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Single Stage Inverter Topology for Renewable Resources

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Abstract—Power sector faces great troubles in the generation of power when the energy sources are renewable resources like wind power, hydro turbines etc. These resources may not be available at a constant rate continuously. Wind power generation is high only when the velocity of the wind is high, but this may not happen all the time. So the input will not be stable, in such situations inorder to produce a stable, stepped up ac voltage with high reliability, high boost gain and efficiency, the use of single stage boost inverter with coupled inductor is suggested.

Keywords- single stage; coupled inductor; boost gain.

I. INTRODUCTION

This provides great opportunity for distributed power generation (DG) systems using renewable energy resources, such as wind turbines, photovoltaic generators, hydro systems, and fuel cells. The voltages produced by theses DG units are not stable due to the fluctuation of the energy resource and impose stringent requirements for the inverter topologies and controls[1],[2],[4]. Normally a boost converter is used to step up the source voltage and then this stepped up voltage forms the input voltage to the inverter. Hence we can obtain a stable, stepped up ac voltage from a variable resource. This kind of set up, although simple may not be able to provide enough dc voltage gain when the input is very low, even when the duty cycle is extreme. Also, large duty cycle operation may result in serious reverse-recovery problems and increase the ratings of switching devices. The boost converter increase the overall size and weight of the system. In conventional voltage source inverter (VSI) the upper and lower devices of the same phase leg cannot be gated on at the same time, as it can cause device failure and shoot-through problems. Dead time is always used inorder to avoid shoot-through problems, but it will cause waveform distortion. So it is desirable to use a single stage boost inverter with no shoot-through issues.

Single stage topologies are the focus of research now a days, in this topology the performance of each stages in a multistage converter are integrated. This reduces the size and cost of the system and also the efficiency and reliability are increased. On the other hand, the control complexity is high in these types of topologies.

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This paper presents a novel single stage boost inverter with coupled inductor. Here the input given can be a variable source. The bus voltage is stepped up using shoot-through zero state to store energy and transfer it within the impedance network. This inverter completely avoids destroying the devices during shoot-through. The shoot-through zero states and coupled inductor's turn ratio are 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.

II. PROPOSED TOPOLOGY

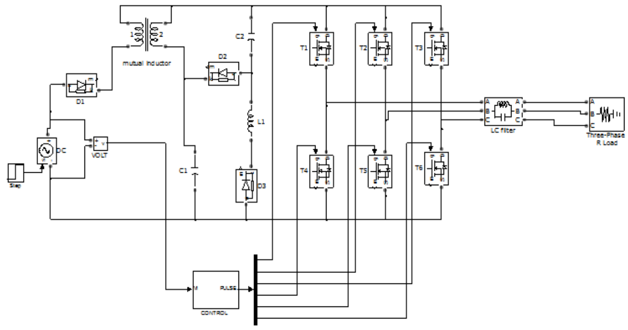

Fig.1 Proposed system

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. 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[5]. In conventional two stage power conversion for wind power generation a dc–dc boost converter is added at the front 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 can produce an ac voltage larger or smaller than the input dc voltage with single stage operation.

III. OPERATING PRINCIPLE

Conventional VSI has eight possible switching states [3], 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.

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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[10].

State 1: The converter is in shoot-through zero state under this duration. Bus voltage *vb* 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.

State 2: During this interval, the converter is in one of the two traditional open-zero states. Inductor *L*1 and secondary winding of the coupled inductor charge capacitors *C*1 and *C*2 through diode *D*2 , respectively. In this state, the current of inductor *L*1 decreases from peak value to zero.

State 3: When the circuit is in one of the six active states, diode *D*3 is reverse biased. The energy stored in the coupled inductor and *C*1 releases to the load, and the bus voltage is stepped up to a higher level.

