

A Novel Single-Stage Boost Inverter for Wind Power Generation

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Abstract: Renewable power systems as distributed generation (DG) units often experience big changes in the inverter input voltage due to fluctuations of energy resources. Often, a front-end boost converter is added to step up the DC voltage when the energy resources are at a weak point. However, when a very high boost gain is demanded, the duty cycle may come to its extreme, and large duty cycle causes serious reverse-recovery problem. This paper proposes a novel single-stage boost-type inverter especially for wind power generation. By introducing a passive network including coupled inductors to the classic three phase bridge inverter, and adjusting the shoot-through duty, the converter can output a stable AC voltage even when it is at a weak wind level. The single stage operation of the converter can lead to improved reliability and higher efficiency. Theoretical analysis, simulation and experimental results are presented to verify its good performance.

Keywords: Single-stage boost inverter; Wind power generation; Coupled inductors; Shoot-through state

应用于风力发电的新型单级可升压逆变器

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摘 要: 构成分布式发电系统的新能源发电单元, 其输出电压易受到环境等因素的影响而产生较大范围的波动。以风力发电为例, 通常需要在逆变器前端加入升压变换器, 将直流电压升到足够大的值, 以保证在风速较低时, 逆变器仍然可以输出稳定的交流电压。然而, 当升压比要求很高时, 升压变换器的占空比就会接近极限。对于 boost 变换器而言, 过大的占空比还会引起严重的反向恢复等问题。本文提出了一种可用于风力发电的新型单级可升压逆变器, 它在典型三相桥式逆变器的输入侧增加了包括耦合电感在内的无源网络, 通过对逆变桥直通时间的控制, 可以使变换器即使在风速很低时也能输出稳定的交流电压。由于采用单级结构, 变换器具有更高的可靠性和效率。本文以该变换器在风力发电中的应用为例, 详细阐述其工作机理, 并通过仿真和实验验证方案的可行性。

关键词: 单级可升压逆变; 风力发电; 耦合电感; 直通零矢量

1 Introduction

The increasing tension of the globe energy supply has given a high impetus to the use of renewable energy resources^[1]. This presents a significant opportunity for distributed power generation (DG) systems using renewable energy resources, including wind turbines, photovoltaic (PV) generators, small hydro systems and fuel cells^[2]. These DG units produce a wide range of voltages due to the fluctuations of energy resources and impose stringent requirements for the inverter topologies and controls^[5]. Usually, a boost type DC-DC converter is added after the DG units to step up the DC voltage.

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However, the classic boost converter may not be able to provide enough DC voltage gain when the input is very low, even for an extreme duty cycle. Large duty cycle operation may also result in serious reverse-recovery problem and increase the rating of switching devices. Furthermore, the added converter may deteriorate the system's efficiency, increase system size, weight and cost. So it's desirable to have a single-stage high-gain inverter if it's efficiency effective.

Single-stage topologies, which integrate performance of each stage in a multistage power converter, are becoming a research focus. Though they may result in increasing control complexity, they have the attractive potentials of higher efficiency, reliability, and lower cost. It is observed that many single-stage topologies have

been proposed^[6]. A Z-source inverter^[11] which can provide a wide range of bus voltage, has been applied to renewable power generation system^{[12][13]}. However, this topology is complex, and the inductors and capacitors in the Z-network should have high consistency. Moreover, only the shoot-through state can be regulated when higher voltage gain is required. Widening shoot-through state will decrease modulation index and output voltage amplitude.

This paper proposes a single-stage boost inverter with coupled inductors. The dc-bus voltage can be stepped up by using shoot-through state to store and transfer the energy of the coupled inductors. It is suitable for applications where the input voltage varies from a relative low level to a higher level continuously when outputting a stable AC voltage. The operating principle of the novel inverter is presented in section 2. Section 3 analyzes the equivalent circuit under two boost modes and its control strategy. Simulation and experiment results are included in section 4.

2 Topology and Operating principle

Variable speed wind turbines are known to provide more effective power tracking than fixed speed wind turbines^[14], while the output voltage of wind turbine may at a low level regarding to a weak wind. Under this condition, the single-stage boost inverter with a passive network is introduced to capture and transfer the maximum power and provide a stable output voltage. Fig. 1 shows the proposed single-stage boost inverter for the wind power system. The system includes a variable speed wind turbine, diode rectifier with a capacitor, a boost network and inverter bridge. The boost network doesn't introduce any switching devices, and may lead to higher efficiency and lower cost. Two boost modes can be achieved by regulating the shoot-through states, and configuring the turn ratio and coupling coefficient of the coupled inductors. The shoot-through state can be assumed by turning on an upper switch and a lower switch from the same phase-leg simultaneously. The control methodology is to replace part or entire short-zero states (upper switches or lower switches turning on simultaneously) with shoot-through states.

