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An Improved T-Z Source Inverter for the Renewable Energy Application

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Abstract: *In this paper for a high-step-up boost voltage, inverter with transformer is used to replace two inductors in the classical Z-source inverter. This is a new family of single-stage impedance inverter called the improved T-Z source inverter. The proposed inverter produces a very high boost voltage gain and can be used in renewable energy application. When compared to the conventional trans-Z and other impedance source inverters, the proposed improved T-Z source inverter uses a lower transformer turn ratio, which reduces the transformer's size and weight while producing the same output voltage gain. The operating principles, analysis, and simulation results are shown. The simulation results verified that the converter has high-step-up inversion ability.*

Index Terms: *Boost inversion ability, embedded-Z-source in-verter, quasi-Z-source inverter (qZSI), shoot-through state, single-stage boost inverter, transformer, Z-source inverter (ZSI).*

I. INTRODUCTION

THE Traditional Z-source inverter (ZSI) topology shown in Fig. 1(a) was first proposed in [1] and had a two-port impedance network that couples the main inverter circuit to a dc voltage source. It consists of two inductors (L1 and L2) and two capacitors (C1 and C2) connected in an X shaped configuration. Unlike traditional voltage-source inverters, the ZSIs present a single-stage power conversion with buck-boost abilities. Also an additional shoot-through zero state is added to the switching states in order to boost the voltage. When the input voltage is large enough to produce the desired ac voltage, the shoot-through zero state is not used, and the ZSI operates as a buck inverter, same as a con-ventional voltage-source inverter. To date, many have reported various ZSI topologies. Some have focused on developing the ZSI into pulse-width modulation (PWM) strategies [2], [3], applications [4], [5], modeling and control [6],[7], while others have worked on developing different Z-network topologies [8]–[16]. In the original ZSI [1], the current drawn from the source is discontinuous. This is a limitation in some appli-cations, and a decoupling capacitor bank at the front end is sometimes used to prevent current discontinuity and protect the energy source.

To overcome the problems in the classical ZSI, quasi-Z-source inverters (qZSIs) were proposed [14], [15]. The qZSI places a lower voltage stress on capacitors. The ratio between the dc-link voltage across the inverter bridge, V_{PN} , and the input dc voltage, V_{dc} (the boost factor of the classical ZSI and

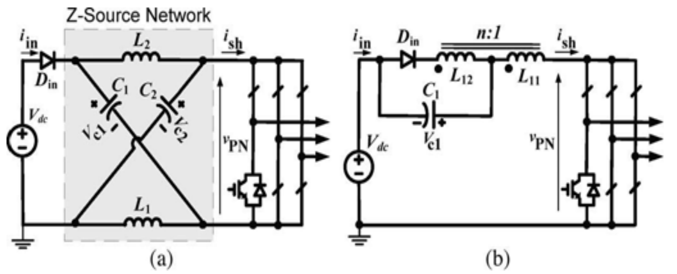

Fig. 1. Prototype of (a) the original Z-source inverter and (b) trans-quasi-Z-source inverter.

qZSI), can be expressed as

$$B = V_{PN}/V_{dc}=1/ 1 - 2T_0 /T= 1/1 - 2D \qquad (1)$$

Where T_0 is the interval of the shoot-through state during the switching period T and $D = T_0/T$ is the duty cycle of each cycle.

The boost factor from (1) indicates that when D is between 0 and 0.5, B varies in (1, ∞). The infinite value of B is not reachable in reality because of the parasitic effects found in the physical components. Therefore, the ZSI and qZSI may not be suitable for applications where both a high boost voltage and a buck voltage gain are required. Even if a large shoot-through state D is used to produce the high boost voltage gain, the modulation index M of the rear-end main inverter must be small due to $M \leq 1 - D$. Using a low M results in reducing the overall dc-to-ac inversion gain and increasing the total harmonic distortion value.

