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Tapped Inductor Quasi-Z-source Inverter With High Inversion Gain

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Abstract—This paper proposes a high inversion gain single stage boost inverter, which introduces a tapped inductor network into the traditional quasi-Z-source inverter (qZSI), called tapped inductor quasi-Z-source inverter (TL-qZSI). The tapped inductor network including one tapped inductor and two diodes and is used to replace one inductor of the traditional qZSI. Similar to the tapped inductor Z-source inverter (TL-ZSI), the proposed inverter can provide high inversion gain. TL-qZSI has all the merits of TL-ZSI except that it also features with continuous input current, common ground with the dc source, and reduced capacitor voltage stress. This paper analyses the circuit operation principle, boost inversion features and its control strategy. Simulation and Experimental results are provided to verify its effectiveness and demonstrate the real features of the proposed circuit.

Keywords— Pulse Width Modulation; Switched Inductor Quasi z Source Inverter; Unipolar PWM.

I. INTRODUCTION

Traditional voltage-source PWM inverter (VSI) is generally a buck-type converter. One of its characteristics is that the instantaneous output voltage is always lower than the dc input. In applications with wide input voltages, such as distributed power generation (DG) systems, a boost type DCDC converter is often added in front of the VSI to step up the dc input voltage [1]-[3] in case of a low level dc input. However, the traditional boost converter may not be able to provide enough dc voltage gain even for an extreme duty cycle. Large duty cycle operation may result in serious reverse-recovery problem and increase the rating of power devices. And also this two stage operation solution will inevitably increase the overall cost and system complexity, and deteriorate system efficiency. On the other hand, the upper and lower devices of the same phase leg cannot be gated on simultaneously in the traditional VSI. Otherwise, shoot through problem would occur and destroy the switching devices. Dead time is always used in case of shoot-through events in bridge-type converters, but it will cause waveform distortion. Though dead-time compensation technology [4]-[5] has been developed, it increases the control complexity. So it is desirable to have a single-stage boost inverter featuring with no shoot through issues. Z-source inverter (ZSI) [6] was proposed to overcome the issues of the traditional inverters, shown in Fig. 1(a). It is a single-stage inverter topology to demonstrate both buck and boost power conversion ability by gating on the two switches in the same phase leg simultaneously. Due to shooting through the phase legs becomes a normal operation mode, the bridge shoot-through is no longer an issue, but utilized as a control variable and is defined as “shoot-through zero state”. So the reliability can be improved. Boost factor B of Z-source inverter can be expressed as:

$$B = \frac{\hat{v}_b}{V_i} = \frac{1}{1-2D_0}, \quad (1)$$

where V_i is the dc input voltage, \hat{v}_b is the amplitude of bus voltage, and D_0 is the shoot-through duty cycle. It is clear that D_0 is confined between 0 and 0.5 when B varies between 1 and ∞ . The upper extreme is unachievable in practice, which would push down the voltage gain of whole converter to a much lower value [7]-[9]. Fig. 1(b) shows one of the voltage-fed quasi-Z-source inverter [10] with continuous input current. It also features with a common ground with the dc input source, and lower capacitor voltage stress. Boost factor of qZSI is the same with that of ZSI.

Traditional ZSI and qZSI can only regulate the shoot through zero state to maintain the set bus voltage amplitude. For applications requiring a large boost factor, a large value of shoot-through zero state should be taken to provide a high boost conversion relation between bus voltage and the low input dc-source voltage. However, by taking the traditional SPWM control method, the modulation index is inverse proportional to shoot-through zero state. Widening shoot through zero state will inevitably decrease modulation index and in turn reduce the output voltage amplitude, and will also increase device voltage stress [7] and output voltage THD

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content [9]. In other words, a smaller modulation index would lead to a smaller overall inversion gain and deteriorate circuit performance. Recent researches on its improvement of boost inversion ability have been proposed in [11]-[16]. The extended-boost qZSI [11] including diode-assisted boost and capacitor assisted boost quasi-Z-source inverter, extend the boost ability of quasi-Z-source inverter. In practice, they are cascaded quasi-Z-source impedance networks with very complex circuit configuration. In [12] and [13], coupled inductor is introduced to provide high boost inversion ability by introducing turns ratio of the coupled inductor as a control variable.

