Reduced switch z-source multilevel inverter using constant boost control methods for renewable energy sources

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Abstract. This paper presents single phase seven level Reduced Switch Z-Source Multi-level Inverter (RSZSMLI) for Renewable Energy Sources (RES). The performance of RSZSMLI topology is analysed using Constant Boost Control (CBC) methods based on sine reference and third-harmonic reference Phase Shift Modulation (PSM) techniques. RSZSMLI will have three DC sources, three Z-source networks, ten power switches and ten main diodes. In the suggested RSZSMLI topology, the output voltage is not limited to summation of DC input voltages compared to traditional Multilevel Inverters (MLIs). The output voltage can be amplified with shoot-through ratio (K) of Z-source network. Hence, additional DC to DC converter is not required and the topology is more immune to short circuit. The RSZSMLIs analysed using two CBC methods with variable shoot-through ratio (K) to gain additional boost capability. The performance of the RSZSMLI topology is validated with simulation results using MATLAB/SIMULINK.

1. Introduction

A Multi-level Inverter (MLI) is a type of converter system used in power electronics to produces the preferred output voltage from input of several DC voltage levels. MLI power conversion technology has rapidly progressed with strong potential for future use [1]. The conventional Multi-Level Inverters has two or three stages of conversion. The first step is to amplify the input DC voltage to the required voltage level using DC – DC converter and second step is to feed the boosted DC voltage to the inverter to convert input DC from RES to AC of required voltage [2]. Due to the varying output voltage of Renewable Energy Sources (RES), a DC-DC boost converter between the inverter and the RES must be integrated to achieve constant DC-link voltage as shown in Figure 1. This is also called a two-stage power transducer. An extra dc – dc converter, however, makes the whole system complex, voluminous, high-cost and less efficient.

Multi-level Inverters has advantage over standard two level and three level inverter because of less cost, complexity, EMI, voltage tension and switching losses [3-6]. The most widely used topologies for MLI are flying capacitors, clamped diodes and cascaded H-bridge inverters. Amidst this topology H-bridge topology has less number of components to generate same output [7].
To overcome the drawbacks associated with two stage and three stage converts, a single stage converter topologies have been proposed as depicted in Figure 2. The Z-source inverter is replaced in place of conventional two stage and three stage inverters to eliminate the use of DC-DC converter. The Z-Source inverters are also called as impedance source inverters since impedance is indicated using alphabet Z. These inverter allows use of Z impedance network between the DC source and the inverter circuit to improve the performance. The Z-source inverters were first introduced by Fang Zheng Peg in 2002 [8]. In ZSI, there are pair of inductors and capacitors in the impedance network arranged in X-shape which integrates the main circuit with the DC supply. The basic Z-source network acts as an inverter which boosts and converts the input DC voltage into AC. Hence, multilevel inverters based on Z-source inverters are gaining prominence in recent days as they have good boosting ability, high reliability, low cost, less complexity, compact in size, high efficient and provides output waveforms which are near sinusoidal. Due to their capacity to handle the wide variations of DC source voltage in single-stage power conversion, Z-source inverters have been extensively studied in renewable energy based systems. [9-14].

In a ZSI both buck and boost for a given input voltage can be achieved [15]. The voltage boost in ZSI is achieved by switching on the power switches on same phase leg and at the same time the input voltage is converted to AC by the H-bridge [16]. The concept of ZSI can be implemented at all type of power conversions such as; AC-DC, DC-AC, AC-AC and DC-DC. Moreover, it can also be used as voltage or current source fed ZSI for multilevel inverter topologies [17]. In spite of all the said advantages, the large number of power switches are required by outstanding MLIs. To overcome all these problems this paper proposes a RSZMLI. The performance of RSZMLI topology is also analysed using CBC methods based on sine reference and third-harmonic reference PSM techniques.

2. Single-phase seven-level RSZMLI topology:

In this section, the switching pattern of a single-phase, seven-level RSZMLI is discussed for the circuit shown in Figure 3. For the selected seven-levels of operation, RSZMLI will have 3 DC sources, 3 Z-source networks (i.e., each Z-source network consists of one diode, two inductors and two capacitors), 10 power switches and 10 main diodes. Proposed RSZMLI topology consists of a
A suitable switching sequence of single-phase RSZSMLI operation was presented in Table 1 along with active/non-shoot-through and shoot-through states.

