Comparison of Performances of Switched DC Sources Inverter and Cascaded H-bridge Inverter

Mithun Kuriakose, Anooja V S

Abstract—Quality of output voltage waveform of a multilevel inverter indicates how much close the waveform to the required sine wave. The quality of output voltage waveform improves as the number of levels increases. But, as the number of levels increases the number of components required also increases. Switched DC sources inverter is a multilevel inverter based on switched DC sources which considerably reduces the number of components required especially for output voltage having large number of levels. Switched DC sources inverter consists of DC sources such that opposite polarities of preceding source is connected to succeeding source through power switches. Cascaded H-bridge inverter is a multilevel inverter based on cascading of H-bridges. The working principle of single phase five level switched DC sources inverter and single phase five level cascaded H-bridge inverter are explained. Performances of single phase five level switched DC sources inverter and single phase five level cascaded H-bridge inverter are compared on the basis of number of switches used, voltage across switches, efficiency, total harmonic distortion (THD) of output voltage waveform and complexity of gate drive circuit. Single phase five level switched DC sources inverter and single phase five level cascaded H-bridge inverter are simulated using MATLAB/Simulink tool. Performances of single phase five level switched DC sources inverter is compared with that of single phase five level cascaded H-bridge inverter on the basis of voltage across switches, efficiency, total harmonic distortion (THD) of output voltage waveform using MATLAB/Simulink tool. Prototypes of both single phase five level switched DC sources inverter and single phase five level cascaded H-bridge inverter are developed in the laboratory with two input DC voltage sources of 12V each and performances of both types of inverters are found out.

Index Terms—Classical topologies, multilevel inverter (MLI), reduced component count, total harmonic distortion (THD).

I. INTRODUCTION

A multilevel inverter (MLI) consists of a linkage structure of multiple input DC sources and/or capacitors and power semiconductor devices to produce a staircase waveform[1]. In the last few decades, multilevel voltage-source inverters have become a satisfactory solution for high-power dc-to-ac conversion applications[2]. Quality of output voltage waveform of an MLI indicates how much close in shape the waveform to the required sine wave. Quality of output voltage waveform of a MLI can be improved by increasing the number of levels. However, it results in a large number of power semiconductor devices and gate driver circuits. Therefore, system complexity and cost will be increased. Also, system reliability and efficiency will be reduced. Therefore, for multilevel inverters having higher number of levels in output voltage waveform, practical considerations necessitate reduction in the number of switches and gate driver circuits[3].

Neutral point clamped (NPC), cascaded H-bridge (CHB) and flying capacitor (FC) converters are the classical topologies which are commercially available and have been studied commonly[2]-[5]. However, as the number of levels in the output voltage increases, the number of power switches and number power semiconductor devices conducting simultaneously increases significantly in these topologies. Therefore, as number of output levels increases overall cost of the system increases. Therefore, researches have been conducting to reduce the component count in MLI topologies. These researches are classified into three: change in topology[6]-[10], use of asymmetric sources[11],[12] and combination of change in topology and asymmetric source configurations[13],[14]. Switched DC sources inverter is novel multilevel inverter based on switched DC sources which reduces number of power semiconductor switches required considerably particularly for output voltage waveforms having large number of levels[1].

For multilevel inverters (MLIs) voltage stress across switches are lower than overall operating voltage level[15]. The quality of multilevel inverter output voltage waveform increases as number of level increases as compared to two level output voltage waveform of produced by conventional inverters. Modular MLIs such as cascaded H-bridge (CHB) possess fault tolerant operation capability[4]. As the number of levels in output voltage increases, output harmonic content decreases. Therefore, small and less expensive output filters can be used[16].

As quality of output voltage waveform is increased by increasing number of voltage levels, number of components required increases. Therefore, as number of switches required increases, the number of accompanying gate driver circuit increases. This results in increased system complexity and cost. Therefore, reliability and efficiency of the system decreases.

MLI topologies such as CHB and switched DC sources...
inverter can be used in renewable energy systems as a utility interface for renewable energy system where a large number of isolated DC sources are available [15],[7]. The switched DC sources inverter may also be suitable for applications using battery such as electric vehicles, submarine propulsion etc. [1].