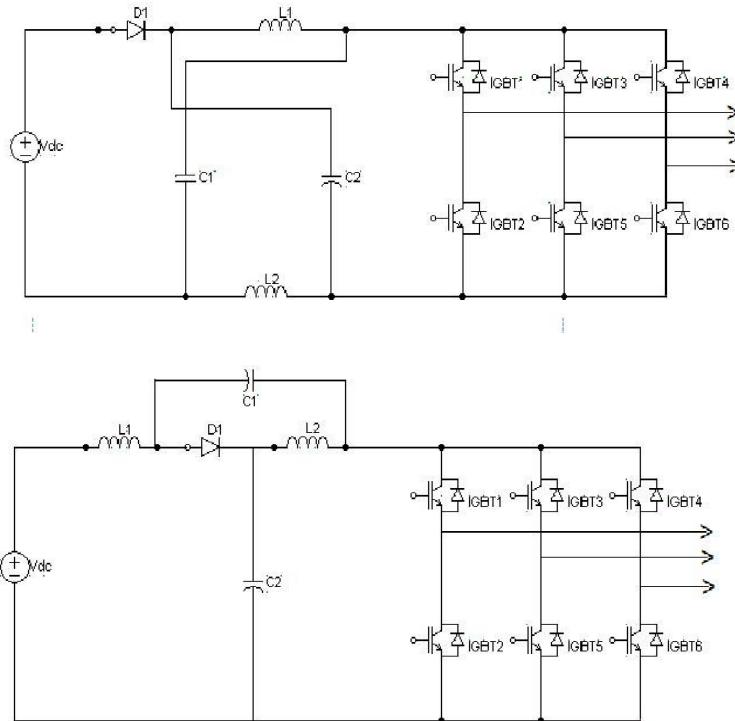


Fig.1. (a) Traditional Z-source inverter and (b) quasi-Z-source inverter with continuous input current.

One advantage of this converter is that the component count is reduced. However, it still cannot avoid its practical limit arising from the leakage inductance even if it is very small. Applying switched-capacitor, switched-inductor, and hybrid switched-capacitor/inductor structures of the high boost gain dc-dc converter, a switched inductor (SL) cell is introduced to combine with the traditional ZSI [14] and qZSI [15] to improve the impedance-type inverters' boost inversion performance. The modified switched-inductor, called tapped inductor, and ZSI of this type is introduced in [16]-[17], which is generally less complex. This paper proposes a new tapped inductor quasi-Z-source inverter. It introduces an impedance network including a tapped inductor and two diodes to replace one inductor of the traditional qZSI. The new converter can improve the boost inversion ability of the traditional qZSI, together with a voltage-buck freedom. This is achieved by using shoot through zero state defined in the traditional ZSI, and also by properly designing the tapping position of the inductor. In the following sections, operation principle, boost inversion feature and control strategy of the proposed converter will be analyzed in detail. Simulation and experimental results are shown to verify the correctness and effectiveness.

II. THE TAPPED INDUCTOR Z-SOURCE INVERTER

Fig. 2 shows the general structure of the tapped inductor Z-source inverter [17]. It obtains high voltage conversion gain with a relative short shoot-through zero state, which improves power quality of the circuit. The switched tapped inductor network composes of four diodes and two tapped inductor cells and is introduced to replace the two inductors of the traditional ZSI. The boost factor can be increased by simply changing the tapping position. Boost factor B of this inverter is

$$B = \frac{1+D_0N}{1-2D_0-D_0N}, \tag{2}$$

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where N is turns ratio of the tapped inductor, supposing coupling coefficient is unity. In order to make the achievable boost inversion operation, the shoot-through duty cycle should be limited to $0 < D < \frac{1}{2N+1}$. Unlike traditional ZSI, boost factor of this converter is influenced by both shoot-through duty cycle D_0 and turns ratio N whose value can be freely varied by changing the TL tapping position. Although the boost inversion ability is improved, the TL-ZSI has several drawbacks: 1) it adds four diodes and two tapped inductors, compared with traditional ZSI, which obviously increases system size and cost; 2) it requires a LC network in the front end to reduce the input current ripple because of its current discontinuity.

