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A Fuel Cell Fed Single Stage Boost Inverter with Unique Impedance Network

K.Sruthi[1], C.B Saravanan[2]

PG Student [PE&ED], Dept. of EEE, SVCET, Chittoor, Andhra Pradesh, India[1]

Associate professor, Dept. of EEE, SVCET, Chittoor, Andhra Pradesh, India[2]

ABSTRACT: In many modern energy conversion systems, a dc voltage, which is provided from a sustainable energy source or energy storage device, must be boosted and converted to an Ac voltage with a fixed amplitude and frequency. The single-stage inverter circuit provides boost inversion ability which can eliminate the limitations of conventional voltage source inverter. By regulating the shoot-through zero state and the parameters of coupled inductor, the proposed inverter can boost the bus voltage and output desired output voltage even when input dc voltage is low. By controlling the shoot-through zero state when the coupled inductor is present, the fuel cell output voltage is controlled. When a very high boost gain is demanded, the duty cycle may come to its extreme and large duty cycles causes serious reverse-recovery problems. The single-stage operation of the converter may lead to improved reliability and higher efficiency .The results are obtained using MATLAB/SIMULINK software.

KEYWORDS: coupled inductor, Boost inverter, and shoot through zero state, fuel cell

I. INTRODUCTION

Increasing global energy consumption and noticeable environmental pollution are making renewable energy more important. Today, a small percentage of total global energy comes from renewable sources, mainly hydro and wind power. However, global energy consumption is expected to expand by 58% between 2001 and 2025. As more countries ratify the Kyoto Accord, an international agreement to reduce greenhouse gas (GHG) emissions, new power generation capacity can no longer be met by traditional methods such as burning coal, oil, natural gas, etc. However, these DG units produce a wide range of voltages[6] due to the fluctuation of energy resources and impose stringent requirements for the inverter topologies and controls. Usually, boost-type dc–dc converters added in the DG units to step up the dc voltage. This kind of topology, although simple may not be able to provide enough dc voltage gain when the input is very low, even with an extreme duty cycle. Also, large duty cycle operation may result in serious reverse-recovery problems and increase the ratings of switching devices. Distributed generation [7] (DG) technologies provide a potential solution of increasing electrical power generation capacity for renewable energy systems. Compared to large, centralized power grids, DG systems are usually small modular devices with increased security and reliability, and are generally[1]-[3] close to electricity users, thus reducing the problems of power transmission and power quality issues due to very long transmission lines. DG systems often need dc-ac converters or inverters as an interface between their power sources and their typical single-phase loads. Single-stage topologies, which integrate performance of each stage in a multistage power converter, are becoming the focus of research. Though they may cause increased control complexity, they may offer higher efficiency, reliability, and lower cost[8]. Its observed that many single-stage voltage source and current source [11], inverters have been proposed.

A Z-source inverter (ZSI) proposed in is able to overcome the problems in conventional VSI and conventional current source inverter.

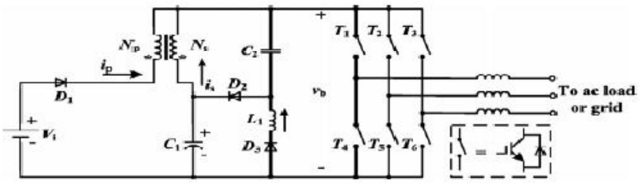

Fig. 1. Topology of single-stage boost inverter with coupled inductor.

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II. SINGLE-STAGE BOOST INVERTER

Fig. 1 shows the general structure of the proposed single stage boost inverter. It employs a unique impedance network to combine the three-phase inverter bridge with the power source. The impedance network does not introduce any switching devices and may lead to improved reliability, higher efficiency, and lower cost. To extend the operation range of the inverter, coupled inductor with a low leakage inductance is used. The DC source can be a battery, diode rectifier, fuel cell, or PV cell. To describe the operating principle and characteristics, this paper focuses on one application example of the single-stage boost inverter: a single-stage boost inverter for wind power generation. For wind power generation system, variable speed wind turbines often adopted because it is known to provide more effective power tracking than fixed speed wind turbines [22]. Fig. 2presents the relationship between the generator power output and rotational speed relating to wind speed changes. Note that the output power of wind turbine may be at a low level under a weak wind condition. Fig. 3 shows the conventional two stage power conversion for wind power generation. A front-end dc–dc boost converter is added to step up bus voltage especially under weak wind condition, because the conventional VSI cannot produce an ac voltage larger than the dc input voltage. The proposed single-stage boost inverter for wind power generation application is shown in Fig. 4. The system can produce an ac voltage larger or smaller than the input dc voltage with single stage operation. The diode *D*1 in series with $L_p$is necessary for preventing reverse current flow.