The objective is to compare performances of single phase five level switched DC sources inverter with single phase five level cascaded H-bridge inverter. Performances of single phase five level switched DC sources inverter and single phase five level cascaded H-bridge inverter are compared on the basis of number of switches used, voltage across switches, efficiency, total harmonic distortion (THD) of output voltage waveform and complexity of gate driver circuit. Voltage across switches, efficiency and total harmonic distortion (THD) are compared using MATLAB/Simulink tool. Also, to develop laboratory prototypes of single phase five level switched DC sources inverter and single phase five level cascaded H-bridge inverter to obtain the output voltage waveforms and compare their gate drive circuit.

This paper is organized as follows. Section II presents the generalized structures of the switched DC sources inverter and cascaded H-Bridge inverter. The working principles of these topologies are also described in this section with the help of a single phase five level inverter. Simulation and hardware implementation of single phase five level switched DC sources inverter and single phase five level cascaded H-Bridge inverter are discussed in Section III. Conclusions are summarized in Section IV.

II. MULTILEVEL INVERTER TOPOLOGIES

In this section, the generalized structures of the switched DC sources inverter and cascaded H-bridge topologies are introduced, and their working principles are explained with the help of a single phase five level inverter.

A. Generalized Structure

1) Switched DC Sources Inverter: The generalized single phase structure of switched DC sources inverter is shown in Fig. 1. There are \( n \) numbers of isolated input DC sources. Lower potential terminal of the preceding DC source is connected to the higher potential terminal of the succeeding DC source and vice versa through power switches. Input DC sources are designated as \( E_j \) (where \( j = 1 \) to \( n \)). Power switches can be implemented using a transistor device having an antiparallel diode such as metal oxide semiconductor field effect transistor (MOSFET), insulated-gate bipolar transistor (IGBT) etc. Here N-Channel MOSFET is used. There are \( n+1 \) complementary pairs of power switches. They are designated as \( (T_j, T_j') \) (where \( j = 1 \) to \( n + 1 \)). The output voltage across load and load current are designated as \( v_o(t) \) and \( i_o(t) \) respectively.

![Fig. 1: Generalized single phase structure of switched DC sources inverter.](image)

2) Cascaded H-bridge Inverter: The generalized single phase structure of cascaded H-bridge inverter is shown in Fig. 2. There are \( n \) numbers of isolated input DC sources.

![Fig. 2: Generalized single phase structure of cascaded H-bridge inverter.](image)
H-bridge is shown in figure 3. Input DC source is designated as \(E_i\). There are four power switches \(S_1, S_2, S_3\) and \(S_4\). Power switches of CHB inverter can be implemented using a transistor device having an antiparallel diode such as metal oxide semiconductor field effect transistor (MOSFET), insulated-gate bipolar transistor (IGBT) etc. Here N-Channel MOSFET is used. Number of power switches required for single phase CHB inverter is \(4n\). The output voltage across load of single phase CHB inverter is designated as \(v_o(t)\).

![Fig. 3: Internal structure of H-bridge.](image)

**B. Working Principle**

1) Single Phase Five Level Switched DC Sources Inverter: In this paper, a single phase five level switched DC sources inverter is used. This is shown in Fig. 4. There are two isolated input DC sources \(E_1\) and \(E_2\) \((E_1 = E_2)\). There are three complementary pairs of power switches (N-Channel MOSFETs) which are designated as \((T_1, T_1')\), \((T_2, T_2')\) and \((T_3, T_3')\). The output voltage across load and load current are designated as \(v_o(t)\) and \(i_o(t)\) respectively. The reference polarities of the output voltage \(v_o(t)\) and reference direction of load current \(i_o(t)\) are shown. The output voltage waveform of a single phase five level switched DC sources inverter when \(E_1 = E_2\) is shown in Fig. 5. The output voltage waveform consists of five levels 0, \(E_1\) or \(E_2\), \(E_1 + E_2\), \(-E_1\) or \(-E_2\), \(-E_1 - E_2\). Time period of output voltage is \(2T\).