A. Lower Voltage Boost Gain Mode

In lower voltage boost gain applications, the key characteristic is that the current through *Lp* generally works in continuous mode. The shoot-through duty cycle *D*0 is the time when the three-phase bridge is in shoot-through state, and the duty cycle

1 − *D*0 as the time when the three-phase bridge is in non shoot-through state, the average voltage across the primary winding during one shoot-through period can be expressed as[10],[7]

$(V_{Lp}(t))^{CCM}{}_{Tsh} = D_0V_i + (1 - D_0)(V_i - V_b) = 0.$ (1)

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

$V_b = V_i/(1 - D_0)$ (2)

Define B as the boost gain, $B = V_b/V_i$, which can be expressed as

$B = 1/(1 - D_0)$ (3)

Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

Continuous current mode

Continuous Current Mode (literally means "continuously flowing stream") is a feature of DC choppers, switched mode power supplies and switching power supplies. In this case, during normal operation, the current flow through the choke of the transducer (high-and-down converter, forward converter) or through the store transformer of a flyback converter never becomes zero. This means that there is no continuous mode is present.

Advantages

- The reactor can be operated at high current up to their thermal limit. This allows the cost of a DC-DC converter solution can be lowered.
- The throttle is operated in the linear region, in the design of one is small signal analysis (AC analysis) are possible.
- The hysteresis losses in the core of the reactor is low.
- The ripple of the output current in buck converter and the forward converter is low.
- The ripple of the input current at the step-up converter and the flyback converter is less than for discontinuous operation .

Disadvantages

- Switching losses, because the switching process is not normally done.
- Stability problems, especially in the boost topology

B. High 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[10],[7].

Define the coupling coefficient as

$k = M/(L_p \times L_s)^{1/2}$

(4)

where L_p, L_s, and M are the self-inductance of each winding and the mutual inductance, and the effective turn ratio.

Define the duty cycle D_1 as the time when the inductor L_p 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

$(V_{Lp}(t))^{DCM}{}_{Tsh} = D_0V_i + D_1(V_i - V_b) + (1 - D_0 - D_1)\,k\,(V_{c1} - V_b)/Ne = 0$ (5)

$(V_{Ls}(t))^{DCM}{}_{Tsh} = D_0V_{c1} + (1 - D_0)(V_{c1} - V_b) = 0.$ (6)

From (5) and (6), the amplitude of bus voltage can be expressed as

$V_b = ((D_0 + D_1)NeV_i)/ D_1Ne + D_0(1 - D_0 - D_1) \times k$ (7)

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

$V_{ac} = (mBV_i)/2$

(8)

The output ac voltage can be stepped up or down by choosing an appropriate voltage gain G

$G = m \times B.$

(9)

From (9), 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* 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.

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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 *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. When the voltage at the diode bridge output provided by the generator in wind power generation system is approximately 300 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.

Discontinuous Conduction Mode

Discontinuous Conduction Mode (DCM) occurs because switching ripple in inductor current or capacitor voltage causes polarity of applied switch current or voltage to reverse, such that the current- or voltage-unidirectional assumptions made in realizing the switch are violated. Commonly occurs in dc-dc converters and rectifiers, having single quadrant switches. May also occur in converters having two-quadrant switches.

Properties of converters change radically when DCM is entered:

M becomes load-dependent

Output impedance is increased

Dynamics are altered

Control of output voltage may be lost when load is removed.

Discontinuous Current Mode, discontinuous conduction mode (DCM short, such as: "Interrupted flow") or continuous mode is a term used in power electronics. It means that the current in the storage inductor within a switching cycle back to zero.

Advantages

Merely switching losses during *turn*

Hardly stability problems

Simple rules possible

Disadvantages

After the commutation (current in the coil becomes zero) rings the common point of coil / diode / switch, ie results held damped oscillations, the frequency of which from the coil inductance and the parasitic capacitances (coil, diode, transistor). The vibrations cause EMI and can possibly damage the circuit or destroy.

Since the coil is not operated in the linear region, the design is not a small-signal analysis(AC analysis) are possible. The stability check is difficult.

IV. PWM TECHNIQUE USED (SVM)

The PWM technique used here for pulse generation for the inverter is Space Vector Modulation.