III. PROPOSED TAPPED INDUCTOR QUASI-Z-SOURCE INVERTER

Fig. 3 shows the proposed tapped inductor quasi-Z-source inverter (TL-qZSI). The combination of L_t , D_2 , and D_3 acts as a switched tapped inductor cell. Compared to the traditional quasi-Z-source inverter with continuous input current, only one tapped inductor and two diodes are added. This configuration allows the impedance network with different inductances under shoot-through state and non-shoot-through state. Only the inductance of winding N_1 is effective during the shoot-through zero state, while both the inductances of winding N_1 and N_2 are effective during the non-shoot-through state. It is impossible for the tapped inductor to achieve a complete coupling effect, so leakage inductance exists in the real circuit as shown in Fig. 4. As the turns ratio can be defined as $N=N_2/N_1$. The leakage inductor L_k and magnetizing inductor L_m can be described as [18]-[19]

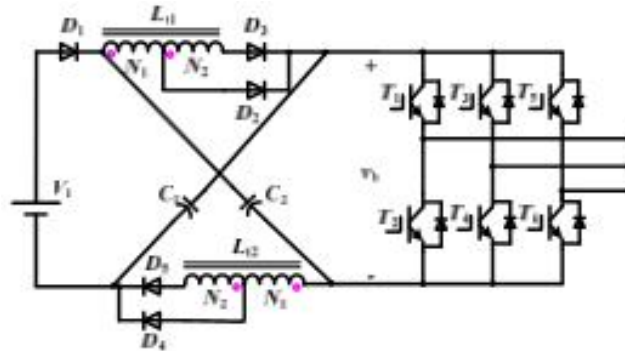


Fig. 2. Tapped inductor Z-source inverter

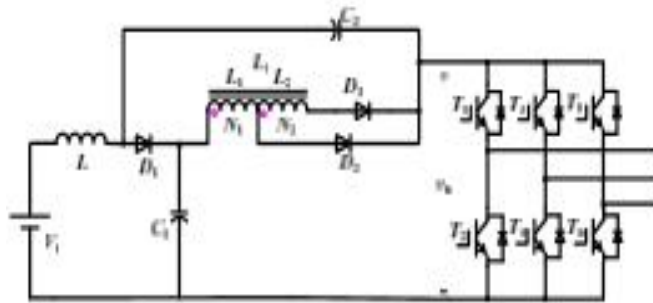


Fig. 3. Tapped inductor quasi-Z-source inverter

$$L_k = (1 - k^2)L_1, \tag{3}$$

$$L_m = k^2L_1, \tag{4}$$

where k is the coupling coefficient. Then the inductance of tapped inductor can be expressed as

$$\frac{L_2}{L_1} = N^2k^2, \quad L_1 + L_2 = L_t, \tag{5}$$

$$L_1 = \frac{1}{1 + N^2k^2}L_t, \quad L_2 = \frac{N^2k^2}{1 + N^2k^2}L_t. \tag{6}$$

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Like the traditional ZSI, the proposed inverter has the extra shoot-through zero states besides the traditional six active and two open-zero states. By regulating the shoot-through zero states when circuit parameters are designed, the energy is stored and transferred within the impedance network to boost the amplitude of the bus voltage. It should be noted that shoot through zero states are allocated into open-zero states without changing the total open-zero state and active state time intervals.

IV. OPERATION PRINCIPLE, BOOST INVERSION FEATURE AND ITS CONTROL

A. Operation Principle

Assuming that the capacitances of C1 and C2 are sufficiently large, and then the capacitor voltages are almost constant. Fig. 4 shows the equivalent circuits of TL-qZSI under different states. Operation principle can be briefly described in these switching states.