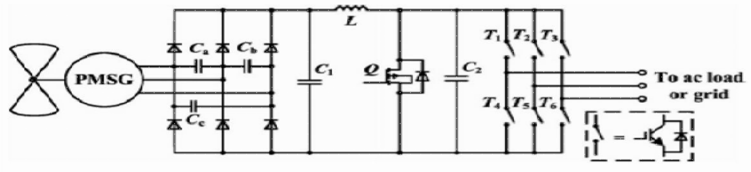


Fig.3. Traditional two-stage power conversion for wind power generation

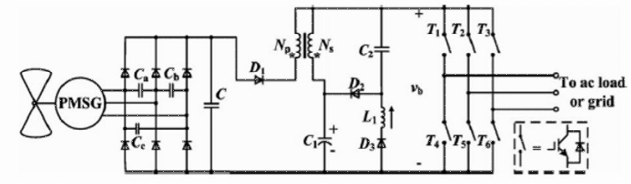
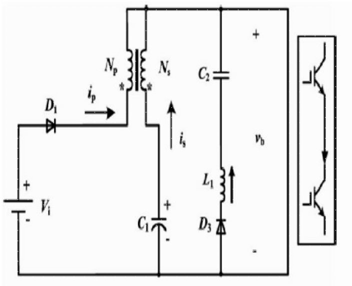


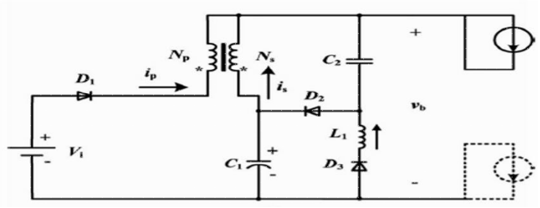
Fig.4. Single-stage boost inverter with coupled inductor for wind power Generation

III. OPERATION PRINCIPLE, BOOST FEATURE ANALYSIS, ANDCONTROL STRATEGY

Conventional VSI has eight possible switching states [23], of which two are zero states and six are active states. Two zero states make load terminals shorted through, and can be assumed by turning on upper or lower three devices, respectively. Six active states can be assumed by turning on the switches from different phase legs, when the input dc voltage is applied across the load. However, the three phase single-stage boost inverter has one extra zero state when the load terminals are shorted through both the upper and lower devices of any one phase leg, any two phase legs, or all three phase legs. To distinguish the two kinds of zero state mentioned earlier, we call the two zero open-zero states, and the extra zero states shoot through zero state. Shoot-through zero state is forbidden in the conventional VSI because it would make device failure events happen. Combined with the impedance network in front of the three-phase bridge, the shoot-through zero state provides the unique boost feature to the inverter. It should be noted that shoot-through zero states are allocated into open-zero states without changing the total open-zero state time intervals. Thetis, the active states are unchanged. Thus, the shoot-through zero state does not affect the pulse width modulation (PWM) control of the inverter, because it equivalently produces the same zero voltage as the open-zero state to the load terminal. In this there are three states shown in fig 5
State 1: The converter is in shoot-through zero state under this duration, as shown in Fig. 5(a). Bus voltage v_b was shorted to ground and diode *D*2 is reversely biased. Input dc voltage is applied across primary winding of the coupled inductor, making primary current linearly increase. The inductive voltage of secondary winding charges *C*1. At the same time, *C*2 is discharged by *L*1 with linearly increasing current, assuming that the capacitor voltage is constant.



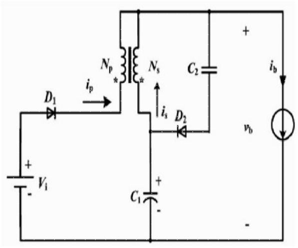
5(a). Shoot-through zero state.



5(b). Open Zero state.

