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Coupled Capacitor Trans Z source Inverter CCT Z Source Inverter

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ABSTRACT

Z Source Inverters (ZSI) are very popular for buck-boost operations. The boost operation is achieved by either short circuiting any one of the phase leg or two phase legs and in some situations by short circuiting all three phase legs of inverter. The buck mode is similar to the traditional voltage inverter operation. The buck-boost capability together cannot be achieved by the traditional inverters since these inverters are either buck or boost inverter. The voltage level obtained for the boost operation with the use of present Z source inverter is not sufficient due to low modulation index. Further ZSI leads to high voltage stress across the components. However, the Trans Z Source Inverter (TZSI) subsequently introduced to overcome the above said problems involves the usage of many windings. In this paper a new configuration to be known as Coupled Capacitor Trans Z Source Inverter (CCTZSI) is introduced and explained. The advantages like higher level of boost voltage compared to earlier inverters (ZSI, TZSI) with less no of windings are demonstrated.

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INTRODUCTION

Semiconductor based power inverters are widely used in industrial applications such as ac motor drives, uninterruptible power supplies, and distributed power systems. The traditional inverter`s output voltage is always less (high) than the input dc voltage. Applications like electric vehicles and renewable energy systems the dc input of the inverter is not predictable but the required output of the inverter is fixed. However, traditional inverters are not suitable for these applications because they are not buck-boost converter. To sort out this problem an additional front end dc–dc converter or single-stage buck–boost inverters are essential. The former converter increases the cost and also reduces the reliability of the system. The latter has a few possible topologies like the Cuk- and SEPIC inverter discussed in (Kikuchi, J .and T.A. Lipo, 2002). Recently the Z source inverters (Peng, F.Z., 2003; Loh, P.C., *et al.*, 2007; Shen, M., *et al.*, 2006) are more attracted than the others. In Z source inverter boost mode of operation is achieved by short circuiting any one of the phase leg or two phase leg or all three phase legs of the inverter. At the same time buck mode of operation is achieved by operating this inverter like a traditional inverter i.e. shoots through period will not be provided.

The dc voltage source followed by X shaped impedance network with three leg inverter forms Z source inverter. It is shown in Fig.1.

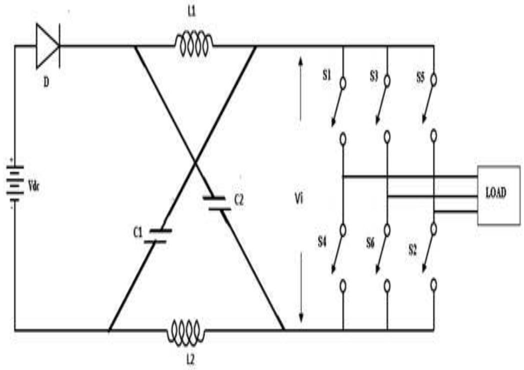

Fig. 1: Traditional Z source inverter

This inverter has nine switching states, including traditional eight non-shoot-through active states and one Shoot-through zero state. *Z*-source inverters are less exaggerated by miss firing of devices due to EMI. The other advantage of the inverter is dead time elimination that enhances the system reliability and waveform distortion. An overview on impedance source inverter control methods, types and performance is discussed in (Radhika, A and L. Sivakumar, 2015). The ZSI has been implemented already with many applications, including the motor drives proposed in (Rajaei, A.H., *et al.*, 2010),

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photovoltaic systems in (Huang, Y., *et al*., 2006), fuel cells in (Shen, M., *et al*., 2007), distribution generation systems in (Vinnikov, D. and I. Roasto, 2011), and uninterruptible power supplies in (Zhou, Z.J., *et al*., 2008).

Though the Z source inverter has more advantages than the other inverters, still it has some demerits. The first demerit is chopped input current which is resolved by embedded Z source inverter (Loh, P.C., *et al*., 2010; Gao, F., *et al*., 2011) Quasi Z source Inverter (Anderson, J. and F.Z. Peng, 2008; Vinnikov, D. and I. Roasto, 2011; Yang, S., *et al*., 2011; Nguyen, M.K., *et al*., 2011) and Trans Z source Inverter (Zhu, M., *et al*., 2010; Qian, W., *et al*., 2011; Adamowicz, M., 2011; Mo, W., *et al*., 2014). Second demerit is stress across the device is high. The newly developed Z source inverter resolves the about said problems. The proposed inverter consists of two inductors in a single core and three capacitors. One of the capacitor is in parallel with one inductor. This forms tuned circuit. By changing the turn`s ratio of the inductor the voltage gain of the inverter is raised to a large extend with reduced shoot through period. The component size of the inverter (inductor and capacitor) greatly reduced.