![Fig. 4: Single phase five level switched DC sources inverter.](image)

![Fig. 5: Output voltage waveform of single phase five level switched DC sources inverter.](image)

There are eight modes of operations for single phase five level cascaded H-bridge inverter and are shown in Fig. 6. Modes of operation are explained below:

Mode 1: In mode 1 operation of single phase five level switched DC sources inverter, switches \(T_1\), \(T_2\) and \(T_3\) are turned on. No source is connected to the load. Output voltage across load is zero.

Mode 2: In mode 2 operation of single phase five level switched DC sources inverter, switches \(T_1\), \(T_2\) and \(T_3\) are turned on. No source is connected to the load. Output voltage across load is zero.

Mode 3: In mode 3 operation of single phase five level switched DC sources inverter, switches \(T_1\), \(T_2\) and \(T_3\) are turned on. Output voltage across load is \(+E_1\).

Mode 4: In mode 4 operation of single phase five level switched DC sources inverter, switches \(T_1\), \(T_2\) and \(T_3\) are turned on. Output voltage across load is \(+E_2\).

Mode 5: In mode 5 operation of single phase five level switched DC sources inverter, switches \(T_1\), \(T_2\) and \(T_3\) are turned on. Output voltage across load is \(+E_1 + E_2\).

Mode 6: In mode 6 operation of single phase five level switched DC sources inverter, switches \(T_1\), \(T_2\) and \(T_3\) are turned on. Output voltage across load is \(-E_1\).

Mode 7: In mode 7 operation of single phase five level switched DC sources inverter, switches \(T_1\), \(T_2\) and \(T_3\) are turned on. Output voltage across load is \(-E_2\).

Mode 8: In mode 8 operation of single phase five level switched DC sources inverter, switches \(T_1\), \(T_2\) and \(T_3\) are turned on. Output voltage across load is \(-E_1 - E_2\).
Fig. 6: Modes of operation of single phase five level switched DC sources inverter.
The modes of operation of single phase five level switched DC sources inverter is summarized in Table I.

**TABLE I: MODES OF OPERATION OF SINGLE PHASE FIVE LEVEL SWITCHED DC SOURCES INVERTER.**

<table>
<thead>
<tr>
<th>Mode</th>
<th>( T_1 )</th>
<th>( T_2 )</th>
<th>( T_3 )</th>
<th>( T_1' )</th>
<th>( T_2' )</th>
<th>( v_o(t)(V) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>( E_1 )</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>( E_2 )</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>( E_1 + E_2 )</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>(-E_1)</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>(-E_2)</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>(-E_1-E_2)</td>
</tr>
</tbody>
</table>

2) **Single Phase Five Level Cascaded H-bridge Inverter:** In this paper, a single phase five level cascaded H-bridge inverter is used. This is shown in Fig. 7. There are two isolated input DC sources \( E_1 \) and \( E_2 \). There are eight power switches (N-Channel MOSFETs) which are designated as \( S_1, S_2, S_3, S_4, S_5, S_6, S_7 \) and \( S_8 \). \( v_o(t) \), \( v_o'(t) \) and \( v_o(t) \) designates output voltages of H-bridge 1, H-bridge 2 and single phase five level cascaded H-bridge inverter respectively. Load current is designated as \( i_o(t) \).

![Fig. 7: Single phase five level cascaded H-bridge inverter.](image-url)

The reference polarities of the output voltage \( v_o(t) \) and reference direction of load current \( i_o(t) \) are shown. The output voltage waveform of a single phase five level cascaded H-bridge inverter is shown in Fig. 8 and detailed output voltage waveform of a single phase five level cascaded H-bridge inverter is shown in Fig. 9. The output voltage waveform consists of five levels \( 0, E_2, E_1 + E_2, -E_2, -E_1 - E_2 \). Time period of output voltage is \( 2T \).

