topologies, allowing an extended range of power conversion applications [3,4]. One such topology is the embedded Z-source inverter (e-ZSI); its main purpose was to pull continuous input current through the inverter [4].

Lately, many industries require medium and low power for their applications where usage of high power may affect its reliability. In such cases, the usage of MLIs [5] is rising to overcome the limitation of the two-level inverters providing less THD (total harmonic distortion), reduced voltage stress, plus reduced switching loss and EMI (electromagnetic interference). The major task for MLI is to provide high power output from medium/low voltage rating which can be obtained from basic renewable sources, capacitors, fuel cells, etc. The multilevel inverter is derived from three types of structurals: Diode clamped (D-Clamp) (Fig. 1(a)), Flying capacitor (F-Cap) (Fig.1(b)), and Cascaded H-bridges multilevel inverter (c-MLI) (Fig. 1(c)) [6]. Each structure has its unique advantages and limitations for any required applications, but on comparison, c-MLI uses the least passive components to achieve the same level of results, provides an optimized circuit layout with compact packing [7]. A c-MLI consists of series-connected power conversion cells (H-bridge) to easily scale the overall power of the topology, each cell can provide the three different voltages level (positive, zero, negative). C-MLIs have proved to be a relatively economical solution for many applications, such as standalone systems, volt ampere reactive (VAR) compensations, and grid-connected PV systems [8,9]. This work will base on cascading one such type of e-ZSI inverter to obtain a multilevel inverter, where the cells will be replaced with the base topology to obtain a novel type c-MLI.

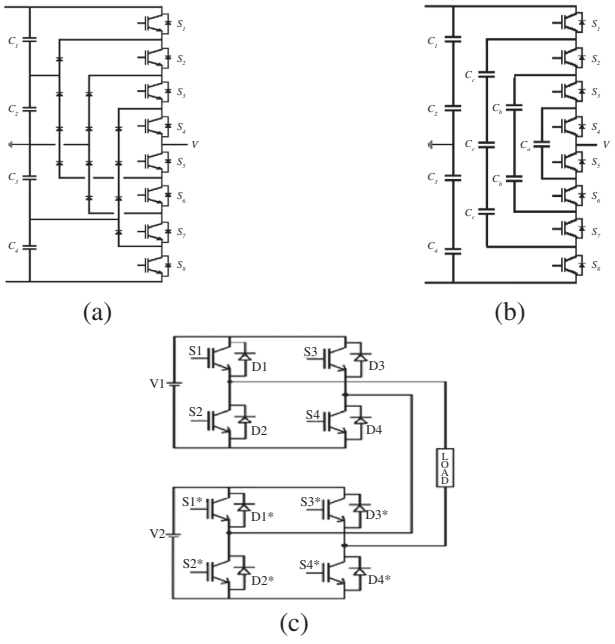

Fig 1. Types of multilevel inverters. (a) D-Clamp MLI; (b) F-CapMLI; (c) C-MLI

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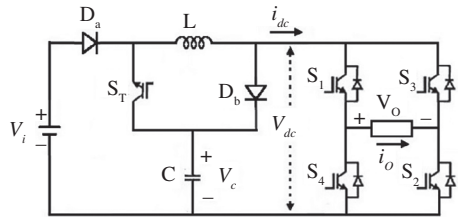

Fig 2. Switched boost inverter (SBI)