To overcome the boost limitations in eqn.(1), there are a number of papers that have recently focused on increasing the boost factor of the ZSI by using a very high modulation index in order to improve the main circuit output power quality [16]. These topologies are suitable in solar cell and fuel cell applications, since they require a high voltage gain in order to match the source voltage to the line voltage. In these topologies, the inductors, capacitors, and diodes were added to the Z-impedance network in order to produce a high dc-link voltage for the main power circuit from a very low input dc voltage. They are, namely, continuous-current diode/capacitor-assisted extended-boost quasi-ZSIs , switched-inductor ZSIs , switched-inductor quasi-ZSIs, tapped-inductor ZSIs, and single-stage boost inverters with couple inductor. Al-though they provide a strong step-up inversion that overcomes the boost limitations of the classic ZSI [1], they also have greater size, loss, and cost because of passive components added to these topologies.

Applying a transformer to the Z-source network in place of inductor has been introduced in the trans-Z-source/-quasi-ZSI. Fig.1(b) shows the voltage-fed trans-quasi-ZSI, where two inductors in the impedance Z-network are replaced by a transformer with a turn ratio of n : 1 in order to obtain a high voltage gain.

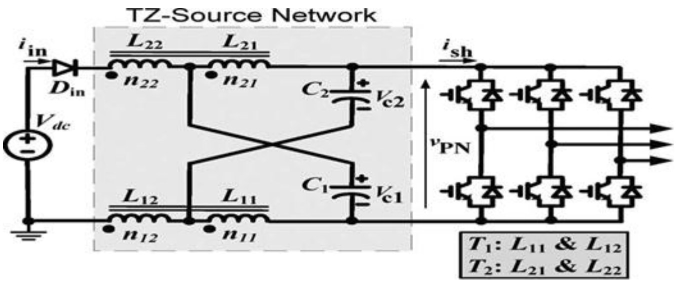

Fig. 2. Proposed basic improved TZ-source inverter.

It consists of one transformer, one capacitor, and one diode. The boost factor of this inverter is increased to

B =1/1 − (1 + n)T0 /T=1/1 − (1 + n)D (2)

Where n is the turn ratio of the transformer as shown in Fig. 1(b). When n = 1, the trans-quasi-ZSI produces the same output voltage gain as the classical ZSI. When n > 1, a high boost inversion ability can be obtained in this inverter. An inductor-capacitor-capacitor-transformer ZSI (LCCT-ZSI) to prevent the transformer core from saturating and improve the input current profile.

This paper applies two transformers to the classical Z-source topology in order to replace two inductors and create a new type of inverter called the improved T-Z source inverter (where "T" is included to represent "transformer"). Then, the proposed improved T-Z source inverter based on a basic X-shape structure is extended to various topologies such as the quasi-ZSI topologies or the embedded topologies to improve the input current profile and place a lower voltage stress on the capacitors. By changing the turn ratio of the transformers, the proposed inverters have very high boost voltage inversion ability with a very low shoot-through duty ratio. Hence, a high modulation index can be used to improve the output power quality of the main circuit. The operating principles, analysis, and simulation results are shown.

II. PROPOSED TOPOLOGY

In the proposed improved T-Z source inverter shown in Fig. 2, the inductors in the original ZSI are replaced by the transformers. It consists of two transformers (T_1 and T_2), two capacitors (C_1 and C_2), and one diode (D_{in}). The turn ratios of the transformers are defined as $N_i = n_{i2}/n_{i1}$, where i = 1 and 2 represent the transformers T_1 and T_2, respectively. The main characteristics of the proposed improved T-Z source inverter are as following:

I. the basic X-shape structure is retained;
II. only two transformers are used, and a very high boost factor can be obtained by changing the turn ratio of the transformers;
III. Although producing a high boost factor, the proposed improved T-Z source inverter does not use any additional diodes, which reduces its size, cost, and loss compared to other existing high-boost Z-network inverter topologies ;

IV. It can be extended to the quasi or embedded ZSI topologies to improve the input current profile and place a lower voltage stress on capacitors.