There are six modes of operations for single phase five level cascaded H-bridge inverter and are shown in Fig. 10. The reference polarities of the output voltage \( v_o(t) \) and reference direction of output current \( i_o(t) \) are shown for different modes of operation. Modes of operation are explained below:

**Mode 1:** In mode 1 operation of single phase five level cascaded H-bridge inverter, switches \( S_3, S_4, S_1 \) and \( S_7 \) are turned on. No source is connected to the load. Output voltage across load is zero.

**Mode 2:** In mode 2 operation of single phase five level cascaded H-bridge inverter, switches \( S_5, S_6, S_3 \) and \( S_8 \) are turned on. No source is connected to the load. Output voltage across load is zero.

**Mode 3:** In mode 3 operation of single phase five level cascaded H-bridge inverter, switches \( S_1, S_6, S_3 \) and \( S_8 \) are turned on. Output voltage across load is \( E_2 \).

**Mode 4:** In mode 4 operation of single phase five level cascaded H-bridge inverter, switches \( S_5, S_7, S_3 \) and \( S_8 \) are turned on. Output voltage across load is \( E_1 + E_2 \).

**Mode 5:** In mode 5 operation of single phase five level cascaded H-bridge inverter, switches \( S_2, S_6, S_3 \) and \( S_8 \) are...
turned on. Output voltage across load is $E_2$.

Mode 6: In mode 6 operation of single phase five level cascaded H-bridge inverter, switches $S_3$, $S_2$, $S_7$ and $S_6$ are turned on. Output voltage across load is $-E_1-E_2$.

The modes of operation of single phase five level cascaded H-bridge inverter are summarized in Table II.

![Fig. 10: Modes of operation of single phase five level cascaded H-bridge inverter.](image)

**TABLE II: MODES OF OPERATION OF SINGLE PHASE FIVE LEVEL CASCADED H-BRIDGE INVERTER.**

<table>
<thead>
<tr>
<th>Mode</th>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$S_3$</th>
<th>$S_4$</th>
<th>$S_5$</th>
<th>$S_7$</th>
<th>$S_8$</th>
<th>$v_o(t)$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>$E_2$</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>$E_1 + E_2$</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>$-E_2$</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>$-E_1 - E_2$</td>
</tr>
</tbody>
</table>

III. SIMULATION AND HARDWARE IMPLEMENTATION

This section discusses about simulation and hardware implementation of single phase five level switched DC sources inverter and single phase five level cascaded H-bridge inverter. A single phase five level switched DC sources inverter and a single phase five level cascaded H-bridge inverter are simulated using MATLAB/Simulink tool. Two input DC sources $E_1=12V$ and $E_2=12V$ are used for simulation. Simulation is conducted with $R$ and $RL$ loads. Hardware implementation and results of single phase five level switched DC sources inverter and single phase five level cascaded H-bridge inverter are discussed in this section.

A. Single Phase Five Level Switched DC Sources Inverter:

This section is divided into two: 1) Simulation and Results and 2) Hardware Implementation and Results. First section discusses about simulation of single phase five level switched
TABLE III: SWITCHING SEQUENCE FOR MATLAB SIMULATION OF SINGLE PHASE FIVE LEVEL SWITCHED DC SOURCES INVERTER.

<table>
<thead>
<tr>
<th>Mode</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T1'</th>
<th>T2'</th>
<th>T3'</th>
<th>Output Voltage(V)</th>
<th>time duration(ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>E1</td>
<td>2.5</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>E1 + E2</td>
<td>2.5</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>E2</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.5</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>-E1</td>
<td>2.5</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>-E1 - E2</td>
<td>2.5</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>-E2</td>
<td>2.5</td>
</tr>
</tbody>
</table>

DC sources inverter. The second section discuss about hardware implementation and its results of single phase five level switched DC sources inverter.

1) Simulation and Results: Simulation of single phase five level switched DC sources inverter with R and RL loads using MATLAB/Simulink tool are discussed in this section. The switching sequence for MATLAB simulation is given in Table III. ON state of a switch is represented by ‘1’ and OFF state of a switch by ‘0’.

1.1) R Load: This section discuss about MATLAB simulation of single phase five level switched DC sources inverter with R load. Efficiency of single phase five level switched DC sources inverter with R load is calculated from MATLAB simulation. Also, voltage across switches are obtained from MATLAB simulation of single phase five level switched DC sources inverter with R load.