State 2: During this interval, the converter is in one of the two traditional open-zero states, as shown in Fig. 5(b). Inductor $L1$and secondary winding of the coupled inductor charge capacitors$C1$ and $C2$ through diode $D2$, respectively. In this state, the current of inductor $L1$ decreases from peak value to zero

State 3: When the circuit is in one of the six active states, as shown in Fig. 5(c), diode $D3$ is reverse biased. The energy stored in the coupled inductor and $C1$ releases to the load, and the bus voltage is stepped up to a higher level.



5(c). Active state.

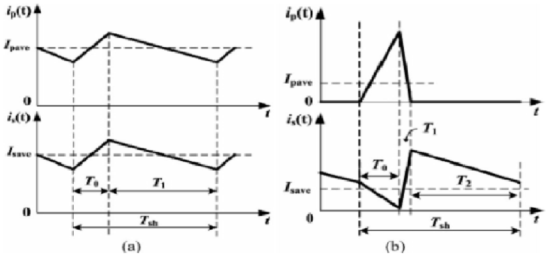


Fig. 6. Coupled inductor current waveforms under two operation modes. (a)Inductor Lp works in CCM. (b) Inductor Lp works in DCM

Two boost modes can be achieved by regulating the shoot through zero state as well as configuring the turn ratio and coupling coefficient of the coupled inductor. Operating principle of the single-stage boost inverter is analysed under these two modes. When applying the converter to voltage drop compensation or applications where lower boost gain is needed, the inductance of coupled inductor should be designed large enough to ensure its continuous current-mode operation. When higher boost gain is required, the inductance of the primary winding L_p should be as small as to keep the circuit working in discontinuous current mode. Fig. 6 shows coupled inductor current waveform in one shoot through period T_{sh} under two operation modes, respectively. Note that the shoot-through period T_{sh} is the equivalent switching period viewed from the impedance network, which is note equivalent to the switching period T_s of the inverter bridge. T_{sh} may be two or six times of T_s, determinedly the modulation scheme it used [16], [24], [25], which reduces the required size and weight of the coupled inductor

A. ***Lower Voltage Boost Gain Mode :***In lower voltage boost gain applications, the key characteristics that the current through L_p generally works in continuous mode, as shown in Fig. 6(a).Define the shoot-through duty cycle $D0$ as the time when the three phase bridge is in shoot-through state, and the duty cycle$1 - D0$ as the time when the three-phase bridge is in non shoot through state, the average voltage across the

$$\langle v_{Lp}(t)\rangle_{T_{sh}}^{\mathrm{CCM}} = D_0 V_i + (1 - D_0)(V_i - v_b) = 0. \qquad (1)$$

From (1), the amplitude of bus voltage can be expressed asfollows:

$$\hat{v}_b = \frac{1}{1 - D_0} \times V_i . \qquad (2)$$

Define B as the boost gain,$B = \_vbVi$, which can be expressedas

$$B = \frac{1}{1 - D_0} . \qquad (3)$$

The boost gain is similar to that of conventional dc–dc boostconverter in this boost mode.

B. ***Higher Voltage Boost Gain Mode:*** In higher voltage boost gain applications, the key characteristics that the inductance of primary winding is less than that of secondary winding, and primary winding current generally works in discontinuous mode, as shown in Fig. 6(b).Define the coupling coefficient as

$$k = \frac{M}{\sqrt{L_p \times L_s}} \tag{4}$$

Where *Lp*, *Ls*, and *M* are the self-inductance of each winding and the mutual inductance, and the effective turn ratio

$$N_e = \sqrt{\frac{L_s}{L_p}}. \tag{5}$$

Define the duty cycle *D*1 as the time when the inductor *Lp* current decreasing from peak value to zero, the average voltage across the both sides of coupled inductor during one shoot through period can be expressed as

$$\langle v_{L_p}(t)\rangle_{T_{sh}}^{DCM} = D_0 V_i + D_1 (V_i - v_b) + (1 - D_0 - D_1)\frac{k(V_{c1} - v_b)}{N_e} = 0 \tag{6}$$

$$\langle v_{L_s}(t)\rangle_{T_{sh}}^{DCM} = D_0 V_{c1} + (1 - D_0)(V_{c1} - v_b) = 0. \tag{7}$$

From (6) and (7), the amplitude of bus voltage can be expressed as

$$\hat{v}_b = \frac{(D_0 + D_1) N_e}{D_1 N_e + D_0 (1 - D_0 - D_1) \times k} \times V_i. \tag{8}$$