This paper is structured as follows: First, a brief discussion about traditional and Trans Z source inverter. The topology of proposed inverter is presented in section III for understanding the principle of operation and it is followed by formation of equation for boost factor and inverter output voltage. The theoretical analysis of the proposed topologies is verified by the simulation in section IV. Section V discusses a complete summary about the proposed topology as a conclusion.

Traditional And Trans-Impedance Source Inverter:

The pair of inductors L1 and L2 and the pair capacitors C1 and C2 associated with traditional Z source inverter is assumed to be the same value. Accordingly, we have

$L1 = L2 = L; \quad C1 = C2 = C;$

The Capacitor voltage Vc, peak dc-link voltage Vi, and peak ac voltage Vac of the ZSI can be written as:

$$Vc = \frac{1-d}{1-2d}Vdc$$

$$Vi = \frac{1}{1-2d}Vdc$$

$$Vac = \frac{1}{1-2d}(0.5MVdc) \quad (1)$$

Where Vdc, d and M represent the input dc voltage, shoot through duty ratio and modulation index of traditional Z source inverter respectively. The equations for Vi and Vac pertaining to Embedded ZSI and Quasi-Z source inverter are also reported (Loh, P.C., *et al*., 2010; Vinnikov, D. and I. Roasto, 2011) to be the same as equation (1).The only difference observed among them are their different capacitor voltages. However, Two constrains are to be ensured:

- The denominator of (1) should be greater than zero. This can be achieved by varying the d in the range of $0 \le d < 0.5$.
- To avoid volt-second error the shoot through states should only be inserted within traditional null intervals. Therefore the variation range of M should be decided by $0 \le M \le 1.15(1-d)$.

From Equation (1) in conjunction with two stated constrains, it is noticed that to get high gain, d must be increased and at the same time M must be lowered. As generally known lower M leads to poorer spectral performance at the inverter output (Shen, M., *et al*., 2006) and high voltage stresses across the components of inverter. To solve these limitations, the Trans Z-source inverters have been proposed (Qian, W., *et al*., 2011) a shown in Fig .2.

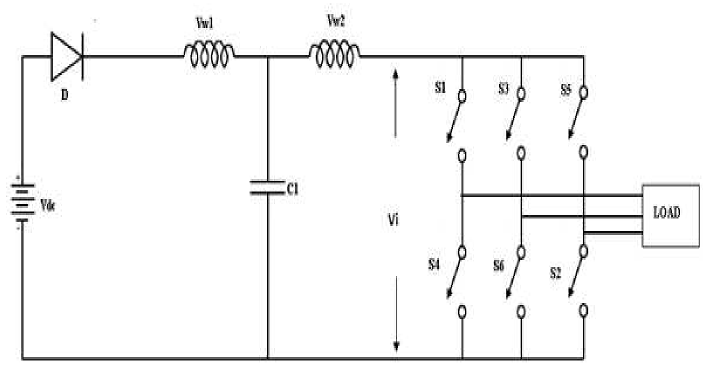

Fig. 2: Trans Z-source inverter

The trans-Z source inverter is capable of producing higher voltage gain because of its coupled transformer. The voltage expressions of trans-ZSI listed as follows (Qian, W., *et al*., 2011; Mo, W., *et al*., 2014).

$$Vc = \frac{1-d}{1-(1+n)d} Vdc$$

$$Vi = \frac{1}{1-(1+n)d} Vdc$$

$$Vac = \frac{1}{1-(1+n)d} (0.5MVdc) \quad (2)$$

Where n represents the transformer turns ratio. The equation (2) clearly states that the inverter voltage gain can be raised by increasing $n \geq 1, d$ or both. The denominator of (2) is made greater than zero by varying d in the range of $0 \leq d < 1/(1+n)$. The corresponding modulation index range is $0 \leq M \leq 1.15(1-d)$ and it resembles the traditional ZSI. However the M is high for smaller maximum d when n > 1. The Trans ZSI are capable of producing high voltage gain with high modulation index but suffers from the disadvantage of the windings getting burnt due to high instantaneous current during shoot through duration. The shoot through current is given by equation (3).

$$Ist = Iw2 = (1+n)Idc \quad (3)$$

Where Idc, is the average dc input current drawn from source. From equation (3) the shoot through current is high for high turns ratio. This causes high current stress across the devices. The authors have proposed a new type of ZSI named Coupled Capacitor Trans Z source Inverter to overcome this serious limitation.