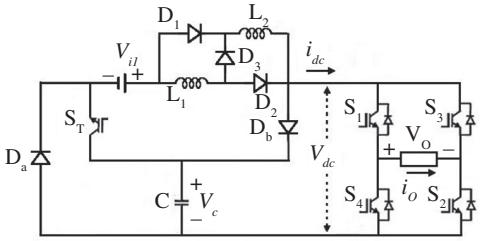

Fig 3. Embedded type switched boost inverter (SBI) with SL cell

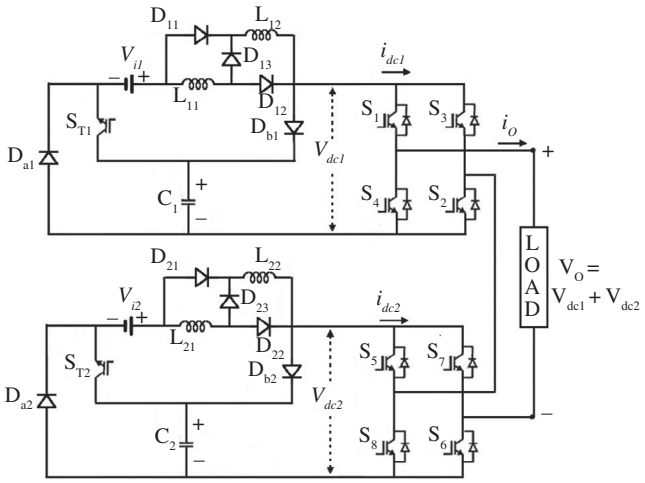

Fig 4. Multilevel embedded type switched boost inverter (MLI e-SBI)

2. Cascading of a 3-Level Inverter

2.1. Embedded type switched boost inverter (e-SBI)

The ZSI being the heart of modern power conversion uses the ST (short-circuit) in the most effective way to boost the output voltage, improving its reliability that widens its application field. Yet it poses few drawbacks to the overall systems due to which many topological changes have been implemented in literature. One such topology is switched boost inverter (SBI) (Fig. 2) which best utilizes the active components for high reliability [10], yet the gain is not enough apart from discontinuous current drawn.

SBI comprises of three working modes, two of which are the normal positive and negative operation while the remaining is the boost mode known as the ST mode. During ST, the switch S is on thereby D_a and D_b are reversed (as $V_C > V_i$), and the inductor (L) charges via Capacitor (C) through closed switch S while the inverter bridge is short-circuited (SC). And for the positive and negative cycle, S_T is off and the inverter behaves like a current

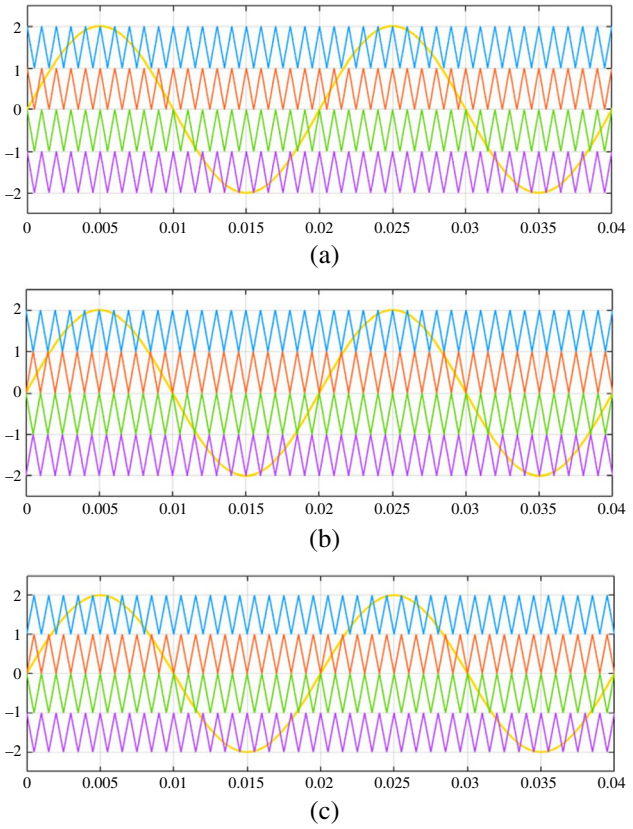

Fig 5. Multicarrier PWM. (a) Phase disposition; (b) A-phase disposition; (c) phase opposition disposition

