Fuel Cell Fed Single-Stage Boost Inverter with Coupled Inductor

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ABSTRACT *Inverter systems that feed electrical power from fuel cells into the grid must convert the direct current of the fuel cell into the alternating current of the grid. The 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 desired output voltage even when input Dc voltage is low. The single-stage operation of the converter may lead to improved reliability and higher efficiency. Theoretical analysis, simulation, and experimental results are presented to verify good performance.*

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 green house 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, a boost-type dc–dc converter is added in the DG units to step up the dc voltage [3]–[4].

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]. It is 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. It can provide a wide range of obtainable voltage [5] and has been applied to renewable power generation systems.

Four quasi-Z-source inverters (qZSIs) derived from the conventional ZSI have been proposed in [2], whose basic principles are similar to those of conventional ZSI. Corresponding control methods and application conditions of conventional ZSI also fit for the qZSIs in theory. Anderson and Peng [10] show some advantages of qZSIs over conventional ZSI, such as lower voltage/current stress of impedance network and lower switch voltage stress. Nevertheless, they do not overcome the limits of conventional ZSI described earlier.

II. PROPOSED 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 turbine is often adopted because it is known to provide more effective power tracking than fixed speed wind turbines. Note that the output power of wind turbine may be at a low level under a weak wind condition. Fig. 2 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. 3. The system can produce an ac voltage larger or smaller than the input dc voltage with single stage operation. The diode $D1$ in series with Lp is necessary for preventing reverse current flow.
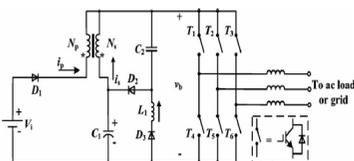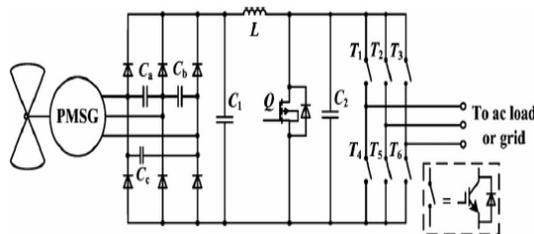

Fig.2. Traditional two-stage power conversion for wind power generation

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

III. Operation and control strategy using fuel cell

To convert the chemicals hydrogen and oxygen into water, and in the process it produces electricity. <u>Battery</u> the other electrochemical device that we are all familiar. A battery has all of its chemicals stored inside, and it converts those chemicals into electricity too. This means that a battery eventually "goes dead" and you either throw it away or recharge it. Fuel cells are environmentally sound renewable energy sources that are capable of operating at efficiencies greater than traditional energy production methods.
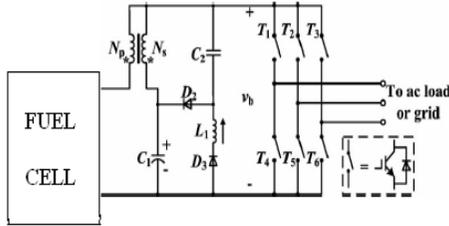

Fig.3. Fuel Cell fed Single-Stage Coupled Inductor Boost Inverter

The fuel cells are electrochemical devices that convert chemical energy directly into electrical energy by the reaction of hydrogen from fuel and oxygen from the air without regard to climate conditions, unlike hydro or wind turbines and photovoltaic array.

## IV. OPERATION PRINCIPLE, BOOST FEATURE ANALYSIS, AND CONTROL STRATEGY

Conventional VSI has eight possible switching states, 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 states 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. That is, 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 below.

State 1: The converter is in shoot-through zero state under this duration, as shown in Fig. 4(a). Bus voltage *vb* was shorted to ground and diode $D2$ 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 $C1$. At the same time, $C2$ is discharged by $L1$ with linearly increasing current, assuming that the capacitor voltage is constant.
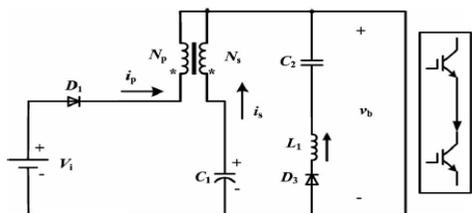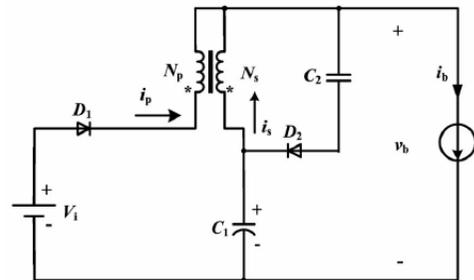

4(a). Shoot-through zero state.

State 2: During this interval, the converter is in one of the two traditional open-zero states, as shown in Fig. 4(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
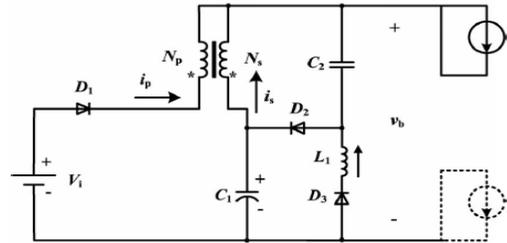

4(b). Open-zero state.