Like the classical ZSI topology [1], the proposed improved T-Z source inverter based on the X-shaped structure has discontinuous input current, and it requires a decoupling capacitor bank at the front end to eliminate current discontinuity and protect the energy source. In addition, it cannot suppress the resonant current at startup, and the resulting voltage and current spike can destroy the devices [16]. The startup resonant problem occurs because a huge resonant current flows to the diode, transformer windings, capacitors, and body diode of the IGBTs. Then, the transformer's windings and capacitors resonate, generating current, and voltage spikes.

Circuit Analysis

Similar to the classical ZSI, the proposed improved T-Z source inverters have extra shoot-through zero states in addition to the traditional six active and two zero states. Thus, the operating principles of the proposed inverters are similar to those of the classical ZSIs. For the purpose of analysis, the operating states are simplified into shoot-through and non-shoot-through states. Fig. 3(a) shows the equivalent circuits of the proposed improved T-Z source inverter.

In the non-shoot-through state with i_D _= 0, as shown in Fig. 3(a), the proposed inverter has six active states and two zero states of the inverter main circuit. During the non-shoot-through state with i_D _= 0, D_{in} is on, and L_{12} and L_{22} are connected in series.

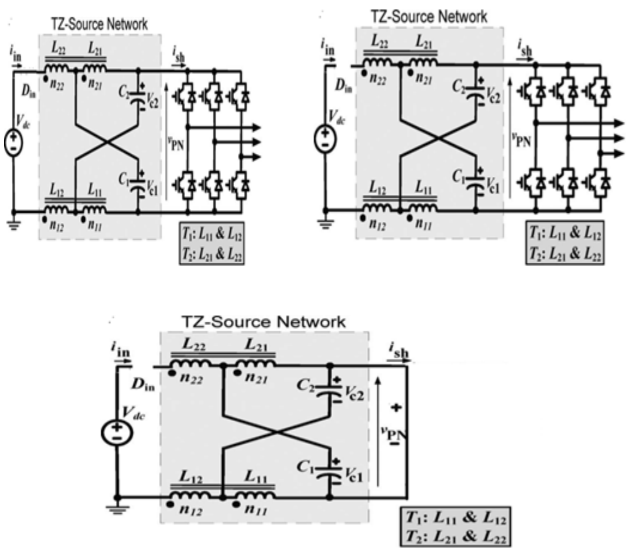

Fig. 3. (a)Equivalent circuit of improved T-Z inverter, non-shoot-through state with iD ≠0, (b) non shoot-through state with iD = 0 and (c) shoot-through state.

The corresponding voltages across the pri-mary and secondary windings of the transformers in this state are V_{L11_non}, V_{L12_non}, V_{L21_non} and V_{L22_non}. We obtain

$$V_{L11} = V_{L11\_non} = V_{C1} - V_{L12\_non} + V_{L22\_non} \quad (3)$$
$$V_{L21} = V_{L21\_non} = -V_{C2} + V_{L12\_non} - V_{L22\_non} \quad (4)$$
$$V_{PN} = V_{C1} + V_{dc} - V_{L21\_non} \quad (5)$$

If the inverter operates with a lighting load, the inverter has one more non-shoot-through state with i_D = 0 as shown in Fig. 3(b). This state occurs after the non-shoot-through state with i_D _= 0. In this state, the transformer winding voltages reduce to zero, D_{in} is off, the diode voltage reaches the capacitor voltage, and the peak dc-link voltage is the total of the input voltage and capacitor voltage ($V_{PN} = V_{dc} + V_{C1} = V_{dc} + V_{C2}$). The inverter operates in discontinuous conduction mode, and the total magnetizing inductance currents are equal to an equivalent load current ($i_{m1} + i_{m2} = i_l$).