Fig. 11: MATLAB simulation diagram for single phase five level switched DC sources inverter with R load.

Fig. 12: Load voltage versus time plot of single phase five level switched DC sources inverter with R load.

MATLAB simulation diagram for single phase five levels switched DC sources inverter with R load is shown in Fig. 11. Here input DC source voltages are of 12V and load is resistance of 10Ω. The load voltage versus time is shown in Fig. 12 has five levels. THD of load voltage is 28.72%. The load current versus time is shown in Fig. 13.

1.1.1) Efficiency Calculation: Voltage provided by source 1 to the inverter circuit ($e_s(i)$) versus time during half cycle time period $T=10ms$ is shown in Fig. 14. This half cycle is repeated.

Fig. 13: Load current versus time plot for single phase five level switched DC sources inverter with R load.

Fig. 14: Voltage provided by source 1 to the switched DC sources inverter circuit ($e_s(i)$) versus time during half cycle time period $T=10ms$.

R.M.S value of voltage provided by source 1 to the inverter circuit, $E_{isi}$ is calculated from Fig. 14 as:

$$E_{si} = \sqrt{\frac{12^2 \times 4T}{8}} = 8.48V$$

R.M.S value of current delivered by source 1 to the inverter circuit, $I_{si}=1.30A$ (measured using current measurement block in MATLAB).

Power delivered by source $i$, $P_{si} = E_{si} \times I_{si}$ (1)

Where $E_{si}$=R.M.S value of voltage provided by source $i$ to the inverter circuit

$I_{si}$=R.M.S value of current provided by source $i$ to the inverter circuit

Using (1),

Power delivered by source 1,

$$P_{s1} = E_{s1} \times I_{s1} = 8.48 \times 1.30 = 11.02W$$
Voltage provided by source 2 to the inverter circuit \( (e_s(t)) \) versus time during half cycle time period \( T = 10\text{ms} \) is shown in Fig. 15. This half cycle is repeated.

Fig. 15: Voltage provided by source 2 to the switched DC sources inverter circuit \( (e_s(t)) \) versus time during half cycle time period \( T = 10\text{ms} \).

R.M.S value of voltage provided by source 2 to the inverter circuit \( E_{s2} \) is calculated from Fig. 15 as:

\[
E_{s2} = \sqrt{\frac{12^2 \times 4T}{8T}} = 8.48V
\]

R.M.S value of current delivered by source 2 to the inverter circuit \( I_{s2} \) is measured using current measurement block in MATLAB.

Using (1),

\[
P_{s2} = E_{s2} \times I_{s2} = 8.48 \times 1.30 = 11.02W
\]

Total power delivered by the sources,

\[
P_s = P_{s1} + P_{s2} = 11.02 + 11.02 = 22.04W
\]

Power consumed by the load, \( P_o = V_o \times I_o \) (2)

where \( V_o = \) R.M.S value of output voltage (measured using voltage measurement block in MATLAB)

where \( I_o = \) R.M.S value of output current (measured using current measurement block in MATLAB)

R.M.S value of output voltage (measured using voltage measurement block in MATLAB), \( V_o = 14.31V \)

R.M.S value of output current (measured using current measurement block in MATLAB), \( I_o = 1.43A \)

Using (2),

\[
P_o = V_o \times I_o = 14.31 \times 1.43 = 20.46W
\]

Efficiency of the MLI is given by,

\[
\eta_{MLI} = \frac{\text{Power consumed by the load}}{\text{Total power delivered by the sources}} \times 100\%
\]

(3)

Using (3),

\[
\eta_{SDI} = \frac{\text{Power consumed by the load}}{\text{Total power delivered by the sources}} \times 100\%
\]

\[
= \frac{20.46}{22.04} \times 100\% = 92.83\%
\]

where \( \eta_{SDI} = \) Efficiency of single phase five level switched DC sources inverter.

1.1.2 Voltage Across Switches: Voltage across switches (expressed as % of input DC source voltage) versus time for single phase five level switched DC sources inverter are shown in figures Fig. 16 to Fig. 21.