State 3: When the circuit is in one of the six active states, as shown in Fig. 4(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.

4(c). Active state.

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 analyzed 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.
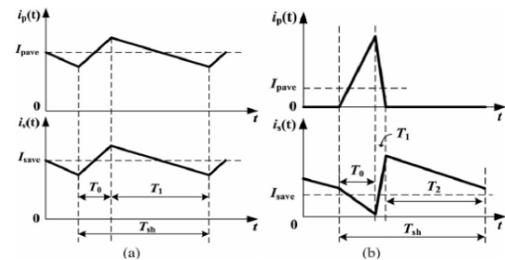
Fig.5. Coupled inductor current waveforms under two operation modes. (a) Inductor Lp works in CCM. (b) Inductor Lp works in DCM.

When higher boost gain is required, the inductance of the primary winding Lp should be as small as to keep the circuit working in discontinuous current mode. Fig.5 shows coupled inductor current waveform in one shoot-through period Tsh under two operation modes, respectively. Note that the shoot-through period Tsh is the equivalent switching period viewed from the impedance network, which is not equivalent to the switching period Ts of the inverter bridge. Tsh may be two or six times of Ts, determined by the modulation scheme it used which reduces the required size and weight of the coupled inductor

Lower Voltage Boost Gain Mode

In lower voltage boost gain applications, the key characteristic is that the current through Lp generally works in continu-

ous mode, as shown in Fig. 5(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 primary winding

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

From (1), the amplitude of bus voltage can be expressed as Fol-

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

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

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

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

Higher Voltage Boost Gain Mode
In higher voltage boost gain applications, the key characteristic is 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. 5(b). Define the coupling coefficient as

$$k = \frac{M}{\sqrt{L_p \times L_s}} \qquad (4)$$

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

$$N_e = \sqrt{\frac{L_s}{L_p}}. \qquad (5)$$

Define the duty cycle $D1$ 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

$$\langle vLp(t)\rangle_{Tsh}^{DCM} = D0Vi + D1(Vi - vb) + (1 - D0 - D1) = 0 \qquad (6)$$

$$\langle vLp(t)\rangle_{Tsh}^{DCM} = D0Vc1 + (1 - D0)(Vc1 - vb) = 0 \qquad (7)$$

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

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

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

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

The output peak phase voltage $\hat{v}ac$ generated by the inverter can be expressed as

$$(v)\hat{}_{ac} = mB V_i/2 \qquad (10)$$

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

$$G=m*B \qquad (11)$$

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 B as expressed in (9) can be controlled by shoot-through duty cycle $D0$, duty cycle $D1$ 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 analyzed 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 $C1$ and $C2$ 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 $‹C1$ voltage because the average voltage across secondary winding of coupled inductor during one shoot-through period is zero. The capacitor $C1$ and $C2$ voltage can be expressed as

$$V_{c1}=*(1-D_o) \qquad (12)$$

$$V_{c2}=*D_o \qquad (13)$$

The duty cycle can be expressed as

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

When the voltage at the diode bridge output provided by the generator in wind power generation system is approximately 300 Vdc, without any boost mode, the voltage at the inverter bridge input will also be approximately 300 Vdc. 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 620 Vdc. 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 $D1$ 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 Ne is determined. Because bus voltage is regulated by means of closed-loop control of shoot-through zero state.

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

V. COUPLED INDUCTOR DESIGN ANALYSIS
As analyzed 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.

Transformer Model of Coupled Inductor
Transformer model can be derived mathematically and can be expressed by the following equations:

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

where mutual inductance M is positive under direct coupling condition. The expressions can be rearranged as follows:

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

Assuming that $Lp = L$, (4) and (5) can be expressed as

$$L_s = N_e^2 L_p = N^2 k^2 L$$
$$M = k\sqrt{L_p L_s} = k^2 N L. \qquad (19)$$

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

$$v_p = L\left(1 - k^2\right)\frac{di_p}{dt} + \frac{1}{N}v_s$$

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

According to (20), an equivalent circuit can be constructed as shown in Fig. 6, where $(1 - k2)$ L and $k2$ L refer to leakage inductance Lk and magnetizing inductance Lm, respectively. This circuit is one form of the transformer models for coupled
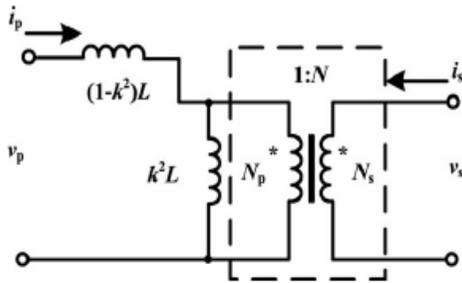

Fig.6. Equivalent circuit of coupled inductor.

inductor, where the leakage inductor appears only on one side. Hence, the coupled inductor is modeled as a magnetizing inductor, an ideal transformer with a turn ratio of N, and a leakage inductor.