In the shoot-through state, as shown in Fig. 3(c), the inverter side is shorted by both the upper and lower switching devices of any phase leg. During the shoot-through state, D_{in} is off. We obtain

$$V_{L11} = -V_{dc} - V_{C2} \quad (6)$$
$$V_{L12} = N_1 V_{L11} = -N_1(V_{dc} + V_{C2}) \quad (7)$$
$$V_{L21} = V_{dc} + V_{C1} \quad (8)$$
$$V_{L22} = N_2 V_{L21} = N_2(V_{dc} + V_{C1}) \quad (9)$$

Assume that the inverter operates in continuous conduction mode (CCM), applying the volt-second balance principle to L_{11}, L_{12}, L_{21}, and L_{22}, from (3) and (4), and (6)–(9), we obtain

$V_{L11\_non} = D/1-D(V_{dc} + V_{C2})$ (10)
$V_{L12\_non} = N_1D/1-D\ (V_{dc} + V_{C2})$ (11)
$V_{L21\_non} = -D/1-D(V_{dc} + V_{C1})$ (12)
$V_{L22\_non} =-N_2D/1-D\ (V_{dc} + V_{C1})$ (13)

The power rating of each transformer in the proposed TZ-source inverter is smaller than that of the transformer in the conventional trans-ZSI under the same output power conditions. As a result of using a lower turn ratio and power rating, the size and weight of transformers in the proposed TZ source inverter are reduced significantly. The size and weight of the proposed inverter are definitely not lower than those of the trans-ZSI because the proposed inverter uses one more transformer and one more capacitor. In practice, however, one transformer with high power rating and greater turn ratio is sometimes difficult to implement compared to two transformers with lower power rating and lower turn ratio.

Compared with the classical ZSI [1] and using the same modulation index, the proposed improved T-Z source inverter provides higher voltage boost inversion. Thus, for the same voltage conversion ratio, the proposed inverter uses a higher modulation index to improve the inverter output quality. The proposed TZ-source inverter only uses two transformers with turn ratio of 2 : 1. The proposed improved T-Z source inverter is added with a BLDC load.

The voltage stress Vs across the switching devices can be defined by the ratio of its peak dc-link voltage to the minimum dc voltage (GVdc) needed for the traditional ZSI to generate the same ac output voltage at M = 1[3]. This ratio relates to the extra cost that the inverters incur to obtain the voltage boost and to the higher voltage stress.

The respective ratios of the voltage stress to the equivalent dc voltage for the proposed improved T-Z source inverter can be expressed as

$$V_S/GV_{dc}=BV_{dc}/GV_{dc} \quad (14)$$

$$BV_{dc}/GV_{dc}=1/1+N_1+N_2(2+N_1+N_2- 1/G) \quad (15)$$

Table I compares the governing equations of the proposed improved T-Z source inverters, the trans-quasi-ZSI, and the classical ZSI [1] for the same *D* and *V*dc . The voltage and current directions in the ZSI are defined according to the equivalent circuits of the TZ-source inverters. *Ss* is the shoot-through switching function in the inverters. *Ss* is equal to 0 when the inverter operates in the non- shoot-through states and 1 when it is in the shoot-through states.

Table I also supplies instructions for calculating the ratings of the main components, such as the active power switch, the diode, the capacitors and the transformers. In Table I, when (*N*1 + *N*2) = 0, some of the governing equations in the improved T-Z source inverter are merged with those of the classical ZSI. Note that when the turn ratio *Ni* (*i* = 1 and 2) is equal to zero, the transformer plays a role as an inductor. When (*N*1 + *N*2) > 0, the proposed improved T-Z source inverters have higher dc-link voltage gain than the classical ZSI [1]. When *N*1 = *N*2 , the improved T-Z source network becomes symmetrical, the primary current of the transformer T1 is equal to that of the transformer T2 and the secondary current of the transformer *T*1 is equal to that of the transformer T2.