Space vector modulation (SVM) is an algorithm for the control of pulse width modulation(PWM) There are various variations of SVM that result in different quality and computational requirements. One active area of development is in the reduction of total harmonic distortion(THD) created by the rapid switching inherent to these algorithms. To implement space vector modulation a reference signal V_{ref} is sampled with a frequency f_s ($T_s = 1/f_s$). The reference signal may be generated from three separate phase references using the $\alpha\beta\gamma$ transform. The reference vector is then synthesized using a combination of the two adjacent active switching vectors and one or both of the zero vectors. Various strategies of selecting the order of the vectors and which zero vector(s) to use exist. Strategy selection will affect the harmonic content and the switching losses [6]Consider the line voltages V_{ab}, V_{bc}, V_{ca},

$V_{ab}=V_g$

$V_{bc}=0$

$V_{ca}=-V_g$

This can be represented in the a,b plane as shown in Fig. 2, where voltages V_{ab}, V_{bc}, and V_{ca} are three line voltage vectors displaced 120° in space. The effective voltage vector generated by this topology is represented as V1(pnn) in Fig. 3. Here the notation 'pnn' refers to the three legs/phases a,b,c being either connected to the positive dc rail (p) or to the negative dc rail (n). Thus 'pnn' corresponds to 'phase a' being connected to the positive dc rail and phases b and c being connected to the negative dc rail

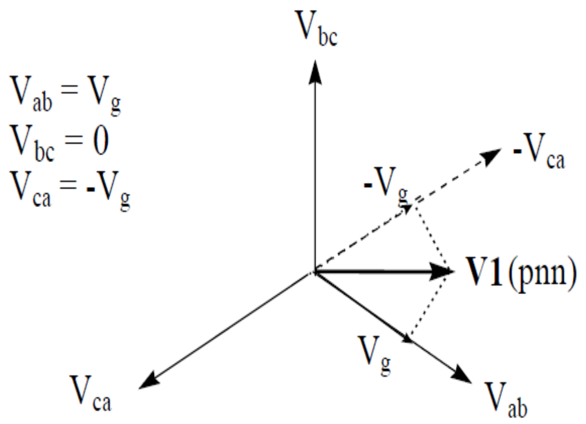

Fig.2 Representation of topology 1 in the a,b plane.

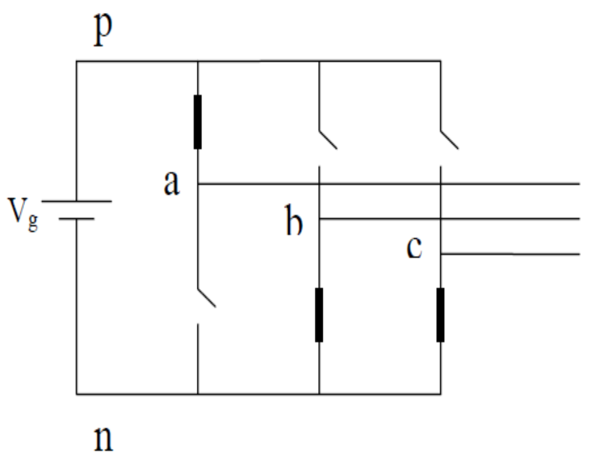

Fig.3 Topology 1-V1(pnn) of a voltage source inverter.

Proceeding on similar lines the six non-zero voltage vectors (V1 - V6) can be shown to assume the positions shown in Fig.4.

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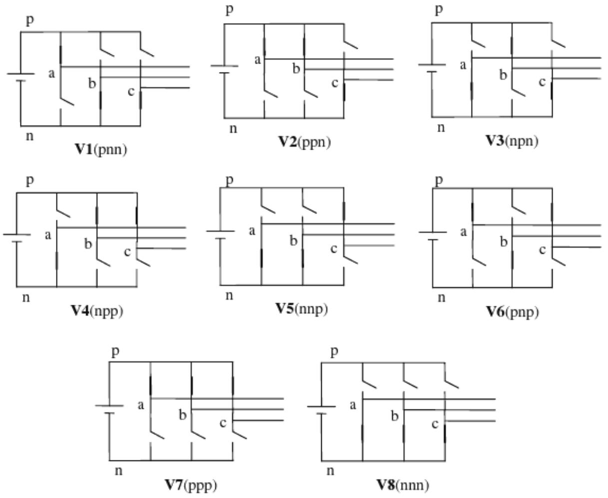