Fig. 16: Voltage across switch \( T_1 \) of single phase five level switched DC sources inverter.

Fig. 17: Voltage across switch \( T_2 \) of single phase five level switched DC sources inverter.

Fig. 18: Voltage across switch \( T_3 \) of single phase five level switched DC sources inverter.

Fig. 19: Voltage across switch \( T_3' \) of single phase five level switched DC sources inverter.

Fig. 20: Voltage across switch \( T_2' \) of single phase five level switched DC sources inverter.

Fig. 21: Voltage across switch \( T_1' \) of single phase five level switched DC sources inverter.

Maximum voltage across switches \( T_j, T_j', T_i \) and \( T_i' \) is 100% of input DC source voltage. Maximum voltage across switches \( T_j \) and \( T_j' \) is 200% of input DC source voltage.
1.2) \( RL \) Load: MATLAB simulation diagram for single phase five level switched DC sources inverter with \( RL \) load is shown in Fig. 22. Here input DC source voltages are of 12V and load is \( R=10\Omega \) and \( L=20\text{mH} \). The load voltage versus time is shown in Fig. 23. THD of load voltage is 29.59%. The load current versus time is shown in Fig. 24.

2) Hardware Implementation and Results: This section discuss about hardware implementation and its results of single phase five level switched DC sources inverter. The schematic diagram of hardware set up for single phase five level switched DC sources inverter is shown in Fig. 25. Input DC sources are \( E_1=12V \) and \( E_2=12V \). Hardware implementation of single phase five level switched DC sources inverter involves implementing control circuit, drive circuit and power circuit. PIC18F4550 is used as the controller. TLP250 is used as drive IC. TLP250 converts logic signals generated in PIC18F4550 into power signals. Also, TLP250 is a photocoupler and it isolates power circuit from control circuit. Six TLP250s (one TLP250 for each switch) are required in the drive circuit. Power switches used are MOSFET IRF830. A prototype of single phase five level switched DC sources inverter is developed in the laboratory with two isolated input DC voltage sources \( E_1=12V \) and \( E_2=12V \). Load used is \( RL \) load. Laboratory prototype of single phase five level switched DC sources inverter is shown in Fig. 26.
TABLE IV: SWITCHING SEQUENCE FOR MATLAB SIMULATION OF SINGLE PHASE FIVE LEVEL CASCADED H-BRIDGE INVERTER.

<table>
<thead>
<tr>
<th>Mode</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
<th>Output Voltage(V)</th>
<th>time duration(ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>E2</td>
<td>2.5</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>E1+E2</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>E2</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.5</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>-E2</td>
<td>2.5</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>-E1-E2</td>
<td>2.5</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>-E2</td>
<td>2.5</td>
</tr>
</tbody>
</table>

B) Single Phase Five Level Cascaded H-Bridge Inverter:

This section is divided into two: 1) Simulation and Results and 2) Hardware Implementation and Results. First section discuss about simulation of single phase five level cascaded H-bridge inverter. The second section discuss about hardware implementation and its results of single phase five level cascaded H-bridge inverter.

1) Simulation and Results: Simulation of Single phase five level cascaded H-bridge with R and RL loads using MATLAB/Simulink tool are discussed in this section. The switching sequence for MATLAB simulation is shown in Table IV. ON state of a switch is represented by ‘1’ and OFF state of a switch by ‘0’.

1.1) RLoad: This section discuss about MATLAB simulation of single phase five level cascaded H-bridge inverter with R load. Efficiency of single phase five level cascaded H-bridge inverter with R load is calculated from MATLAB simulation. Also, voltages across switches are obtained from MATLAB simulation of single phase five level cascaded H-bridge inverter with R load. MATLAB simulation diagram for single phase five level cascaded H-bridge inverter with R load is shown in Fig. 28.

![Fig. 28: MATLAB simulation diagram for single phase five level cascaded H-bridge inverter with Rload.](image)

Fig. 28: MATLAB simulation diagram for single phase five level cascaded H-bridge inverter with R load.