Table1

	TZ-Source Inverter	Continuous Current Quasi-TZ-Source Inverter	Discontinuous Current Quasi-TZ-Source Inverter	Trans-Quasi-ZSI [22]	Classical ZSI [1]
V_{C1}	$\frac{1-D}{1-(2+N_1+N_2)D}V_{dc}$	$\frac{1-D}{1-(2+N_1+N_2)D}V_{dc}$	$\frac{(1+N_1+N_2)D}{1-(2+N_1+N_2)D}V_{dc}$	$\frac{nD}{1-(1+n)D}V_{dc}$	$\frac{1-D}{1-2D}V_{dc}$
V_{C2}	$\frac{1-D}{1-(2+N_1+N_2)D}V_{dc}$	$\frac{(1+N_1+N_2)D}{1-(2+N_1+N_2)D}V_{dc}$	$\frac{(1+N_1+N_2)D}{1-(2+N_1+N_2)D}V_{dc}$	NA	$\frac{1-D}{1-2D}V_{dc}$
v_{PN}	$\overline{S}_s\frac{1}{1-(2+N_1+N_2)D}V_{dc}$	$\overline{S}_s\frac{1}{1-(2+N_1+N_2)D}V_{dc}$	$\overline{S}_s\frac{1}{1-(2+N_1+N_2)D}V_{dc}$	$\overline{S}_s\frac{1}{1-(1+n)D}V_{dc}$	$\overline{S}_s\frac{1}{1-2D}V_{dc}$
v_D	$S_s\frac{1+N_1+N_2}{1-(2+N_1+N_2)D}V_{dc}$	$S_s\frac{1+N_1+N_2}{1-(2+N_1+N_2)D}V_{dc}$	$S_s\frac{1+N_1+N_2}{1-(2+N_1+N_2)D}V_{dc}$	$S_s\frac{n}{1-(1+n)D}V_{dc}$	$S_s\frac{1}{1-2D}V_{dc}$
I_l	$(1-D)V_{PN}/R_l$	$(1-D)V_{PN}/R_l$	$(1-D)V_{PN}/R_l$	$(1-D)V_{PN}/R_l$	$(1-D)V_{PN}/R_l$
i_L	$i_{L11}=\frac{1-(1+N_1)D+S_sN_1}{1-(2+N_1+N_2)D}I_l$ $i_{L21}=\frac{1-(1+N_2)D+S_sN_2}{1-(2+N_1+N_2)D}I_l$ $i_{L12}=i_{L22}=\frac{\overline{S}_sI_l}{1-(2+N_1+N_2)D}$	$i_{L11}=\frac{1-(1+N_1)D+S_sN_1}{1-(2+N_1+N_2)D}I_l$ $i_{L21}=\frac{1-(1+N_2)D+S_sN_2}{1-(2+N_1+N_2)D}I_l$ $i_{L12}=i_{L22}=\frac{\overline{S}_sI_l}{1-(2+N_1+N_2)D}$	$i_{L11}=\frac{1-(1+N_1)D+S_sN_1}{1-(2+N_1+N_2)D}I_l$ $i_{L21}=\frac{1-(1+N_2)D+S_sN_2}{1-(2+N_1+N_2)D}I_l$ $i_{L12}=i_{L22}=\frac{\overline{S}_sI_l}{1-(2+N_1+N_2)D}$	$i_{L11}=\frac{1-(1+n)D+S_sn}{1-(1+n)D}I_l$ $i_{L12}=\overline{S}_s\frac{1}{1-(1+n)D}I_l$	$\frac{1-D}{1-2D}I_l$
i_D	i_{L12}	i_{L12}	i_{L12}	i_{L12}	$\overline{S}_s(2i_{L1}-I_l)$
i_{in}	i_{L12}	i_{L11}	$\overline{S}_sI_l+S_s(i_{L11}+i_{L21})$	i_{L11}	$\overline{S}_s(2i_{L1}-I_l)$
i_{sh}	$\overline{S}_sI_l+S_s(i_{L11}+i_{L21})$	$\overline{S}_sI_l+S_s(i_{L11}+i_{L21})$	$\overline{S}_sI_l+S_s(i_{L11}+i_{L21})$	i_{L11}	$\overline{S}_sI_l+S_s2i_{L1}$

I_l, R_l, i_{sh}, and n are the average load current, the equivalent load register, the instantaneous shoot-through current, and the transformer turn ratio of the trans-Z-source inverter, respectively.