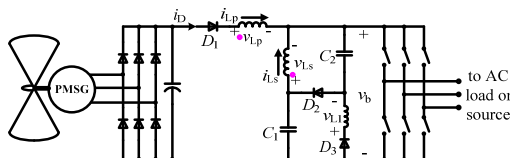


Figure 1. Topology of the Novel Single-stage Boost Inverter

Operating principle of the single-stage boost inverter is analyzed under two conditions. When applying

the single-stage boost inverter to voltage drop compensation or applications where lower boost gain is needed, the inductance of coupled inductors should be designed large enough to ensure its continuous current mode. When applying the single-stage boost inverter to higher boost gain requirement, the inductance of the primary inductor L_p should be as small as to keep the circuit work in discontinuous current mode. It needs to note that diode D_1 series with L_p is necessary to prevent load current feedback to dc source.

3 Boost feature analysis and Control

Fig. 2 shows the equivalent circuit of the single-stage boost inverter. The inverter bridge is equivalent to a short circuit when the circuit is in shoot-through states, as shown in fig. 2(a); while the inverter bridge is equivalent to a current source when the circuit is in one of the active states or in one of the short-zero states (the current source is equal to zero), as shown in fig. 2(b). Fig. 3 shows the operation waveform of the current through both sides of coupled inductors in one shoot-through cycle T_{sh} under two working conditions, respectively.

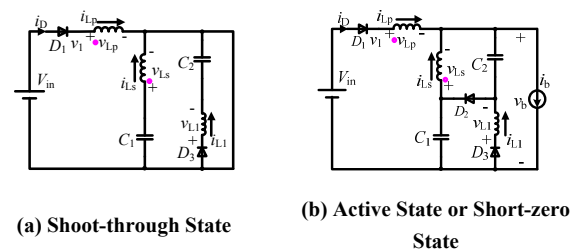


Figure 2. Equivalent Circuit of the Single-stage Boost Inverter

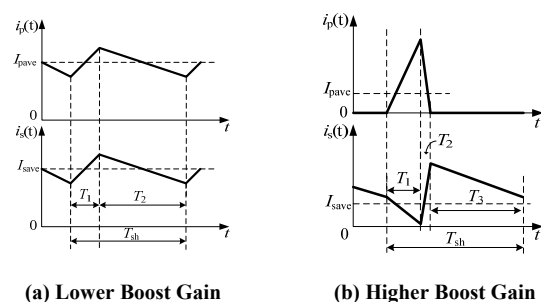


Figure 3. Operation Waveform of Current through Both Sides of the Coupled Inductors under Two Boost Modes

3.1 Lower Voltage Boost Gain Application

In the lower voltage boost gain application, the key point is the current through L_p generally works in continuous mode, as showed in fig. 3(a).

Assuming that during one shoot-through cycle T_{sh} ,

the inverter bridge operates in the shoot-through state for an interval of T_1 , and the diode D_2 is off. The voltages across the both sides of coupled inductors are

$$T_1: v_{Lp} = V_{in}, v_{Ls} = V_{C1} \quad (1)$$

During the non-shoot-through state for an interval of $T_{sh}-T_1$, the inverter bridge operation states include the active states and short-zero states. In the short-zero states, the energy stored in inductor L_1 and capacitors C_2 transfer to the capacitors C_1 and inductor L_s through the diode D_2 , respectively. The voltages across the both sides of coupled inductors are

$$T_{sh}-T_1: v_{Lp} = v_b - V_{in}, v_{Ls} = v_b - V_{C1} \quad (2)$$

where v_b is the dc-bus voltage.

Considering that the average voltage of the coupled inductors over one shoot-through cycle should be zero in steady state, we have

$$(v_b - V_{in}) \times T_2 = V_{in} \times T_1 \quad (3)$$

$$(v_b - V_{C1}) \times T_2 = V_{C1} \times T_1 \quad (4)$$

From (1), (2), (3) and (4), the relationship between dc-bus voltage and input voltage can be found as follows

$$v_b = \frac{1}{1-T_1/T_{sh}} \times V_{in} = \frac{1}{1-D_1} \times V_{in} \quad (5)$$

where $D_1=T_1/T_{sh}$ is shoot-through duty cycle. Define B is boost gain, which can be expressed as

$$B = \frac{1}{1-D_1} \quad (6)$$

The boost gain is similar to that of classical boost converter.

3.2 Higher Voltage Boost Gain Application

In the higher voltage boost gain application, the key character is the inductance of primary side of coupled inductors is less than that of secondary side, and the current through L_p generally works in discontinuous mode, as showed in fig. 3(b).

In the T_1 interval of shoot-through state as shown in fig. 2(a), the voltages across the both sides of coupled inductors can be expressed by (1).