Fig. 29: Load voltage versus time plot for single phase five level cascaded H-bridge inverter with R load.

![Fig. 29: Load voltage versus time plot for single phase five level cascaded H-bridge inverter with R load.](image)

Here input DC source voltages are of 12V and load is resistance of 10Ω. The load voltage versus time is shown in Fig. 29 has five levels. THD of load voltage is 28.72%. The load current versus time is shown in Fig. 30.

![Fig. 30: Load current versus time plot for single phase five level cascaded H-bridge inverter with R load.](image)

1.1.1) Efficiency Calculation: Voltage provided by source 1 to the inverter circuit(e_s1(t)) versus time during half cycle time period T = 10ms is shown in Fig. 31. This half cycle is repeated.

R.M.S value of voltage provided by source 1 to the inverter circuit(E_s1) is calculated from Fig. 31 as:

![Fig. 31: Voltage provided by source 1 to the CHB inverter circuit(e_s1(t)) versus time during half cycle time period T = 10ms.](image)

\[ E_{s1} = \sqrt{\frac{12^2}{T}} \times \frac{2T}{8} = 6V \]

R.M.S value of current delivered by source 1 to the inverter circuit, I_s1 = 1.15A (measured using current measurement block in MATLAB).

Similar to switched DC sources inverter, using (1)

\[ P_{s1} = E_{s1} \times I_{s1} \times 6 \times 1.15 = 6.9W \]

Voltage provided by source 2 to the inverter circuit(e_s2(t)) versus time during half cycle time period T = 10ms is shown in Fig. 32. This half cycle is repeated.
R.M.S value of voltage provided by source 2 to the inverter circuit \( E_{s2} \) is calculated from Fig. 32 as:

\[
E_{s2} = \sqrt{\frac{12^2 \times 6T}{8}} = 10.39V
\]

R.M.S value of current delivered by source 2 to the inverter circuit, \( I_{s2} = 1.42A \) (measured using current measurement block in MATLAB).

Similar to switched DC sources inverter, using (1)

Power delivered by source 2,

\[
P_{s2} = E_{s2} \times I_{s2} = 10.39 \times 1.42 = 14.75W
\]

Total power delivered by the sources,

\[
P_s = P_{s1} + P_{s2} = 6.9 + 14.75 = 21.65W
\]

R.M.S value of output voltage (measured voltage measurement block in MATLAB), \( V_o = 14.17V \)

R.M.S value of output current (measured current measurement block in MATLAB), \( I_o = 1.42A \)

Similar to switched DC sources inverter, using (2)

Power consumed by the load,

\[
P_o = V_o \times I_o = 14.17 \times 1.42 = 20.12W
\]

Similar to switched DC sources inverter, using (3)

\[
\eta_{CHB} = \frac{\text{Power consumed by the load}}{\text{Total power delivered by the sources}} \times 100\% = 20.12 \times 100\% = 92.93\%
\]

where \( \eta_{CHB} \) is Efficiency of single phase five level cascaded H-bridge inverter.

1.1.2) Voltage across switches: Voltage across switches (expressed as % of input DC source voltage) versus time are shown in figures Fig. 33 to Fig. 40.
Maximum voltage stress across any switch in a single phase five level cascaded H-bridge inverter is 100% of input DC source voltage.

1.2) **RL Load:** MATLAB simulation diagram for single phase five level cascaded H-bridge inverter with RL load is shown in Fig. 41. Here input DC source voltages are of 12V and load is \( R=10\,\Omega \) and \( L=20\,\text{mH} \). The load voltage versus time is shown in Fig. 42. THD of load voltage is 29.34%. The load current versus time is shown in Fig. 43.