**Table 1.** Switching sequence of single-phase seven-level RSZSMLI topology

| Switch Sequence | LGU switches | PCU switches | State       | Output voltage levels |
|-----------------|--------------|--------------|-------------|-----------------------|
|                 | S1 | S2 | S3 | S4 | S5 | S6 | P1 | P2 | N1 | N2 |           |                     |
| 1                | 0  | 1  | 0  | 1  | 0  | 1  | 1  | 1  | 0  | 0  | Active    | 3 \(V_{dc}\)       |
| 2                | 0  | 1  | 0  | 1  | 1  | 0  | 1  | 1  | 0  | 0  | Active    | 2 \(V_{dc}\)       |
| 3                | 0  | 1  | 1  | 0  | 1  | 0  | 1  | 1  | 0  | 0  | Active    | 1 \(V_{dc}\)       |
| 4                | 1  | 0  | 1  | 0  | 1  | 0  | 1  | 1  | 0  | 0  | Active    | 0                   |
| 5                | 0  | 1  | 1  | 0  | 1  | 0  | 1  | 1  | 0  | 0  | Active    | -1 \(V_{dc}\)      |
| 6                | 0  | 1  | 0  | 1  | 1  | 0  | 0  | 0  | 1  | 1  | Active    | -2 \(V_{dc}\)      |
| 7                | 0  | 1  | 0  | 1  | 0  | 1  | 0  | 0  | 1  | 1  | Active    | -3 \(V_{dc}\)      |
| 8                | 1  | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 1  | Shoot-through | 0                 |
| 9                | 0  | 0  | 1  | 1  | 0  | 0  | 0  | 0  | 1  | 1  | Shoot-through | 0                 |
| 10               | 0  | 0  | 0  | 0  | 1  | 1  | 0  | 0  | 1  | 1  | Shoot-through | 0                 |
The requirement of number of Z-source networks \((Z_n)\), DC sources \((V_{dcn})\) and power switches \((S_n)\) for \(m\)-level RSZSMLI topology is mentioned in equations (1) and (2) respectively.

\[
Z_n = V_{dcn} = \frac{m-1}{2} \\
S_n = m + 3
\]  

(1) 

(2)

Where, \(m\) = number of levels (in this case, \(m=7\) for seven-level RSZSMLI topology).

Since all the dc voltage sources are equal, maximum output voltage \((V_o)\) of RSZSMLI topology under non-shoot-through condition \((K=0)\) can be calculated using equation (3).

\[
V_o = \sum_{n=1}^{m-1} V_{dcn}
\]  

(3)

The boosted output voltage \((V_o)\) of RSZSMLI topology under shoot-through \((K>0)\) condition can be calculated using equation (4).

\[
V_o = \sum_{n=1}^{m-1} V_{dcn} \frac{1}{1-2K}
\]  

(4)

### 3. CBC methods:

As defined in [21], two modulation control methods, characterized as the CBC method based on sine and third-harmonic reference based PSM methods have been applied to RSZSMLI to extend the boosting capability. The suggested CBC methods requires three triangular carriers (i.e., carrier1, carrier2 and carrier3), one reference signal (i.e., sine or third-harmonic) and one shoot-through control signal to generate the pulses for single-phase seven-level RSZSMLI [21-22].

#### 3.1 CBC method using sine reference based PSM:

In [21], a CBC method was used to control the shoot-through \((K)\) ratio. Figure 4 illustrates the CBC method based on sine reference which employs a straight line greater than or equal to the maximum value of the sine reference to control ‘K’.

![CBC method based on sine reference based PSM](image)

**Figure 4. CBC method based on sine reference based PSM**

The boost factor of RSZSMLI topology using CBC method with sine reference based PSM technique is defined by equation (5).

\[
B = \frac{1}{2M-1}
\]  

(5)

Where, ‘M’ is the modulation and it is defined by the ratio of the peak amplitudes of reference \((A_{ref})\) by carrier \((A_{carrier})\) waveforms.
\[ M = \frac{A_{\text{ref}}}{A_{\text{carrier}}} \quad (6) \]

The shoot-through ratio ‘K’ is obtained by equation (7) for the CBC method with sine reference based PSM technique.
\[ K = 1 - M \quad (7) \]

### 3.2 CBC method using third-harmonic reference based PSM:

Figure 5 illustrates the CBC method based on third-harmonic reference which employs a straight line greater than or equal to the maximum value of the third-harmonic reference to control ‘K’.

The generation of third-harmonic reference wave is obtained by using equation (8).

**Third – harmonic reference,\( V_{\text{ref}} = \frac{2}{\sqrt{3}} \sin(x) + \frac{1}{3\sqrt{3}} \sin(3x) \) \quad (8)**

From equation (8), it is clear that the value of ‘M’ is increased from 1 to 1.154 times when compared to sine reference hence it increases the boost capability.

The boost factor of RSZSMLI topology using CBC method with sine reference based PSM technique is defined by equation (9).
\[ B = \frac{1}{\sqrt{3}M-1} \quad (9) \]

The shoot-through ratio ‘K’ is obtained by equation (10) for the CBC method with third-harmonic reference based PSM technique.
\[ K = 1 - \frac{\sqrt{3}}{2}M \quad (10) \]

### 4. Simulation Results:

This section contains simulation analysis of single-phase seven-level RSZSMLI topology using CBC methods based on sine and third-harmonic references based PSM has been carried for the circuit shown in Figure 3 for an input voltage of 300V (i.e., \( V_{d_1} = V_{d_2} = V_{d_3} = 100V \)) and Z-source network ratings of \( L_1 = L_2 = 4mH \), \( C_1 = C_2 = 2300uF \) and switching frequency of 10kHz.