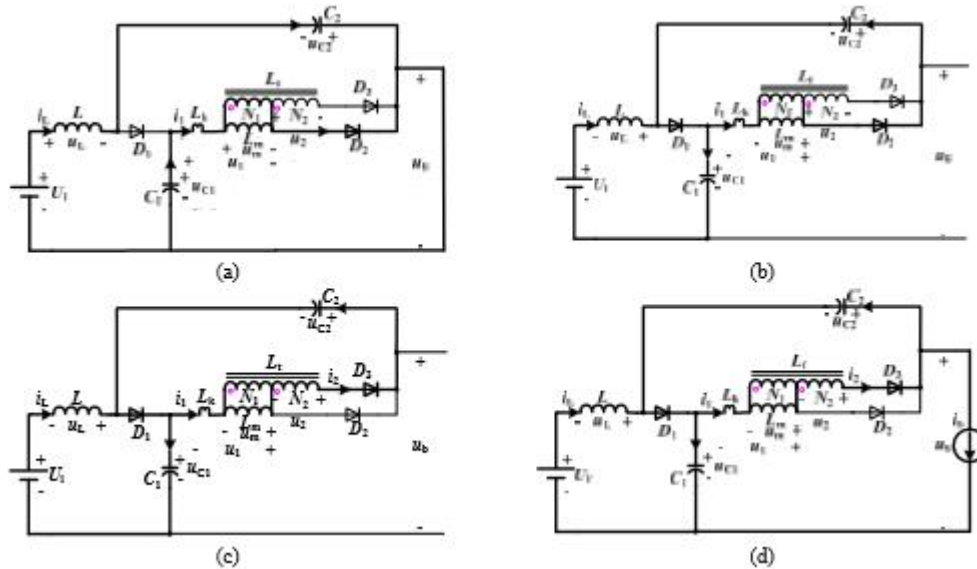


Fig. 4. Equivalent circuit under three switching states: (a) shoot-through zero state, (b), (c) open-zero state, and (d) active state.

- 1) *State 1:* The converter is in shoot-through zero state under this duration, as shown in Fig. 4(a). A short circuit has been explicitly drawn in place of the dc bus viewed from the TL network and $v_b=0$. Input dc source voltage and capacitor C2 voltage is applied across inductor L, making inductor L current linearly increase, $v_L=V_i+VC_2$. Voltage applied across winding N1 is reflected to winding N2, and $v_2=N_2v_1=Nk_2VC_1$, leading to diode D3 reverse biased. Diode D1 also becomes reverse biased, due to $VC_1 > VC_2$. Voltage of winding N1 in shoot-through zero state is only related to capacitor C1.
- 2) *State 2:* During this time interval, the converter is in one of the two traditional open-zero states, as shown in Fig. 4(b), (c). C1 is charged by L and input dc source V_i , therefore $v_L=VC_1-V_i$. In the initial time, leakage inductor L_k and capacitor C2 start to resonate. After the resonant current decreases to a certain value, winding N2 reverses its polarity causing diode D3 to become forward biased. The magnetizing current is reflected to winding N2. Winding N2 series with the winding N1 and transfers the earlier stored magnetizing energy to capacitor C2. Diode D2 turns off naturally.
- 3) *State 3:* During this time interval, the converter is operating in the active state, as shown in Fig. 4(d). The inverter bridge can be viewed as a current source. Winding N2 series with winding N1 and transfers the earlier stored magnetizing energy to the load. And the bus voltage is stepped up. Capacitor C1 is continuously charged by L and input dc source V_i , therefore $v_L=VC_1-V_i$.

B. Boost Inversion Feature Analysis

When the converter operates in shoot-through zero state, C1 charges winding N1 of tapped inductor with linearly increasing current, the voltage across winding N1 can be expressed as

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$$T_0: v_1 = V_{C1} . \tag{7}$$

Define the resonant time interval of the leakage inductor and C2 as T1, and T1=D1Ts. The voltage across winding N1 during T1 can be expressed as

$$T_1: v_1 = V_{C2} . \tag{8}$$

After T1, winding N2 reverses its polarity and series with winding N1 to transfer energy. Define the time interval of state 3 as T2, and T2=(1-D0-D1) Ts. The voltage of winding N1 is

$$T_2: v_1 = V_{C2} - v_2 = V_{C2} - Nk^2 v_1 , \tag{9}$$

which can be simplified as

$$T_2: v_1 = \frac{V_{C2}}{1+Nk^2} . \tag{10}$$

The average voltage across winding N1 of the tapped inductor can be expressed as

$$D_0 V_{C1} - D_1 V_{C2} - (1-D_0-D_1) \frac{V_{C2}}{1+Nk^2} = 0 . \tag{11}$$

The voltages across inductor L during T0, T1+T2 time intervals are described in “operation principle” section. The average voltage of inductor L can be expressed as

$$D_0 (V_i + V_{C2}) + (1-D_0)(V_i - V_{C1}) = 0 . \tag{12}$$

Combining (11) and (12), then the voltage across C1 and C2 can be derived as

$$V_{C1} = \frac{(1-D_0 + D_1 Nk^2) V_i}{Nk^2 (D_1 - D_0^2 - D_0 D_1) + 1 - 2D_0} , \tag{13}$$

$$V_{C2} = \frac{(1+Nk^2) D_0 V_i}{Nk^2 (D_1 - D_0^2 - D_0 D_1) + 1 - 2D_0} . \tag{14}$$