![Fig. 41: MATLAB simulation diagram for single phase five level cascaded H-bridge inverter with RL load.](image)

![Fig. 42: Load voltage versus time plot for single phase five level cascaded H-bridge inverter with RL load.](image)

![Fig. 43: Load current versus time plot for single phase five level cascaded H-bridge inverter with RL load.](image)

2) **Hardware Implementation and Results:** The schematic diagram of hardware set up for single phase five level cascaded H-bridge inverter is shown in Fig. 44. Input DC sources are \( E_1=12\,\text{V} \) and \( E_2=12\,\text{V} \). Hardware implementation of single phase five level cascaded H-bridge inverter involves implementing control circuit, drive circuit and power circuit. PIC18F4550 is used as the controller. FAN7392 is used as drive IC. TLP250 is used to isolate second input DC source \( E_2 \) from first source \( E_1 \). Each FAN7392 drives two switches of one arm of a bridge. Four FAN7392s and four TLP250s are required in the drive circuit. Power switches used are MOSFET IRF830. A prototype of single phase five level cascaded H-bridge inverter is developed in the laboratory with two isolated input DC voltage sources \( E_1=12\,\text{V} \) and \( E_2=12\,\text{V} \). Load used is \( R \) load. Laboratory prototype of single phase five level cascaded H-bridge inverter is shown in Fig. 45. Output voltage waveform obtained using DSO is shown in Fig. 46.

![Fig. 44: Schematic diagram of hardware for single phase five level cascaded H-bridge inverter.](image)

![Fig. 45: Laboratory prototype of single phase five level cascaded H-bridge inverter.](image)
TABLE V: COMPARISON OF SINGLE PHASE FIVE LEVEL SWITCHED DC SOURCES INVERTER AND SINGLE PHASE FIVE LEVEL CASCADED H-BRIDGE INVERTER.

<table>
<thead>
<tr>
<th>Sl.no.</th>
<th>Parameter</th>
<th>Single phase five level CHB inverter</th>
<th>Single phase five level switched DC sources inverter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Switches</td>
<td>$2 \times (N-1) = 2 \times (5-1) = 8.$</td>
<td>$N + 1 = 5 + 1 = 6.$</td>
</tr>
<tr>
<td>2</td>
<td>Maximum voltage stress across switches (from simulation).</td>
<td>For all switches, input DC sources voltage=12V.</td>
<td>For four switches, input DC source voltage=12V and for other two switches, $2 \times$ (input DC source voltage) $= 2 \times (12) = 24V.$</td>
</tr>
<tr>
<td>3</td>
<td>THD of load voltage with $R$ load (from simulation).</td>
<td>28.72%</td>
<td>28.72%</td>
</tr>
<tr>
<td>4</td>
<td>THD of load voltage with $RL$ load (from simulation).</td>
<td>29.34%</td>
<td>29.59%</td>
</tr>
<tr>
<td>5</td>
<td>Efficiency($\eta$) with $R$ load (from simulation).</td>
<td>$\eta_{CHB} = 92.93%$</td>
<td>$\eta_{SDI} = 92.83%$</td>
</tr>
<tr>
<td>6</td>
<td>Drive circuit</td>
<td>Drive circuit consists of four FAN 7392 and four TLP 250.</td>
<td>Drive circuit consists of six TLP 250.</td>
</tr>
</tbody>
</table>

Fig. 46: Output voltage waveform obtained using DSO for single phase five level cascaded H-bridge inverter.

IV. CONCLUSION

The conclusions of this work are summarized below:

1) Single phase five level switched DC sources and single phase five level cascaded H-bridge inverters with $R$ load and $RL$ load are simulated using MATLAB/Simulink tool.

2) Performances of single phase five level switched DC sources inverter is compared with that of single phase five level cascaded H-bridge inverter on the basis of voltage across switches, efficiency, total harmonic distortion (THD) of output voltage waveform using MATLAB/Simulink tool.

3) Hardwares of single phase five level switched DC sources inverter and single phase five level cascaded H-bridge inverter with two input DC sources $E_1=12V$ and $E_2=12V$ are fabricated and implemented and output voltage waveforms are obtained using DSO.

4) Gate drive circuits of single phase five level switched DC sources inverter and single phase five level cascaded H-bridge inverter are compared through hardware implementation.

Comparison of the performances of single phase five level switched DC sources inverter and single phase five level cascaded H-bridge inverter are summarized in Table V. ‘$N$’ in Table V indicates number of levels in output voltage waveform of MLI.

REFERENCES


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