#### 4.1 Simulation results of RSZSMLI using CBC method based on sine reference based PSM:

For the requisite value, \( M = 0.1 \) the corresponding values of \( B \), \( K \), and \( V_o \) have been calculated based on equations represented in (5), (7) and (4) and the respective values are \( B = 1.25 \), \( K = 0.9 \) and \( V_o = 375 \) V. Simulation results of CBC method based on sine reference based PSM technique for the shoot through state operation are as shown in Figure 6 to 8. The Figure 6 shows the LGU output of
single-phase seven-level RSZSMLI topology. The output of LGU can be changed to AC by using the PCU power switches which is shown in Figure 7 and the respective harmonic plot is shown in Figure 8. It is observed that, the output of CBC method using sine reference based PSM has been boosted from 300V to 373V with a boost factor of 1.25 and the respective Total Harmonic Distortion (THD) is 24.18% with a fundamental value of 314.3V.

![Figure 6. Output voltage of LGU for M=0.1](image1)

![Figure 7. Output voltage of PCU for M=0.1](image2)

![Figure 8. Harmonic plot of CBC method based sine reference PSM technique](image3)
4.2 Simulation results of RSZSMLI using CBC method based on third-harmonic reference based PSM:

For the requisite value, $M = 0.1$ the corresponding values of $B$, $K$ and $V_o$ have been calculated based on equations represented in (9), (10) and (4) and the respective values are $B = 1.78$, $K = 0.22$ and $V_o = 536.7$ V. Simulation results of CBC method based on third-harmonic reference based PSM technique for the shoot through state operation are as shown in Figure 9 to 11. The Figure 9 shows the LGU output of single-phase seven-level RSZSMLI topology. The output of LGU can be changed to AC by using the PCU power switches which is shown in Figure 10 and the respective harmonic plot is shown in Figure 11. It is observed that, the output of CBC method using third-harmonic reference based PSM has been boosted from 300V to 532.3V with a boost factor of 1.78 and the respective THD is 22.76% with a fundamental value of 493.4V.

![Figure 9. Output voltage of LGU for M=0.1](image1)

![Figure 10. Output voltage of PCU for M=0.1](image2)

![Figure 11. Harmonic plot of CBC method based third-harmonic reference PSM technique](image3)
4.3 Comparison of CBC methods:

Table 2 and 3 shows simulation results comparison of single-phase seven-level RSZSMLI using sine and third-harmonic reference based PSM techniques respectively. It is observed that boosting capability of CBC method using third-harmonic reference based PSM is more with least %THD for the various values of ‘M’ due to the increase of ‘K’ when compared to sine reference based PSM, however the %THD is increases by decreasing the value of ‘M’ due to increasing the value of shoot through value.

Table 2. Results of RSZSMLI topology using CBC sine reference based PSM

| S.No. | M   | K   | Expected V₀ | Obtained V₀ | B   | %THD |
|-------|-----|-----|-------------|-------------|-----|------|
| 1     | 0.9 | 0.1 | 375V        | 373V        | 1.25| 24.18|
| 2     | 0.8 | 0.2 | 500         | 496         | 1.66| 25.95|

Table 3. Results of RSZSMLI topology using CBC third-harmonic reference based PSM

| S.No. | M   | K   | Expected V₀ | Obtained V₀ | B   | %THD |
|-------|-----|-----|-------------|-------------|-----|------|
| 1     | 0.9 | 0.22| 536.7       | 532.3       | 1.78| 22.76|
| 2     | 0.8 | 0.307| 777.2      | 773.1       | 2.59| 23.95|

5. Components comparison of ‘m’ level RSZSMLI with conventional Z-source based MLIs

Table 4 represents the number of components requires for suggested RSZSMLI topology and compared with conventional Z-source based MLIs.

Table 4. Components comparison of Z-source based MLIs

| Topology/ Components | Conventional Z-source MLIs | Suggested Z- Source MLI |
|----------------------|---------------------------|-------------------------|
|                      | Diode clamped  | Flying Capacitor | Cascaded H-bridge | RSZSMLI |
| Power Switches       | 2 (m-1)      | 2 (m-1)        | 2 (m-1)          | (m-1)/2 |
| DC Source            | 1             | 1              | (m-1)/2          | (m-1)/2 |
| DC-Bus Capacitor     | m-1           | m-1            | 0                | 0       |
| Clamping Capacitors  | 0             | (m-1)/2        | 0                | 0       |
| Clamping Diodes      | 2 (m-2)       | 0              | 0                | 0       |
| Z-source networks    | m-1           | m-1            | m-1              | (m-1)/2 |

6. Conclusion:

The suggested CBC method using sine and third-harmonic reference based PSM techniques with shoot-through ratio for a single-phase seven-level RSZSMLI have been analyzed in MATLAB/Simulink. From the theoretical and simulation tests, a detailed comparative analysis for the RSZSMLI topology was conducted with respect to various performance parameters such as shoot-through ratio, power boosting and percent THD. The comparative analysis shows clearly that apart from the PSM techniques, essential boost factor for RES is controlled by the option shoot through ‘K’ ratio. This eliminates the use of additional DC-DC converter and makes the entire system an efficient with less number of power switches. The simulation analysis assists a control designer in choosing the correct PSM technique and shoot-through ratio for a selected application.
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