source charging the capacitor. The output equation is given as,

$$V_o = \frac{(1 - D_s)}{(1 - 2D_s)} V_{in} \tag{1}$$

As another improvisation, e-SBI is obtained by adding the features of both e-ZSI and SBI together [11]. Like e-ZSI, the source is added within the boosting network hence it exhibits the same functionality as ZSI along with providing continuous input current that is lacking in the latter. On the whole, this topology employs lesser passive elements, while having the same operational merits. Therefore, to amplify the gain of the inverter, a switched-inductor (SL) replaces L adjacent to the source of the inverter, while the shoot-through duty cycle (D_s) remains as the central boost factor (Fig. 3).

This can be noted that the overall gain of the inverter has by far increased compared to its basic topology, from the literature the boost factor of the inverter is given by

$$B = \frac{(1 + D_s)}{(1 - 3D_s)} \tag{2}$$

Usage of a SL cell might increase the passive components of the inverter but it should be noted that the rating of the component is considerably low when compared with other topologies to achieve the same gain. Thereby, the loss produced from such component has less effect on the overall working of the topology.

2.2. Multilevel embedded type boost inverter (MLI e-SBI)

Two separate 3-level (3L) e-SBI are cascaded to obtain

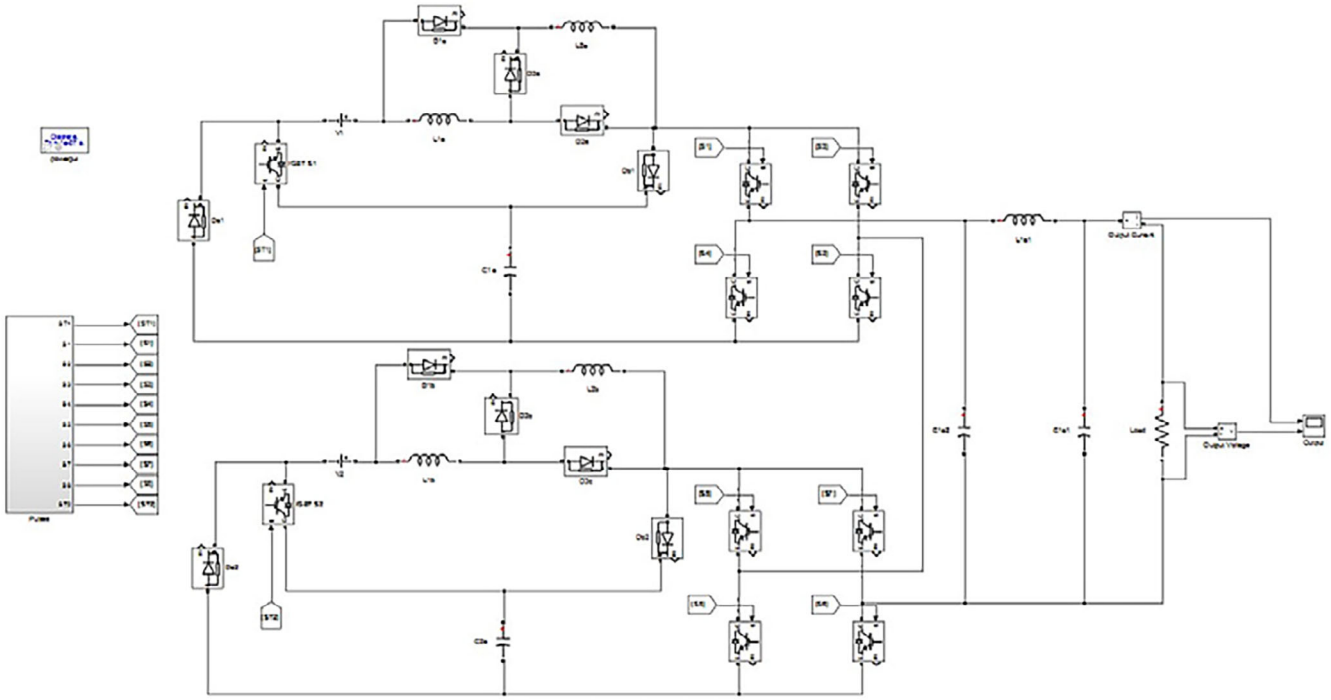

Fig 6. The overall circuit of MLI e-SBI

a multilevel embedded type switched boost inverter (Fig. 4), the topological operation will remain the same as a basic c-MLI with stepped output. Two different sources and boosting networks are provided to power the inverter for their operation, connected over a common load. The highest peak of the output of the c-MLI is the sum of peaks of individual inverter output of the inverter, in (3)

$$V_0 = V_{dc1} + V_{dc2} \tag{3}$$