Fig.4 Non-zero voltage vectors

The tips of these vectors form a regular hexagon. We define the area enclosed by two adjacent vectors, within the hexagon, as a sector. Thus there are six sectors numbered 1 – 6 .Considering the last two topologies of Fig.4.we see that the output line voltages generated by this topology are given by

$V_{ab}=0$

$V_{bc}=0$

$V_{ca}=0$

These are represented as vectors which have zero magnitude and hence are referred to as zero-switching state vectors or zero voltage vectors. They assume the position at origin in the a,b plane as shown in Fig.7. The vectors V1-V8 are called the switching state vectors (SSVs).

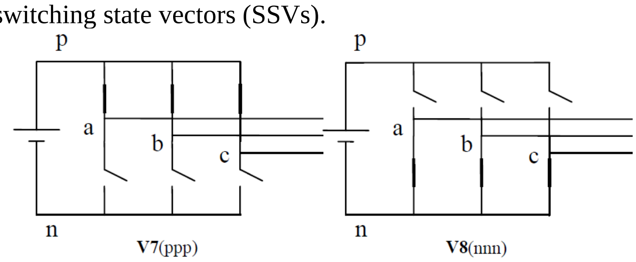

Fig.5 Zero output voltage topologies.

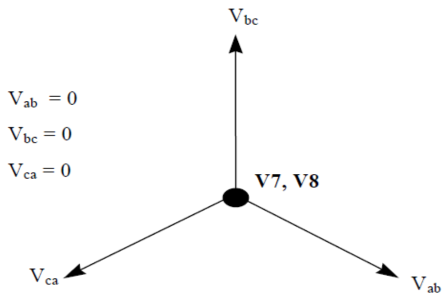

Fig.6 Representation of the zero voltage vectors in the a,b plane.

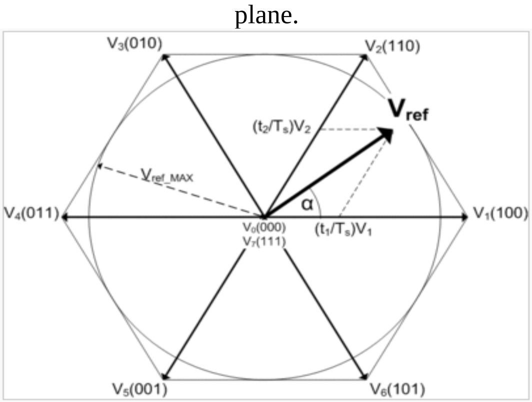

Fig.7 Vref representation

The desired three phase voltages at the output of the inverter could be represented by an equivalent vector V rotating in the counter clock wise direction. The magnitude of this vector is related to the magnitude of the output voltage and the time this vector takes to complete one revolution is the same as the fundamental time period of the output voltage.

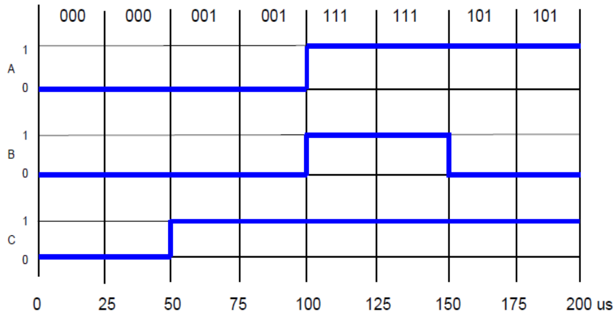

Fig .8 Visualizes the switching states of leg A,B and C .