Define physical turn ratio of ideal transformer as *N* = *Ns*/*Np*. According to the relationship of *Ne* and *N*: *Ne* = *N* × *k*, (8) can be simplified as

$$B = \frac{\hat{v}_b}{V_i} = \frac{(D_0 + D_1) N}{D_1 N + D_0 (1 - D_0 - D_1)}. \tag{9}$$

The output peak phase voltage ˆvac generated by the inverter can be expressed as

$$\hat{v}_{ac} = mB\frac{V_i}{2} \tag{10}$$

Where *m* is the modulation index, *m* ≤ 1 for synchronized PWM (SPWM), and *m* ≤ 2/√3 for space vector PWM. The output ac voltage can be stepped up or down by choosing an appropriate voltage gain *G*

$G = m*B$ (11)

From (11), the voltage gain *G*Is determined by the modulation index *m* and boost gain *B*. The available output ac voltage is able to change in a wide range by regulating *G*. The boost gain as expressed in (9) can be controlled by shoot-through duty cycle *D*0 , duty cycle *D*1 and physical turn ratio *N* of the coupled inductor. It should be noted that the available shoot-through duty cycle is limited by the traditional open-zero duty cycle which is determined by the modulation index *m*. The shoot-through zero state does not affect the PWM control of the inverter, because it equivalently produces the same voltage to the load terminal. As analysed earlier, by designing different coupled inductor and regulating the duty cycle, the single-stage boost inverter not only can be applied to voltage drop compensation or applications where lower boost gain is needed, but it can also can be applied to higher boost requirements. The capacitor *C*1 and *C*2 voltage are dependent on the shoot through state and can be stepped up by changing the shoot through duty cycle. The average bus voltage is identical to the capacitor *C*1 voltage because the average voltage across secondary winding of coupled inductor during one shoot-through period is zero. The capacitor *C*1 and *C*2 voltage can be expressed as

$$V_{c1} = \hat{v}_b \times (1 - D_0) \tag{12}$$

$$V_{c2} = \hat{v}_b \times D_0. \tag{13}$$

$$D_1 = \frac{[NV_i - (1 - D_0)\hat{v}_b] D_0}{(N - D_0)\hat{v}_b - NV_i} \tag{14}$$

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When the voltage at the diode bridge output provided by the generator in wind power generation system is approximately300 V_{dc}, without any boost mode, the voltage at the inverter bridge input will also be approximately 300 V_{dc}. The inverter can only output a phase voltage of 106 Vrms based on SPWM control under modulation index m being 1. In order to obtain phase voltage of 220 Vrms, the minimum voltage at the inverter bridge input must be greater than 620V_{dc} . Therefore, the voltage at the diode bridge output needs to be boosted, and the single stage boost inverter with higher boost gain should be used. According to aforementioned analysis, in higher voltage boost gain applications, boost gain B as expressed in (9) is not only determined by shoot-through duty cycle $D0$, but also by duty cycle $D1$, and the physical turn ratio of coupled inductor.

Duty cycle D_1 can be expressed as

$$D_1 = \frac{[N_e/k - (1-D_0)\,B]\,D_0}{(N_e/k - D_0)\,B - N_e/k}. \qquad (15)$$

Combined with (5) and (15), we know that when inductances of the coupled inductor are fixed, the effective turn ratio $N_e$is determined. Because bus voltage is regulated by means of closed-loop control of shoot through zero state.

$$D_0 = 1 - \frac{\sqrt{3}m}{2} \qquad (16)$$

IV. COUPLED INDUCTOR DESIGN ANALYSIS

As analysed earlier, the bus voltage of the proposed converter can be stepped up to a higher level by regulating the shoot-through duty cycle and configuring the turn ratio and the coupling coefficient of the coupled inductor. This paper takes higher voltage boost gain applications as an example to demonstrate the operating principle of coupled inductor in detail.