Fig. 4 shows the boost factor versus duty cycle for the pro-posed improved T-Z source inverter with various turn ratios of ($N1 + N2$). When $N1 + N2 = 0$, $B = 1/(1-2D)$, the secondary winding of the transformers is omitted, and the proposed inverter becomes the classical ZSI. When $N1 + N2 = 1$, $B = 1/(1-3D)$, the boost factor of the proposed inverter equals that of the trans-ZSI with turn ratio of 2 [16]. When $N + N2 > 1$, the proposed improved T –Z source inverter produces a very high boost inversion ability compared to the conventional high boost ZSI .

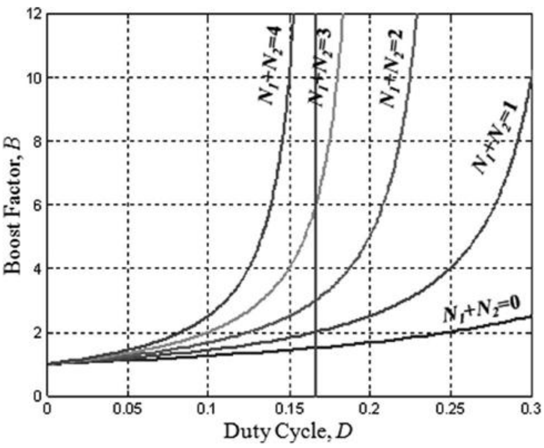

Fig. 4. Boost ability of proposed TZ-source inverter with various turn ratios of $(N1 + N2)$

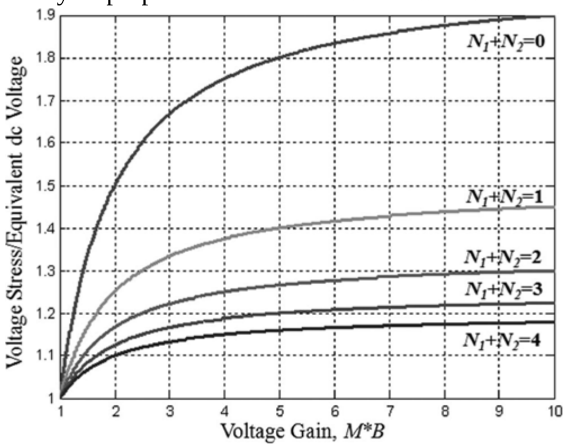

Fig. 5. Voltage stress of proposed TZ-source inverters with various turn ratios of $(N1 + N2)$

Fig. 5 shows the active switch voltage stress comparison of the proposed TZ-source inverter to the classic ZSI (N1 + N2 =0). As shown in Fig. 9, for the same dc-ac output voltage gain, the proposed inverter has a lower voltage stress across the active switching devices compared to the classic ZSI.

III. COMPARISONS WITH OTHER ZSI TOPOLOGIES

The proposed improved T-Z source inverter only uses two transformers with turn ratio of 2 : 1, whereas the trans-ZSI uses the turn ratio of 5 : 1 to produce the same $(1/1 - 6D)V_{dc}$ dc-link voltage from the same V_{dc} and D. In addition, the power rating of each transformer in the proposed improved T-Z source inverter is smaller than that of the transformer in the conventional trans-ZSI for the same output power conditions. As a result, by using a lower turn ratio and power rating, the size and weight of transformers in the proposed improved T-Z source inverter are reduced significantly. The size and weight of the proposed improved T-Z source inverter for renewable energy application are definitely not lower than those of the trans-ZSI because the proposed inverter uses one more transformer and one more capacitor.

IV. SIMULATION

The MATLAB simulation was used to verify the advantages of the proposed improved T-Z source inverters for renewable energy application. Fig.6 shows the system configuration for the simulation circuit. The system is considered with a d.c input & an high step up inverted a.c output is obtained.