In the T_2 interval of non-shoot-through state, the current through L_p decreases to zero in few microseconds. The voltages across the both sides of coupled inductors are

$$T_2: v_{Lp} = v_b - V_{in}, v_{Ls} = v_b - V_{C1} \quad (7)$$

In the T_3 interval of non-shoot-through state, the voltage v_1 as shown in fig. 2(b) is higher than V_{in} due to the current through diode D_1 keeps zero. The energy stored in L_s and C_1 supply the inverter bridge.

$$v_1 = M \frac{\Delta i_{Ls}}{\Delta t} \quad (8)$$

where M is the mutual inductance. The voltages across the both sides of coupled inductors are

$$T_3: v_{Lp} = v_b - v_1, v_{Ls} = v_b - V_{C1} \quad (9)$$

From (1), (7) and (9), the relationship between dc-bus voltage and input voltage can be found as follows

$$v_b = \frac{(D_1 + D_2)L_s}{D_2L_s + D_1M(1-D_1-D_2)} \times V_{in} \quad (10)$$

where $D_2=T_2/T_{sh}$. However, to define the coupling coefficient

$$k = M / \sqrt{L_p \times L_s} \quad (11)$$

and the effective turn ratio

$$n_e = \sqrt{L_s / L_p} \quad (12)$$

The boost gain B can be expressed as

$$B = \frac{(D_1 + D_2)n_e}{D_1n_e + D_1(1-D_1-D_2) \times k} \quad (13)$$

The output peak phase voltage v_{ac} generated by the inverter can be expressed as

$$v_{ac} = \frac{1}{2} m B V_{in} \quad (14)$$

where m is the modulation index.

From equation (13), the boost gain is determined by duty cycle D_1 , D_2 , the turn ratio and the coupling coefficient of coupled inductors. As analyzed above, by designing different coupled inductors and regulating the duty cycle, the single-stage boost inverter can be applied to voltage drop compensation or applications where lower boost gain is needed, also can be applied to higher boost requirement.

When the voltage at the diode bridge provided by generator in wind power generation approximately 300Vdc, without any boost mode, the voltage at the inverter bridge will also be approximately 300Vdc. So, the inverter can only output voltage of 184Vrms based on SPWM and the modulation index of 1. In order to obtain voltage of 380Vrms, the minimum voltage at the inverter bridge must be 620Vdc. Therefore, the voltage at the inverter bridge needs to be boosted, and the single-stage boost inverter with higher boost mode will be used.

All the traditional pulse width modulation schemes can be used to control the inverter^[15]. Fig. 4 shows the simple boost PWM control method which directly inserts shoot-through states into short-zero states without changing the total zero state and the active state time intervals. The equivalent dc-bus voltage is boosted because of the shoot-through states. Shooting through three phase legs at the same time can reduce the current stress

of each device, but the switching frequency is doubled. When the modulation index m is set, the maximum shoot-through state can be calculated by $1-m$. So the maximum shoot-through duty cycle is limited by modulation index.

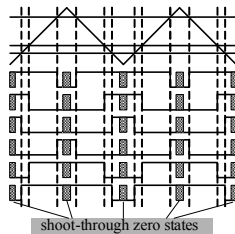


Figure 4. The Simple Boost PWM Control Method

4 Simulation and Experimental Results

To confirm the principle presented above, simulations and experiments have been performed on prototype. The DC input voltage generates from a wind power generator operating in a weak wind. The DC input voltage of the single-stage boost inverter is 300V, and the AC output voltage of the inverter is held constant at 380Vrms and 50Hz. The symmetric resistor-inductor load is 300 Ω , $\cos \phi = 0.8$. The boost network parameters are $L_p = 354\mu\text{H}$, $L_s = 2.2\text{mH}$, the coupling coefficient $k = 0.8$, $C_1 = 10\mu\text{F}$, $C_2 = 47\mu\text{F}$, $L_1 = 12\mu\text{H}$. The modulation index is set to 0.8, and switching frequency is 10 kHz. From the simulation and experimental results of Fig. 5 and Fig. 6, it is clear that the dc-bus voltage is stepped up to around 750V and the output voltage is 380Vrms.

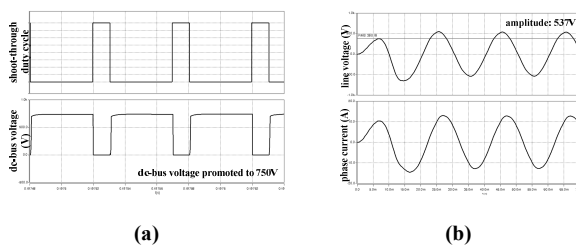


Figure 5. Simulation Results

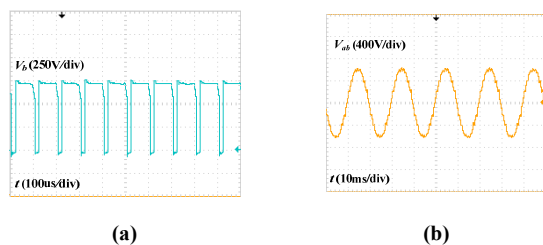


Figure 6. Experimental Results

5 Conclusions

This paper presents a novel single-stage boost inverter with coupled inductors which can output a stable AC voltage even when the input is at a relative low level. The inverter employs a unique passive network to connect the inverter bridge to the power source, to provide sufficient AC voltage to the load terminal. Boost operation happens when DC input is lower than the desired dc-bus voltage, with properly designing the turn ratio and coupling coefficient of the coupled inductors, and adjusting shoot-through duty cycle. An application on wind power generation of this converter was analyzed, simulated, and experimented with a common result of good performance.

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