The overall gain of the system depends on the D_s of the topology which remains common for all the inverters. The system consists of two separate sources that can be operated as a 3-level inverter fully in case of any failures in the switch in any one of the inverters. This increases the system's reliability to produce a constant output, and also in interfacing grid with hybrid renewable resources.

2.3. Performance characteristics

2.3.1. Gain The gain factor is calculated utilizing the inductor voltage balance law, characterized by (4) over T (the time period) [11]. The following equation is the voltage balance law of a 3L e-SBI.

$$\int_0^T V_{\mathrm{L}} \mathrm{dt} = 0 \tag{4}$$

The same equation can be written for given multilevel topology as (5) for inverter 1 for all the modes,

$$\int_0^T \left[(V_{i1} + V_{\mathrm{c1}}) + \left(\frac{V_{i1} - V_{\mathrm{c1}}}{2} \right) \right] dt = 0 \tag{5}$$

Solving the above equation we get the following capacitor equations (6) for inverter 1 and solving similarly we get (7) for inverter (2),

$$V_{\mathrm{c1}} = \frac{V_{i1}\,(1 + D_{\mathrm{s}})}{(1 - 3D_{\mathrm{s}})} \tag{6}$$

$$V_{\mathrm{c2}} = \frac{V_{i2}\,(1 + D_{\mathrm{s}})}{(1 - 3D_{\mathrm{s}})} \tag{7}$$

The peak output voltage of the topology is the summation of the capacitor voltages, given in (8),

$$V_{\mathrm{po}} = V_{\mathrm{c2}} + V_{\mathrm{c2}} = \frac{(1 + D_{\mathrm{s}})}{(1 - 3D_{\mathrm{s}})}\ (V_{i1} + V_{i2}) \tag{8}$$

The output voltage of MLI e-SBI is given in (9),

$$V_{\mathrm{O}} = \pm V_{\mathrm{po}} = B\ (V_{\mathrm{i1}} + V_{\mathrm{i2}}) \tag{9}$$

where $B = \frac{(1+D_s)}{(1-3D_s)}$.

2.3.2. Current ripple The inductor current ripple is derived from the inductor voltage (V_{L}) equation, $L = \frac{di_{\mathrm{L}}}{dt} = (V_{i1} + V_{\mathrm{c1}})$, which represents the V_{L} of inverter 1 on solving the equation. We get a common equation for all any inverter cascaded in the topology as,

$$\left|\Delta i_{L_k}\right| = \frac{D_{\mathrm{s}}}{L_k f_{\mathrm{s}}} \frac{(1 - D_{\mathrm{s}})}{(1 - 3D_{\mathrm{s}})} \tag{10}$$

where k represents the inverter number, the current ripple is computed from the system frequency and inverter inductance that is inversely proportional to the ripple.