Advantages

Space Vector Modulation for a three phase UPS inverter makes it possible to adapt the switching behaviour to different situations such as: half load, full load, linear load, non-linear load, static load, pulsating load, etc. In combination with a zig-zag three phase transformer in the output this provides the following advantages:

- Very low values can be reached for the output voltage THD (<2% for linear loads., <3% for non linear loads)
- Robust dynamic response (<3% deviation at 100% load step, recovery time to <1%: <20ms)
- The efficiency of the inverter can be optimized, for each load condition.
- Because of the strong regulation in combination with a zig-zag transformer the inverter can accept a 100% unbalanced load and maintain the performance
- SVM enables more efficient use of the DC voltage (15% more than conventional PWM techniques, so the inverter will accept a 15% lower DC voltage making full use of the available battery energy)
- By applying special modulation techniques the peak currents in the IGBTs can be reduced compared to similar inverters. This improves the MTBF of the inverter, since there is less thermal stress on the IGBT chip.
- By changing the switching behaviour of the inverter, the audible noise can also be influenced and therefore be minimized.
- Space Vector Modulation provides excellent output performance, optimized efficiency, and high reliability compared to similar inverters with conventional Pulse Width Modulation.

V. RESULT ANALYSIS

The system is intended to produce a three-phase 220 V ac output from a relative low level input source. It is clear that the bus voltage is stepped up to 700V, indicating a successful boost inverting operation of the converter. In this case, the modulation index was set to 0.86, the shoot-through duty cycle was set to 0.255, and every traditional open-zero state, achieving an equivalent switching frequency of 16 kHz the switching frequency was 8 kHz.

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The shoot-through zero state was inserted in viewed from the impedance network.

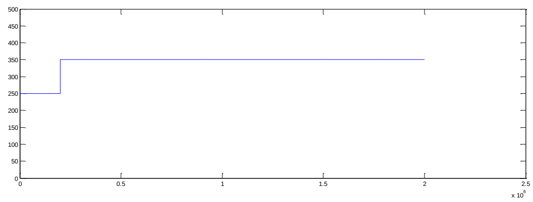

Fig. 9 Variable input DC voltage

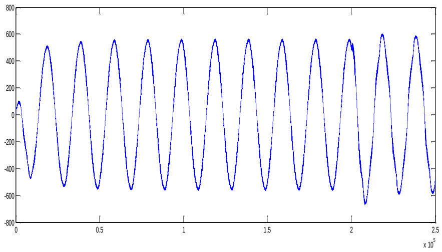

Fig. 10 Output voltage

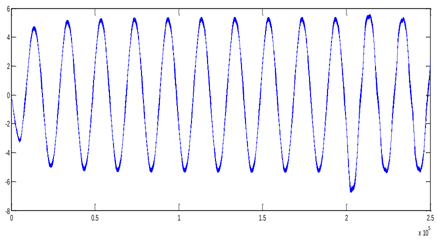

Fig.11 Output current

When the input voltage is low, the shoot-through zero state was regulated to boost the amplitude of bus voltage to about 700V, enough to output the desired ac voltage. The total harmonic distortion of output voltage is 1.8%. Fig.10 shows a constant output phase voltage when input voltage varies from 350 to 250V. The waveforms are consistent with the simulation results. By controlling the shoot-through duty cycle D_0 or the boost gain B when the coupled inductor has been designed, the desired output voltage can be obtained even when the input voltage is at a low level. The tested efficiency only achieves 83.4%. This may be because the circuit parameters have not been optimized.

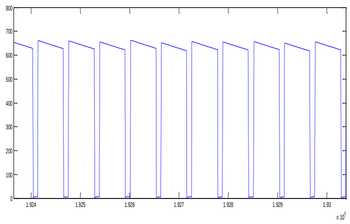

Fig. 12 When the input voltage is low, the shoot-through zero state was regulated to boost the amplitude of bus voltage to about 700V.

Table. 1. Parameters

PARAMETERS	VALUES
Primary inductance, Lp	332.3µH
Secondary inductance, Ls	1.87mH
Capacitor, C1	10µF
Capacitor, C2	40µF
Inductor, L1	30µH

Table.2. Performance Metrices

PERFORMANCE METRICES	CALCULATED VALUES
BOOST GAIN	2
THD	1.8%
EFFICIENCY	83.2%

VI. CONCLUSION

With the use of this inverter a stepped ac voltage was obtained with high gain, high reliability and high efficiency. The shoot-through zero state and coupled inductor's turns ratio are adjusted to to vary the amplitude of the bus voltage.

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