Coupled Capacitor Trans Z Source Inverter:

The proposed Coupled Capacitor Trans Z Source Inverter is shown in Fig. 3. In general, the T-source inverter has one coupled transformer and one capacitor.

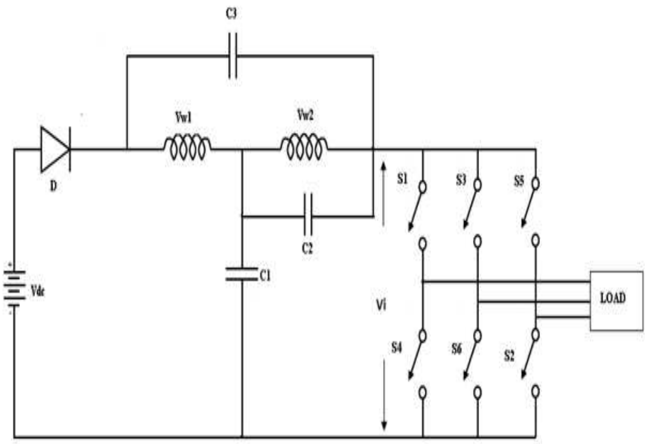

Fig. 3: Proposed Coupled Capacitor Trans Z Source Inverter

Comparing with the Trans Z source inverter, two more capacitor connected with Trans Z source Inverter to improve the boost capability and it will act as tank and tuned circuit. In general, six active states, two null states and one shoot through state have been introduced in Z source inverter for boosting of dc input voltage. The coupled capacitor T source inverter is capable of raising the gain with lower turns ratio. Operation of CCTSI is similar to the traditional Z-source and Trans-Z source inverters. The details of coupled capacitor T source inverter are described as follows:

Beginning with the non shoot-through state is shown in Fig. 4. Diode D starts to conduct, capacitors C1 and C2 start to charge in one direction and capacitor C3 charges in reverse direction.

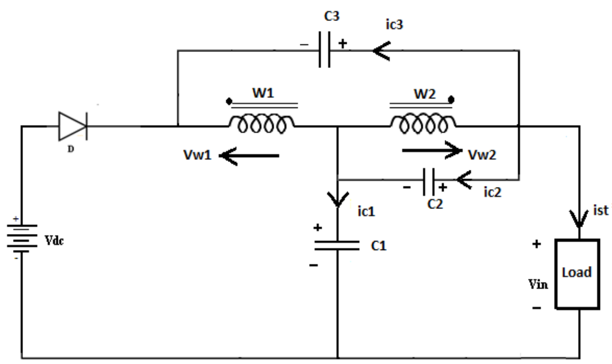

Fig. 4: Non shoot-through state

The corresponding voltage and current expressions are written as

$$Vc2 = -Vw2$$
$$Vc1 - Vc2 = Vin$$
$$Vw1 + Vc1 = Vdc$$
$$iw1 = ic1 + ic2 + iw2$$
$$idc + ic3 = iw1$$
$$iw1 = \frac{iw2}{n} + \mathrm{Im}$$

Im – magnetizing current

Two switches in the same leg are turned on during shoot through period. It is shown in fig.(5).

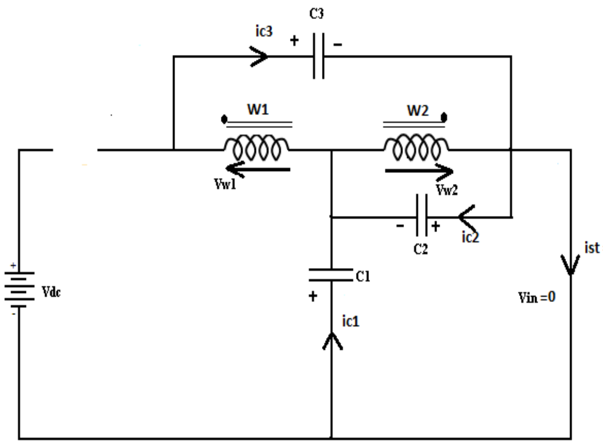

Fig. 5: Shoot through state

The input diode D reverses bias and capacitor C1 and C2 release their stored energy to the transformer. The corresponding voltage and current expressions are written as