2.3.3. Voltage ripple Voltage ripple is derived from the capacitor current, $\frac{dv_{\mathrm{c}}}{dt} C = -2\mathrm{i}_{\mathrm{L}}$ which is obtained from its base topology, on solving the above equation we get the capacitor voltage of the individual capacitor which can be commonly represented as

$$\left|\Delta V_{\mathrm{c}_k}\right| = \frac{D_{\mathrm{s}}\ (1 - D_{\mathrm{s}})\,(1 + D_{\mathrm{s}})\,V_{\mathrm{ik}}}{RC_k f\ (1 - 3D_{\mathrm{s}})^2} \tag{11}$$

The voltage is computed that capacitor voltage ripple is inversely proportional to the capacitance of the inverter.

Table I. Component parameters for simulation

Components	Values for simulation
Input voltage (V_{i1}/V_{i2})	40–50 V
Switching frequency (f_s)	25 kHz
Inductors (L_1, L_2)	1.5 mH
Capacitor (C)	60 μF
Load (R)	55 Ω
Filter capacitors (C_{f1}/C_{f2})	5 μF
Filter inductor (L_f)	1.2 mH

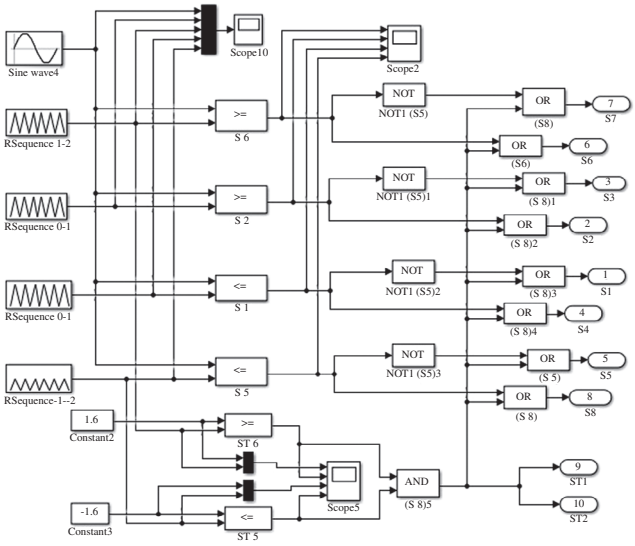

Fig 7. The circuit of PD multicarrier modulation

2.4. Multicarrier PWM PWM is the most generally used control approach for all inverters, and the most commonly used is the sinusoidal PWM where a reference (modulating) wave, generally sinusoidal is compared with a carrier (triangular). For a multilevel inverter, a set of carriers are computed with the modulating signal to obtain the respective pulses for the inverter switches [9,12,13] known as multicarrier PWM. There are three types of multicarrier based on level-shifts used in inverters: (i) Phase disposition (all carriers are identical) (Fig. 5(a)), (ii) A-phase disposition (each carrier displaced by 180°) (Fig. 5(b)), and phase opposition disposition (the above and below the zero lines are displaced by 180°) (Fig. 5(c)) [13].

For simplicity, a PD multicarrier modulation is considered in this work, all the carrier signals are identical triangular waveforms as discussed. The shoot-through signal is obtained by comparing a straight-line index (V_{st}) with a single carrier (V_{car}); the index is chosen based on the D_S requirement that can be equated for this work as [10].

$$V_{st} = V_{car}\ (1 - D_s) \tag{12}$$

3. Simulation of the Topology

Based on the above information, simulation of the multilevel embedded type switched boost inverter is carried out in this section. The simulation parameters are based upon the literature of the base topology, the inverter is designed to get an output power around 1 kW (Fig. 6). The modulation index of the inverter is taken to be 0.7. The parameters are mentioned in Table I.