A. Transformer Model of Coupled Inductor:

Transformer model can be derived mathematically and can be expressed by the following equations:

$$\begin{aligned} v_p &= L_p\frac{di_p}{dt} + M\frac{di_s}{dt} \\ v_s &= M\frac{di_p}{dt} + L_s\frac{di_s}{dt} \end{aligned} \qquad (17)$$

Where mutual inductance M is positive under direct coupling condition. The expressions can be

$$\begin{aligned} v_p &= L_p\left(1 - \frac{M^2}{L_pL_s}\right)\frac{di_p}{dt} + \frac{M}{L_s}v_s \\ v_s &= \frac{M}{L_p}v_p + L_s\left(1 - \frac{M^2}{L_pL_s}\right)\frac{di_s}{dt}. \end{aligned} \qquad (18)$$

$$\begin{aligned} L_s &= N_e^2 L_p = N^2k^2L \\ M &= k\sqrt{L_pL_s} = k^2NL. \end{aligned} \qquad (19)$$

According to (4) and (19), (18) can be simplified as

$$\begin{aligned} v_p &= L\left(1 - k^2\right)\frac{di_p}{dt} + \frac{1}{N}v_s \\ v_s &= k^2Nv_p + (Nk)^2\left(1 - k^2\right)L\frac{di_s}{dt}. \end{aligned} \qquad (20)$$

According to (20), an equivalent circuit can be constructed as shown in Fig. 10,
where $(1 - k^2)$ $L$and k^2L refer to leakage inductance L_k and magnetizing inductance Lm, respectively. This circuit is one form of the transformer models for coupled inductor, where the leakage inductor appears only on one side. Hence, the coupled inductor is modelled as a magnetizing inductor, an ideal transformer with a turn ratio of N, and a leakage inductor.

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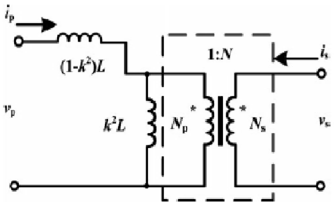

Fig. 7. Equivalent circuit of coupled inductor.

V. GRID INTERCONNECTION OF FUEL CELL SYSTEM

The fuel cells generate DC electrical energy from hydrogen by using a chemical process and their emissions are water. Therefore, power electronic circuits are an enabling technology that is necessary to convert DC electrical power generated by a fuel cell into usable AC power for passive loads, automotive applications, and interfaces with electric utilities. The fuel cell DG system is interfaced with the utility network via boost DC/DC converters and a three-phase pulse-width modulation (PWM) DC/AC inverter. In recent decades, various power electronic circuits have been proposed to interface fuel cell DG system with the utility grid. The DC voltage generated by a fuel cell stack varies widely and is low in magnitude. Grid interconnection of fuel system requires high ac voltage. But conventional dc-dc and dc-ac (two stage conversion) is more complex and costlier. For eliminating these disadvantages, in this paper single stage boost inverter is proposed for grid connection of fuel cell system. The boost inverter directly converts the low voltage dc into high voltage ac, which can be easily grid connected.

VI.MATLAB MODELLING AND SIMULATION RESULTS

Here simulation is carried out in different cases 1).Proposed Single Stage Boost Inverter with Coupled Inductors 2) Proposed Single Stage Boost Inverter with Coupled Inductors with Fuel Cells.

Case 1: ***Proposed Single Stage Boost Inverter with Coupled Inductors***

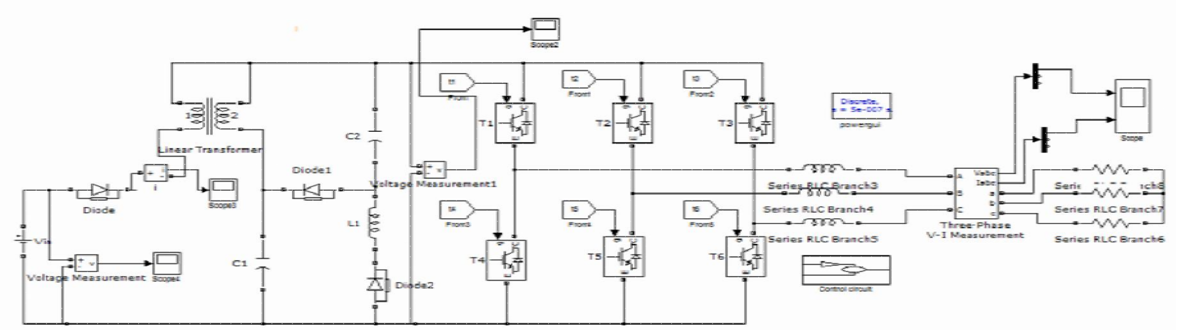

Fig.8 Mat lab/Simulink Model of Proposed Single Stage Boost Inverter with Coupled Inductors

As Fig.8 shows the Mat lab/Simulink Model of Proposed Single Stage Boost Inverter with Coupled Inductors using Mat lab/Simulink Platform.