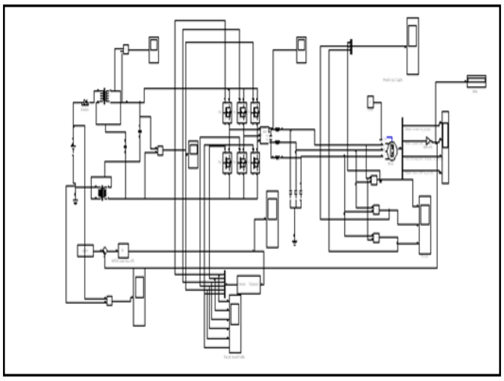

Fig. 6 MATLAB simulation circuit.

The simulation results show that the proposed improved T-Z source inverter achieves high boost inversion using a very low shoot-through duty ratio or a very high.

Simulation Results

The proposed improved T-Z source inverter used two transformers to replace two inductors in the classical Z-source inverters. The size and weight of transformers in the proposed improved T-Z source inverter are reduced significantly because the power rating and turn ratio of each transformer in the proposed inverter for renewable application are smaller than those of the transformer in the conventional trans-ZSI under the same output power and voltage gain conditions.

The experimental results for dc 100-V input verified the high-step-up inversion ability, and the simulation and experimental results show that the proposed inverter has high boost inversion ability.

The proposed improved T-Z source inverter is applicable for fuel cells or photovoltaic applications where a low input voltage is inverted to a high boosted ac output voltage.

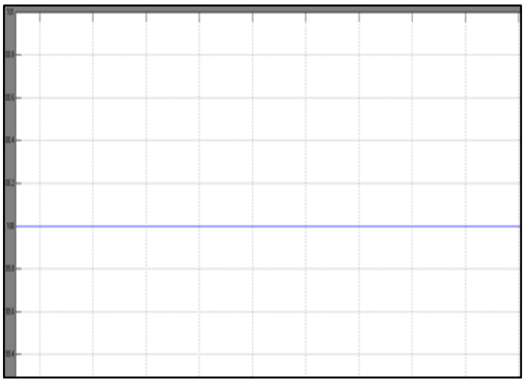

Fig. 7 Input DC voltage.

The input dc voltage applied to the improved T-Z inverter network is 100V. A boosted AC output voltage of 160V is obtained across the inverter output terminal.

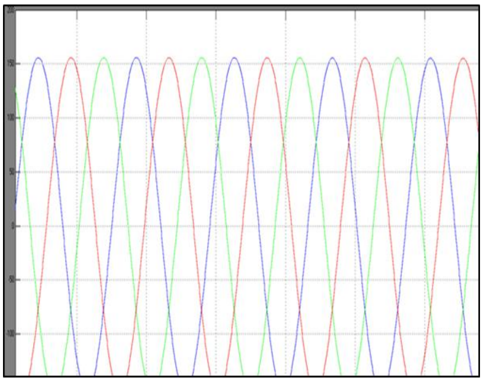

Fig. 8 Boosted AC 0utput voltage.

By using the improved T-Z inverter with two low turns ratio transformer, the output voltage obtained across the inverter terminal is an boosted AC voltage of 160V. The simulation output of the BLDC motor load is shown in Fig 9.

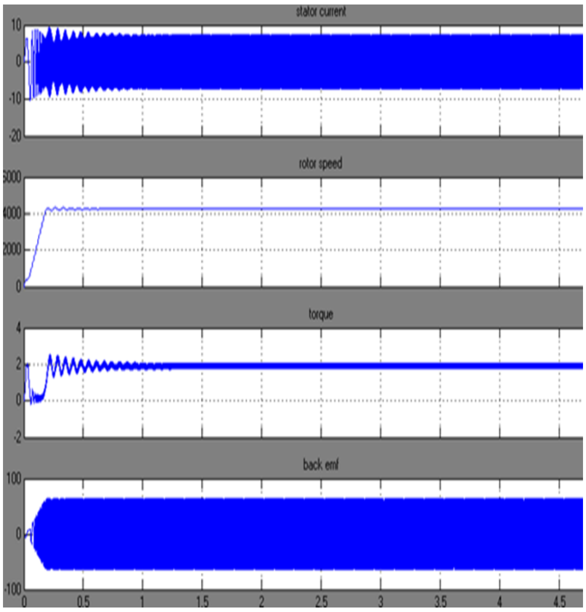

Fig. 9 BLDC motor 0utput.

