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Research Article

Simulation of Single-Phase Uninterruptible Power Supply Based On Z-Source Inverter

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Abstract: This paper proposes a topology of uninterruptable power supply (UPS) by using a Z-source inverter, where a symmetrical LC network is employed to couple the main power Circuit of an inverter to a battery bank. In this project, we suggested a new topology of the UPS is proposed by using a Z-source inverter. With this new topology, the proposed UPS offers the following advantages over the traditional UPSs: 1) The dc/dc booster and the inverter have been combined into one single-stage power conversion; 2) the distortion of the ac output-voltage waveform is reduced in the absence of dead time in the PWM signals; and 3) the system has achieved fast transient response and good steady state performance by adopting dual-loop control.

This inverter use a unique impedance network (Z-source network), coupled between the power source and converter circuit to provide both voltage buck and boost properties, which cannot be achieved with conventional voltage-source and current-source inverter. To overcome the problem of traditional UPS V-Source and I-Source Inverters we used impedance-source (or impedance fed) power inverter (abbreviated as Z-Source Inverter) and its control method for implementing DC-to-AC, AC-to-DC, AC-to-AC and DC-to-DC power conversion. The unique feature of the Z-source inverter is that the output ac voltage can be any value between zero and infinity regardless of the input voltage. That is, the Z-source inverter is a boost inverter that has a wide range of obtainable voltage With this new topology, the proposed UPS can maintain the desired AC output voltage at the significant voltage drop of the battery bank with high efficiency, low harmonics, fast response and good steady-state performance. Simulation results are presented to validate the advantage of the proposed Z-source based UPS by using MATLAB/SIMULINK model.

Keywords: Dual loops shoot-through, uninterruptible power supply (UPS), Z-source inverter.

INTRODUCTION

Uninterruptible power supplies (UPSs) are widely used to supply critical loads, such as airline computers and life-supply systems in hospitals providing protection against power failure or anomalies of power-line voltage. Due to the recent advancement in the fields of energy conversion and energy storage, a need has arisen to design inverters which can operate successful with variable voltage sources such as fuel cells and ultra-capacitor. DC-to-AC converters are known as inverters. The function of inverter is to change a DC input voltage to a symmetric AC output voltage of desired magnitude and frequency. The output voltage could be fixed or variable at a fixed or variable frequency. A variable output voltage can be obtained by varying the input DC voltage and maintaining the gain of the inverter constant. On the other hand, if the DC input voltage is fixed and is not controllable, a variable output voltage can be obtained by varying the gain of the inverter, which is normally accomplished by Pulse Width Modulation (PWM) control within the inverter

In general, there are two types of traditional single-phase UPSs. The first one couples a battery bank to a full-bridge inverter with a low-frequency transformer as shown in Fig. 1(a). In this type of UPSs, the ac out-put voltage is higher than that of the battery bank; thus, a step-up transformer is required to boost voltage. Due to the presence of the step-up transformer, the inverter current is much higher than the load current, causing high current stress on the switches of the inverter. The transformer also increases the weight, volume, and cost of the system.

The second one couples a battery bank to a dc/dc booster with a full-bridge inverter as shown in Fig. 1(b). In this type of UPSs, the additional booster is needed, leading to high cost and low efficiency. The controlling of the switches in the booster also complicates the system. Furthermore, the dead time in the pulse width-modulation (PWM) signals to prevent the upper and lower switches at the same phase leg from shooting through has to be provided in the aforementioned two types of UPSs, and it distorts the voltage waveform of the ac output voltage.

In this paper, a new topology of the UPS is proposed by using a Z-source inverter. With this new topology, the proposed UPS offers the following advantages over the traditional UPSs:

1) The dc/dc booster and the inverter have been combined into one single-stage power conversion

2) The distortion of the ac output-voltage waveform is reduced in the absence of dead time in the PWM signals

3) The system has achieved fast transient Response and good steady state performance by adopting dual-loop control

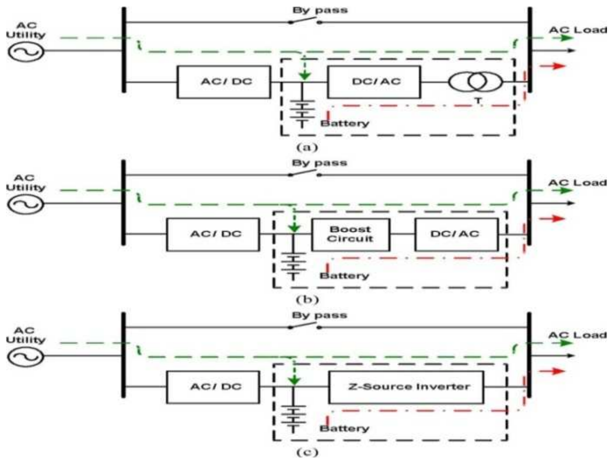


Fig.1: Topologies of UPS. (a) DC/AC inverter + transformer. (b) DC/DC booster + DC/AC inverter. (c) Z-source inverter.