$$Vw2 = -Vc2 = -Vc1$$
$$Vw2 = Vw1 + Vc3$$
$$iw1 = ic3$$
$$ic1 = iw1 - iw2$$

Average value of $Vc1 = 0$

$$(Vdc - Vw1)T1 - Vw2To = 0$$
$$Vw1 = nVw2$$
$$VdcT1 - Vw2(nT1 + To) = 0$$
$$Vw2 = \frac{VdcT1}{nT1 + T0} \quad (4)$$

Average Value of $Vc2 = 0$

$$(Vc1 - Vin)T1 + Vc1T0 = 0$$
$$Vc1 = \frac{VinT1}{T} \quad (5)$$
$$Vin = \frac{VdcT1}{(nT1 + T0)d} \quad (6)$$

$Vin = BVdc$ Where

$$B = \frac{T1}{(nT1 + T0)d} \geq 1 \quad (7)$$

B is the boost factor obtained from the shoot through state. Vin the peak dc link voltage of the inverter and the output peak phase voltage of the inverter can be expressed as

$$Vac = MB\frac{Vdc}{2} \quad (8)$$
$$Vac = M\frac{T1Vdc}{(nT1 + T0)2d} \quad (9)$$

Here M is modulation index. Comparing Vac of CCTSI with the traditional Z source inverter shows that CCTSI output is always higher than that of traditional ZSI for 0.1< n < 6. The turns ratio greater than 6 (n > 6) the inverter will act as a buck converter. The expression (9) tells that the CCTSI gain is raised by lowering the turns ratio, instead of increasing it like with the Trans Z Source Inverters. Other feature of the inverter is narrower shoot through range. The wider modulation index remains unchanged. Smaller turns ratio reduces the size, weight and cost of the inverter. Table 1 gives the detailed comparative analysis between the traditional ZSI, Trans ZSI and CCTSI.

Table I: Comparative Analysis Between The Traditional Zsi, Trans Zsi And Cctsi

	Traditional ZSI	Trans ZSI	CCTSI
Switch Number	6	6	6
Inductor number	2	2	2
Capacitor number	2	1	3
Turns requirement	Nil	n ≥ 2	0.1< n < 6
Control Method	Linear	Linear	Linear

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RESULTS AND DISCURSIONS

In order to verify and compare the performance of the proposed CCTSI with traditional ZSI and with Trans ZSI simulation has been done in Simulink/Matlab Platform. The circuit parameter of the CCTSI is shown in Table II.

Table II: Circuit Parameters Of The Cctsi

Parameters of System	Value
Dc voltage source, Vdc	100 V
Switching frequency	10KHz
Capacitors C1,C2 and C3	33 µF
Transformer Winding W1	108 turns
Transformer Winding W2	72 turns
Transformer coupling coefficient, k	0.998
Y connected RL load	10Ω, 40mH
Modulation index, M	0.85
Shoot through duty ratio, D (Boost mode)	0.16
Transformer turns Ratio, n	1.5
Fundamental AC frequency ,f	50Hz

The simulation has been done for the switching frequency of 10 KHz. The switching time period for this frequency is (1/ 2x 10,000) $5x10^{-5}$sec. Fig.6 shows the simulation waveform of Six IGBT's gate pulses. The shoot through pulse duration is 0.08×10^{-4} sec. In this case, the modulation index was set to

M=0.85 and the shoot-through duty cycle was set to *T0/T* = 0.16. The purpose of the system is to produce a three phase 150 Vrms power from dc voltage source of 100V. Based on above analysis; we have the following theoretical calculations:

$$B = \frac{T1}{(nT1+T0)d} = 4.11$$

$$Vin = \frac{VdcT1}{(nT1+T0)d} = 411V$$

$$Vac = MB\frac{Vdc}{2} = 0.85x4.11x100/2 = 175 \text{ V}$$

The above result shows the phase peak voltage, for that the line-to-line voltage is 303 Vrms or 214 V peak. Fig(6),(7),(8),(9) and (10) showing the simulation results of gate control signals, dc link voltage, capacitor Voltage, transformer primary current and phase peak inverter output voltage and current respectively. Table III shows that comparison of simulation results with calculated values for the CCTSI.