A BLDC motor is connected at the output terminal of an improved T-Z inverter and the motor runs at 4100 rpm. The current across the stator of the motor is 10A and the back emf is 80V.

V. PARAMETER SELECTION AND EFFICIENCY

Parameter design of the TZ-source inverter is considered under the CCM condition. The capacitance parameters are chosen according to the voltage ripple in shoot-through state.

$$C_1 = \frac{I_{m1} \cdot D \cdot T}{\Delta V_{c1}}$$

&

$$C_2 = \frac{I_{m2} \cdot D \cdot T}{\Delta V_{c2}}$$

The transformer is selected to avoid core saturation and to obtain the smallest size and weight with acceptable power loss. The magnetizing inductance parameter of the transformers is chosen according to the current ripple in shoot-through state from (6) and (8).

If we limit the peak-to-peak current ripple through the magnetizing inductor by *y*%, the inductance for *Lm*1 and *Lm*2 in the proposed TZ-source inverter should be

$$Lm1 = \frac{D \cdot (1-D) \cdot T \cdot V_{dc}^{2}}{y\% \cdot (1+N1) \cdot [1-(2+N1+N2) \cdot D] \cdot Po}$$

$$Lm2 = \frac{D \cdot (1-D) \cdot T \cdot V_{dc}^{2}}{y\% \cdot (1+N2) \cdot [1-(2+N1+N2) \cdot D] \cdot Po}$$

From the component selection guidelines shown in Table I and parameter design mentioned above, we selected some loss- related parameters to calculate the efficiency of the classical ZSI and proposed inverter. The efficiency of the classical ZSI is calculated in case of low voltage gain, while others are calculated in case of high voltage gain.

The equivalent series resistance of a capacitor is used to calcu-late the capacitor loss. The core loss and winding resistance loss of the transformers are also calculated through simulation. The main power losses of the inverters such as transformer loss, capacitor loss and semiconductor loss can also be calculated. The semiconductors and transformers are the main contributors to total losses during the maximal shoot-through operation. However overall, the semiconductor loss is largest.

VI. Conclusion

A new type of improved T-Z source inverters for renewable energy application has been proposed. The proposed inverter used two transformers to replace two inductors in the classical Z-source inverters.The improved T-Z source inverter retain the basic X-shape structure as the conventional Z-source inverter. In this paper only two transformers are used, and a very high boost factor is obtained by changing the turn ratio of transformers and adjusting the shoot-through duty ratio.

The proposed improved T-Z source inverter does not use any additional diodes, although producing a high boost factor, which reduces size, cost, and loss compared to other existing high boost Z-network topologies. The proposed topology can be extended to variable topologies such as dc-link type and embedded type.

Moreover, the size and weight of transformers in the proposed improved T-Z source inverter are reduced significantly because the power rating and turn ratio of each transformer in the proposed inverter are smaller than those of the transformer in the con-ventional trans-ZSI under the same output power and voltage gain conditions. The experimental results for dc 100-V input verified the high-step-up inversion ability, and the simulation results show that the proposed inverter has high boost inversion ability. Also the BLDC load is added at the output of the inverter & the performance is viewed.

The proposed improved T-Z source inverter is applicable for fuel cells or photovoltaic applications where a low input voltage is inverted to a high ac output voltage. The transformers in the improved T-Z source inverter should be designed with low leakage inductance to improve the boost factor and eliminate the spike on the dc-link voltage. The proposed inverters can be applied to various dc-dc, dc-ac, ac-ac, and ac-dc power conversion applications as well.

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