While the bus voltage amplitude can be expressed as

$$\hat{v}_b = V_{C1} + V_{C2} . \tag{15}$$

Boost factor $B = V_b/V_i$ can be obtained from (13), (14), and (15)

$$B = \frac{1+Nk^2(D_0+D_1)}{1-2D_0+Nk^2(D_1-D_0^2-D_0D_1)} . \tag{16}$$

It is desired to have a tightly coupled inductor to achieve higher boost factor. Supposing the tapped inductor is of completely coupled, the boost factor can be expressed as

$$B = \frac{1+ND_0}{1-2D_0-ND_0^2} . \tag{17}$$

The shoot-through duty cycle is limited to $D_0 < (\sqrt{N+1}-1)/N$, and N is getting larger while D0 is getting smaller. The boost factor of traditional ZSI(qZSI), TLZSI proposed in [16]-[17], and TL-qZSI can be compared as shown in Fig. 5. The boost factor of the proposed inverter is higher than that of the traditional ZSI(qZSI), and lower than that of TL-ZSI.

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C. Control Strategy

The basic PWM control methods, including simple, maximum, and constant boost control, are all fit for the proposed TL-qZSI. For simple boost control method, the maximum shoot-through duty cycle equals to 1-m. The voltage gain G of the whole converter can then be expressed as:

$$G = mB = \frac{m[N(1-m)+1]}{2m - N(1-m)^2 - 1} \tag{18}$$

The peak value of the output phase voltage can be expressed as

$$\hat{V}_{ph} = \frac{mB}{2} V_i \tag{19}$$

Fig. 6 shows the voltage gain versus modulation index of different topologies under simple boost control method when k=1. For the same voltage gain, the modulation index of the proposed inverter is higher than that of the traditional ZSI, leading to improved THD of output phase voltage. While the modulation index of the proposed inverter is lower than that of TL-ZSI.

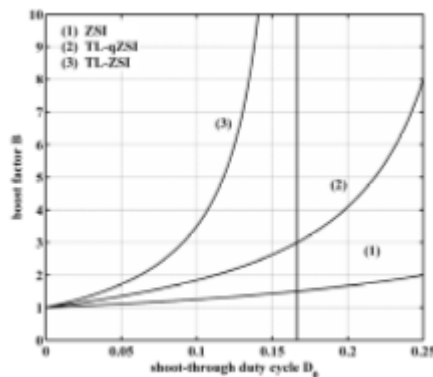


Fig. 5. Boost factor comparison of different topologies when k=1.

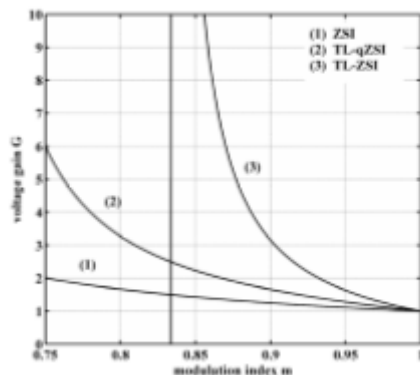


Fig. 6. Voltage gain comparison of different topologies when k=1.

V. SIMULATION AND EXPERIMENTAL RESULTS

A 600VA prototype of the tapped-inductor quasi-Z-source inverter with 80V input voltage and 110Vrms output phase voltage was built for operation validation purposes. System configuration for the simulation and experiments is shown in Fig. 7. Simple boost control is adopted for the prototype. The switching frequency of the inverter bridge is 10KHz. The shoot-through zero state was inserted in every traditional open-zero state of three phase legs, achieving an equivalent switching frequency of 20kHz, viewed from the impedance network. Turns ratio of the tapped inductor is 1:4.3 and the coupling coefficient is 98%. The magnetizing inductance measured from the primary side is 81μH. The inductance of L is 840μH. Capacitance of C1 and C2 are 330μF and 100μF, respectively. Simulation and experimental results of the boost operation are shown in Fig. 7 and Fig. 8, respectively.