Table III: Comparison Of Simulation Results With Calculated Values For The Cctsi

Variable	Vpeak	IL	Pout(W)
Calculated	214	7.5	2230
Simulation	205	7.8	2215

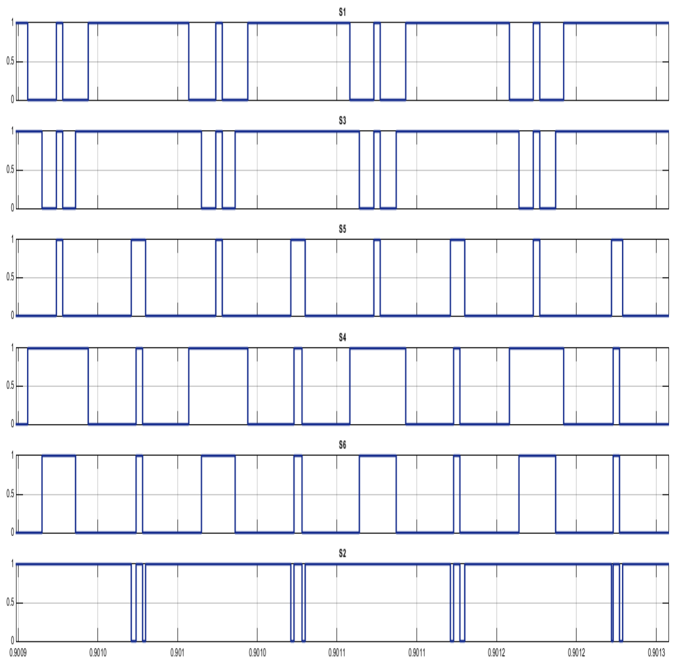

Fig. 6: Simulation results of gate control signals

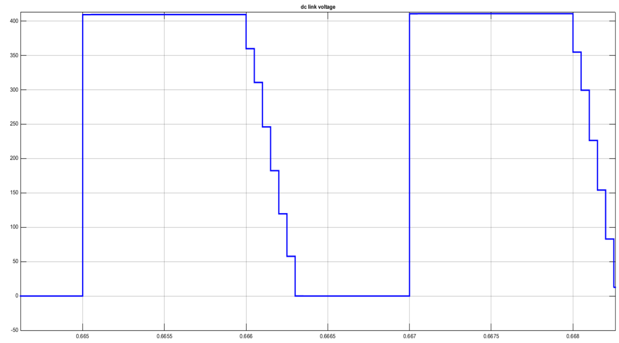

Fig. 7: Simulated dc link voltage

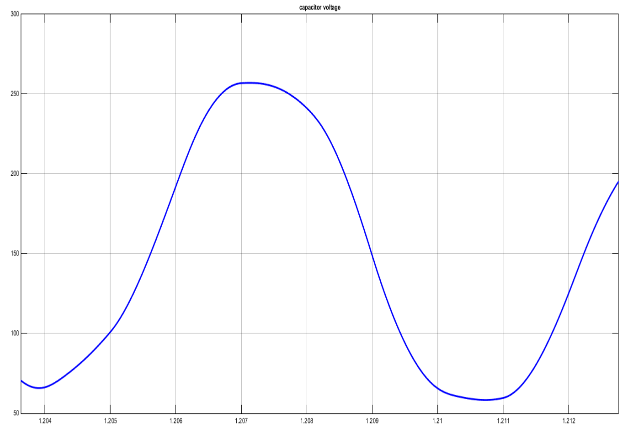

Fig. 8: Simulated capacitor Voltage

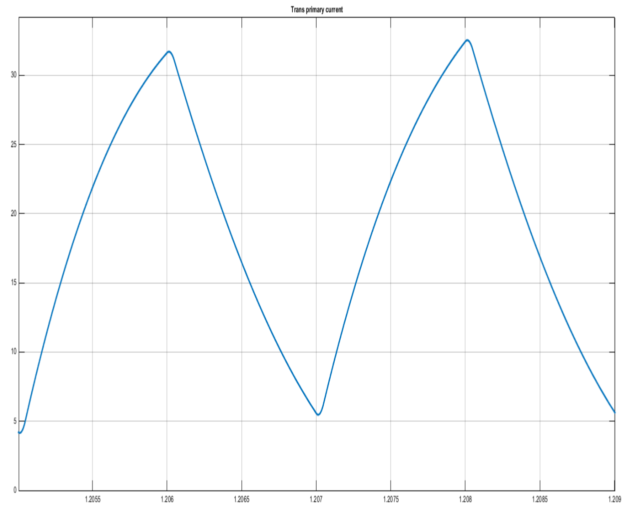

Fig. 9: Simulated transformer primary current

The dc link voltage is the addition of capacitor voltage ($Vc1$) and the voltage across the primary winding ($Vw1$). The capacitor voltage is decided by the active time period (T1) and the switching period (T). The active time period T1 = 4.2×10^{-5}sec and the switching period T = 5×10^{-5}sec. From equation (5) the calculated capacitor voltage is 280 V. The simulation result of capacitor voltage shows the value of 260V. The simulated primary winding current is 30A which is the summation of capacitors current and the secondary winding current.

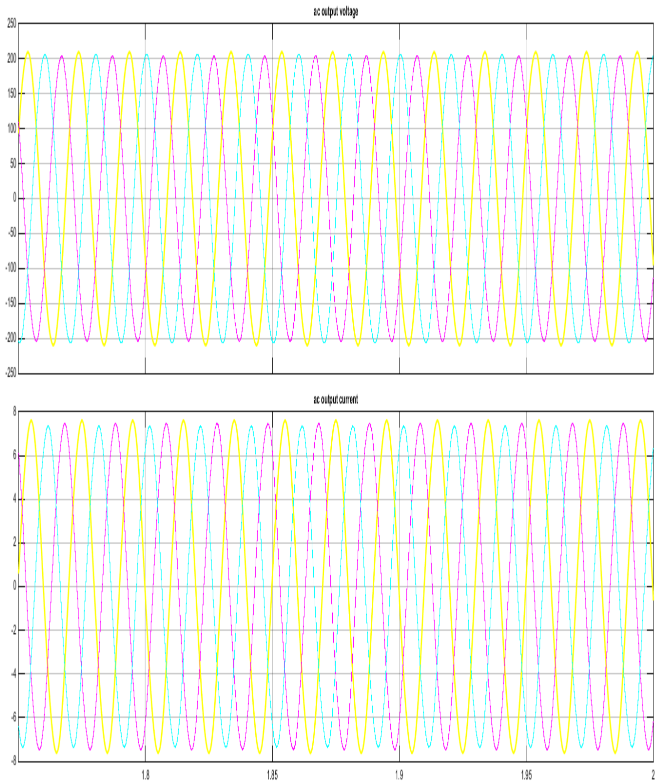

Fig. 10: Simulation results of phase peak inverter output voltage and current

Table IV: Comparative Results Of Cctsi With Zsi And Trans Zsi

	ZSI	TZSI	CCTZSI
Input dc Voltage (VDC)	100 V	100 V	100 V
Turns ratio (n)	------	3.6	1.5
DC Link Voltage (Vi)	352 V	378 V	411 V
Output Peak phase Voltage (VAC)	113 V	123 V	175 V
Modulation index (M)	0.64	0.65	0.85
Shoot through Period (T0)	0.179 µsec	0.08 µsec	0.08 µsec
Duty ratio	0.358	0.16	0.16

Table IV shows the comparative results of CCTSI with ZSI and Trans ZSI. This results show us the turn's ratio requirement of CCTZSI is very less compared to TSI. This reason the size, weight and cost of passive components are reduced. Compared to ZSI the shoot through period of CCTSI is very less because of this stress across the device is less. The CCTSI output voltage is high compared to other two inverters.

Conclusions:

A new type of T source inverter named coupled capacitor T source inverter. CCTSI lends itself for high boost capacity as well as for three phase applications. The high boost capacity is achieved by adjusting turn's ratio of the coupled transformer. It has been demonstrated that the gain of the inverter is raised by lowering the turn's ratio from 0.1 to 6. Further it is observed the shoot through period requirement is very less. Because of these reasons the size, weight and cost of passive components are reduced. The simulation has been done in Matlab/Simulink platform for the load capacity of 2.2KW.

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