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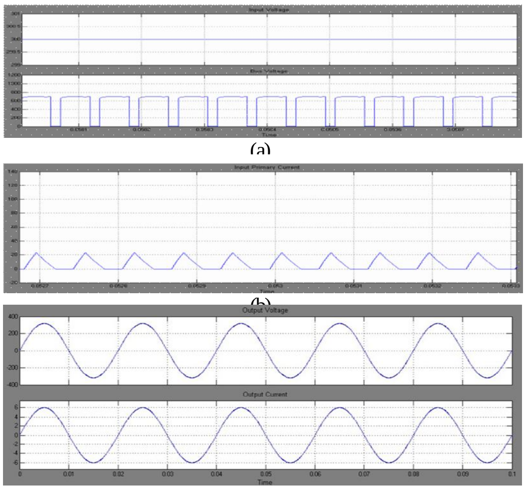


(a)

(b)

(c)

Fig. 9Simulation waveforms. (a) Input dc voltage *Vi* and bus voltage *vb*

b) Primary winding current *ip* (c) Input dc voltage *Vi* and output phase voltage *va b.*

As Fig.9 shows the Simulation waveforms of proposed Single Stage Boost Inverter (a) Input dc voltage *Vi* and bus voltage *vb* .(b) Primary winding current *ip* (c) Input dc voltage *Vi* and output phase voltage *va b*.

*Case 2: **Proposed Single Stage Boost Inverter with Coupled Inductors with Fuel Cells***

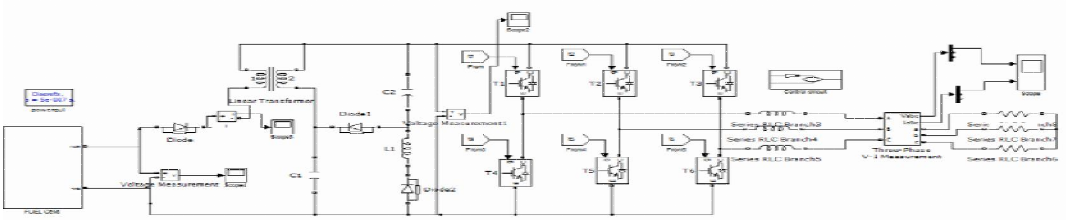
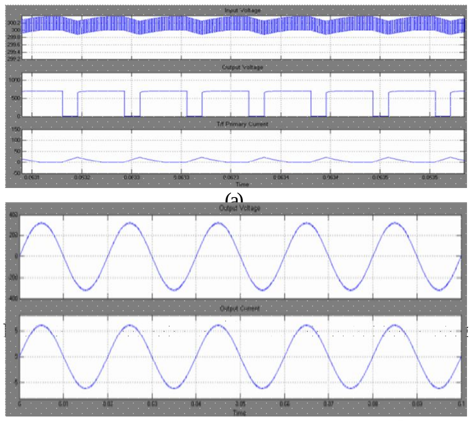


Fig.10 Mat lab/Simulink Model of Proposed Single Stage Boost Inverter with Coupled Inductors with Fuel Cells

Fuel Using Mat lab/Simulink



(a)

e

,Fig. 11Simulation waveforms. (a) Input dc voltage *Vi* and bus voltage *vb*, Primary winding current *ip* (b) Input dc voltage *Vi* and output phase voltage *va b.*

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VII. CONCLUSION

This paper has presented a novel single-stage boost inverter with coupled inductor with constant DC source as well as Fuel Cell energy source, which exhibits several merits. It employs a unique impedance network including coupled inductor to connect the three-phase inverter bridge to the power source. By designing the coupled inductor properly and adjusting the previously forbidden shoot-through zero state, the magnitude of the bus voltage can be greatly stepped up. By configuring turn ratio and coupling coefficient of the coupled inductor differently, the impedance network can work in two boost modes making it suitable for different inverting applications. Shoot-through states, which are forbidden in conventional VSIs, are utilized to store and transfer energy within the impedance network to boost the amplitude of the bus voltage. Waveform distortion of the ac output voltagecaused by dead time is essentially avoided.

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