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When the input voltage is low, the shoot-through zero state was regulated to boost the amplitude of the bus voltage to 390V, enough to output the desired ac voltage. The voltage and current stresses are consistent with the analysis above. Both the input voltage and the voltage stress of capacitor C1 are lower than the reported results of quasi-Z-source inverter in [10], given the same output voltage. By controlling the shoot-through duty cycle D0 or the boost factor B when the tapped inductor parameters has been designed, the desired output ac voltage can be obtained even when the input voltage is at a low level.

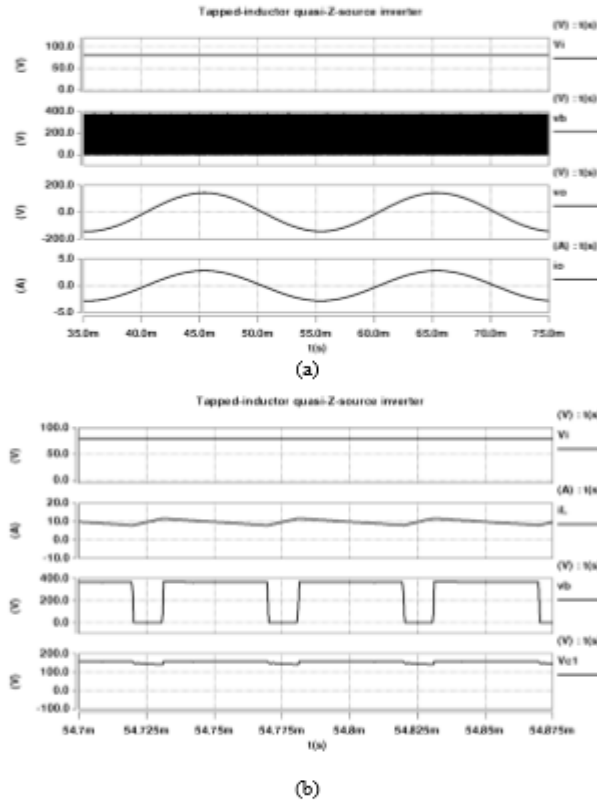


Figure 7. Simulation results.

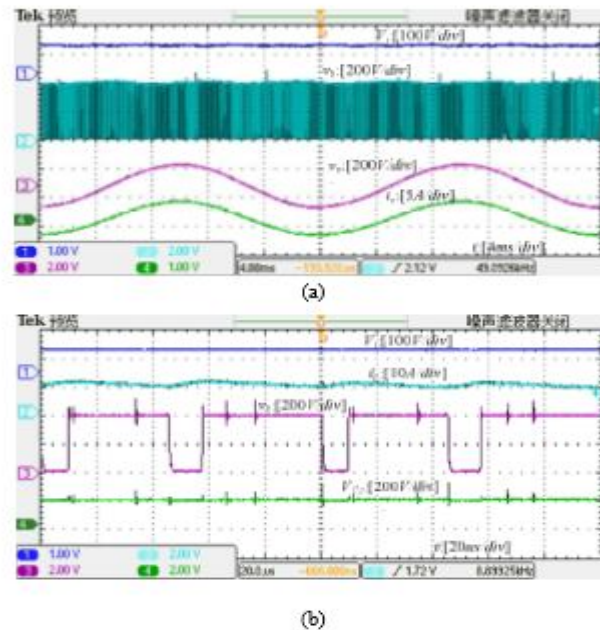


Fig. 8. Experimental results.

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VI. CONCLUSION

This paper has proposed a tapped inductor quasi-Z-source inverter (TL-qZSI) which improving the boost inversion ability of the traditional qZSI. The proposed converter introduces an impedance network with tapped inductor to couple the low dc input voltage source to the inverter bridge. The boost ability is decided by the tapping positions and the shoot-through zero state. Turns ratio and leakage inductance of the tapped inductor affect the performance of whole inverter greatly. The proposed converter has some merits.

- A. By designing the tapped inductor properly and adjusting the previously forbidden shoot-through zero state, the amplitude of the bus voltage can be greatly stepped up and the boost inversion ability of the whole inverter can be greatly improved.
- B. By inheriting the unique "shoot-through" time interval of the traditional ZSI, the reliability of whole inverter can be improved.
- C. Input current of the proposed converter is continuous. Capacitor voltage stresses are reduced, and component count is minimized compared to traditional ZSI.
- D. The concepts of TL quasi-Z-source impedance network can also be applied to ac-dc, ac-ac, and dc-dc power conversion.

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