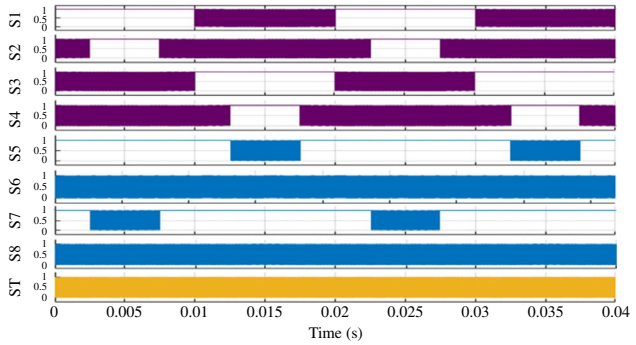

Fig 8. The pulse waveform (inverter switches and ST switches) for the MLI e-SBI

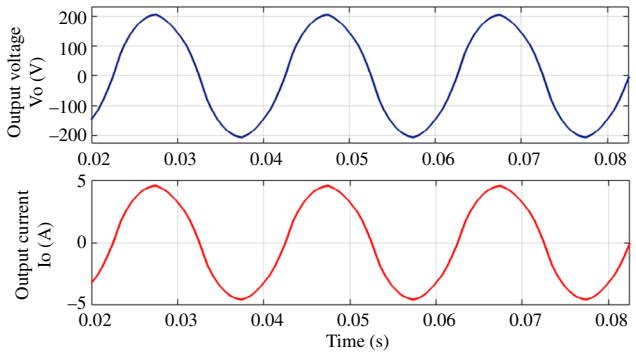

Fig 9. The output waveform of the MLI e-SBI

Since the output of the inverter may have unwanted frequency waves, a pie (CLC) filter is employed across the load to provide an almost sinusoidal output suitable for applications. The filter was designed to keep the THD within a low range, thereby providing a better output.

The PD multicarrier modulation circuit is designed to obtain D_s of 0.2 which was considered a feasible value based on the literature (Fig. 7). The resulting pulse form is given in Fig. 8.

The output waveform of the topology is presented in Fig. 9, where we can see that the obtained output verifies with the theoretical calculation derived before. The harmonic analysis of the output is displayed in Fig. 10 showing an acceptable value of THD for the inverter.

4. Result

Conventional power inverters produce an output (voltage) that majorly switches between two/three levels only, whereas MLI generates several levels of output from different dc input levels for the PV-grid interface. A cascaded H-bridge type MLI provides levels double that of its source with easy control compared to other types. This work concentrates on achieving a cascaded multilevel inverter by replacing the generic H-bridge with a high gain inverter to produce higher output.

Topological changes were made to the existing switched boost inverter (SBI) to overcome these limitations leading to embedded type switched boost inverter (e-SBI) which is cascaded to produce a multilevel inverter. The characteristic parameters were derived

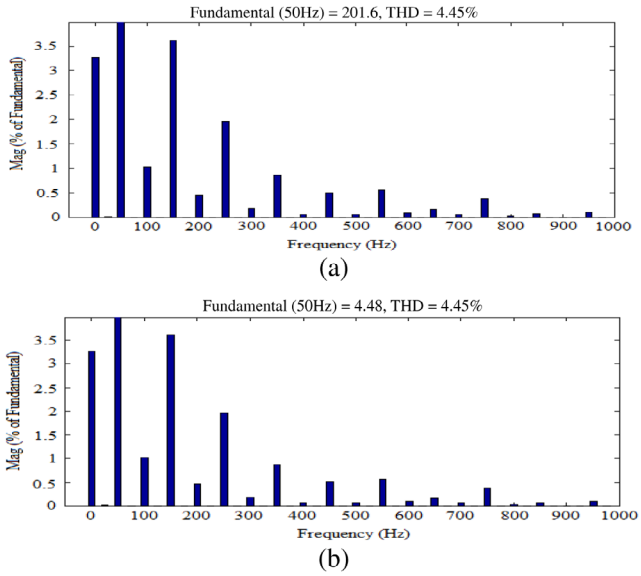

Fig 10. THD analysis of output values. (a) FFT analysis of voltage; (b) FFT analysis of current

and studied, based on which a simple simulation was carried out to verify the above facts. A PD multicarrier modulation was carried out to provide the gate pulses for the inverter and the output was obtained. Further study on this topology along with the hardware implementation will be carried out in future works.

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