VI. SIMULATION AND EXPERIMENTAL RESULTS
case 1: single-stage boost inverter with coupled inductor
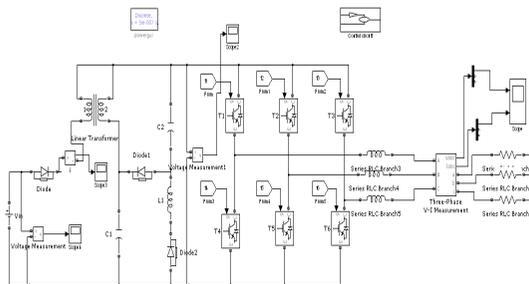
Fig.7. circuit diagram of the single-stage boost inverter with coupled inductor
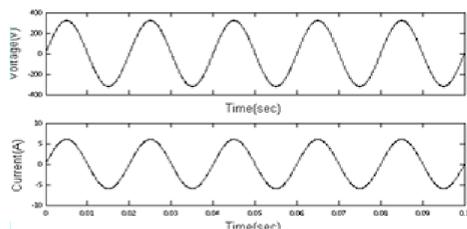

Fig.8. output voltage and current wave form.

The output wave form for the proposed single stage Boost Inverter with Coupled Inductor voltage and current wave forms.
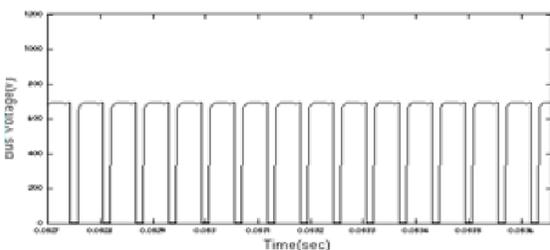
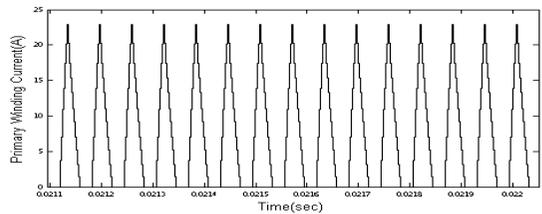

Fig.9. wave form of bus voltage *vb*.

Fig.10. wave form of primary winding current ip

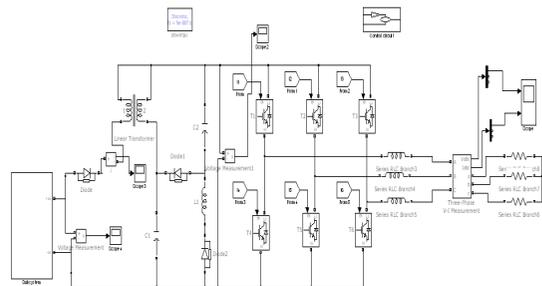### Case2: Fuel Cell fed Single-Stage Coupled Inductor Boost Inverter

Fig.11. circuit diagram of Fuel Cell fed Single-Stage Coupled Inductor Boost Inverter
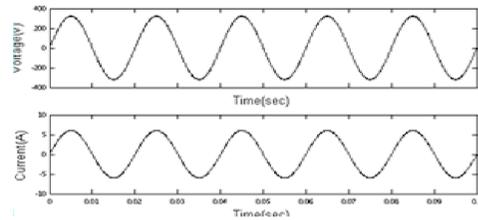

Fig.12. output voltage and current wave form using fuel cell

The extended portion of Fuel Cell fed Single-Stage Coupled Inductor Boost Inverter output voltage and current wave form
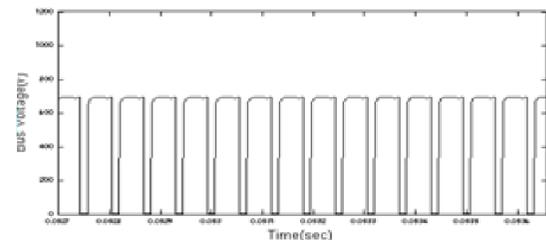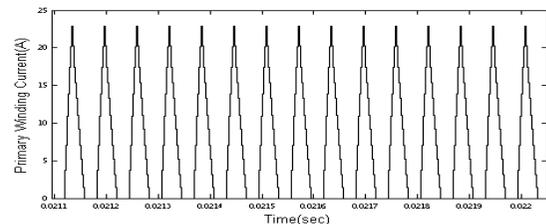

Fig13.wave form of bus voltage vb using fuel cell

Fig.14. Output wave form of primary winding current using fuel cell

VII. CONCLUSION

This paper presents A Fuel Cell fed Single-Stage Boost Inverter with Coupled Inductor circuit. The single-stage boost inverter completely avoids destroying devices during shoot-through zero states. So, it has improved reliability. Second, the inductors and capacitors do not have to be of high consistency, leading to easier circuit parameters design. Third, both shoot-through zero states and coupled inductor's turn ratio can be regulated to control the boost gain. So, the output voltage can be regulated in a wide range and can be stepped up to a higher value. By config-

uring turns 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. Waveform distortion of the ac output voltage caused by dead time is essentially avoided. The simulation results are shown in above. Therefore the single stage boost inverter with coupled inductor is useful for the Fuel Cell applications

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