SYSTEM CONFIGURATION AND OPERATING PRINCIPLE

Fig. 1(c) shows a new topology of the UPS with a Z-source inverter. In the normal operation, the rectifier provides power to the inverter. In the case of power outage, the battery bank supplies the inverter, as shown in Fig. 2. It consists of a dc source (E, C3, and D), a Z-source symmetrical network (L1 = L2 and C1 = C2), an H-bridge inverter (S1–S4), and a filter (L*s* and C*s*) . Table I shows a total of nine switching states and their vector representations, where the switching function S*x* (*x* = 1, 2, 3, or 4) is defined as 1 when switch S*x* turns on and as 0 when switch S*x* turns off.

Thus, when two active vectors {1 0}, {0 1}) are taken, the battery bank voltage is applied to the load through two inductances (L1 and L2); when two null vectors ({0 0}, {1 1}) are taken, the load terminal is shorted by either the upper or lower two switches.

When the shoot-through zero vectors are taken, the load is shorted by the upper and lower switches at the same phase leg. These zero vectors are allowed in the Z-source inverter, whereas they are forbidden in the voltage source inverter. Because of this unique feature of the Z-source inverter, the proposed UPS can generate the desired ac output voltage *u*o, regardless of the battery bank voltage *u*B, by using the shoot-through zero vectors.

Inductor and capacitor requirement: The inductor and capacitor requirement should be smaller compared than the traditional inverters. The two inductors (L_1 and L_2) are small and approach zero, the impedance source network reduces to two capacitors (C_1 and C_2) in parallel and becomes traditional voltage source, therefore, a traditional voltage inverters capacitor requirements and physical size is worst case requirement for the impedance source inverter.

Considering additional filtering and energy storage provided by inductors, the impedance source network should require less capacitance and smaller size compare with the traditional voltage inverter. Similarly, when the two capacitors (C_1 and C_2) are small and approach zero, the impedance source network reduces to two inductors (L_1 and L_2) in series and becomes a traditional current source. Therefore, a current source inverters inductor requirements and physical size is a worst case requirement for the impedance source inverter. Then two capacitors are small; the impedance source network reduces to two inductors in series and becomes a traditional current sources. Considering additional filtering and energy storage by the capacitors, the impedance source network should require less inductance and smaller size compared with the traditional current source inverter

TABLE-1: SWITCHING STATES AND VECTOR REPRESENTATIONS OF THE Z-SOURCE INVERTER

Switching States	S_1	S_2	S_3	S_4
Active {1 0}	1	0	0	1
Active {0 1}	0	1	1	0
null {0 0}	0	1	0	1
null {1 1}	1	0	1	0
Shoot through	1	1	0	1
Shoot through	1	1	1	0
Shoot through	0	1	1	1
Shoot through	1	0	1	1
Shoot through	1	1	1	1

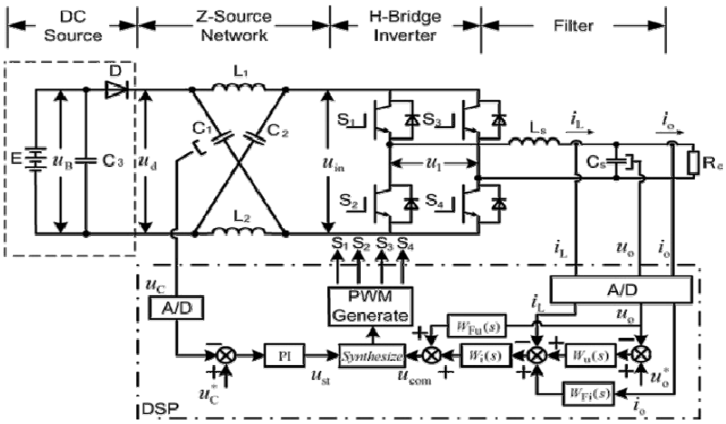


Fig. 2: Z-source inverter for the proposed UPS

As shown in Fig. 2, the voltage equations of the Z-source inverter can be written as

$$U_{C1} = U_{C2} = U_C = U_{L1} = U_{L2} = U_L$$

When the Z-source inverter is working in nonshoot-through states during time interval T_1, the diode D is on, and the H-bridge inverter can be considered as a current source i_{in}. Consequently, the equivalent circuit of the Z-source inverter at nonshoot-through states is shown in Fig. 3(a), and its voltage equations are

$U_B=U_D=U_C+U_L$………….. (2)

$U_{in}=U_c-U_L$………………... (3)

Substituting (2) into (3) yields,

$U_{in}=2U_C-U_B$………………. (4)

When the Z-source inverter is working in shoot-through states during time interval T_0, where $T_0 = T_s - T_1$, and T_s is the switching period, the diode D is off, and the H-bridge inverter can be considered as a short circuit. As a result, the equivalent circuit of the Z-source inverter at shoot-through states is shown in Fig. 3(b), and its voltage equations are

$U_C = U_L$ $U_{in} = 0$… (5)

It is recognized that the average voltage of inductor L1 (or L2) over one switching period in steady-state operation is zero

$(u_B - u_C)T_1 + u_C T_0 = 0$ (6)

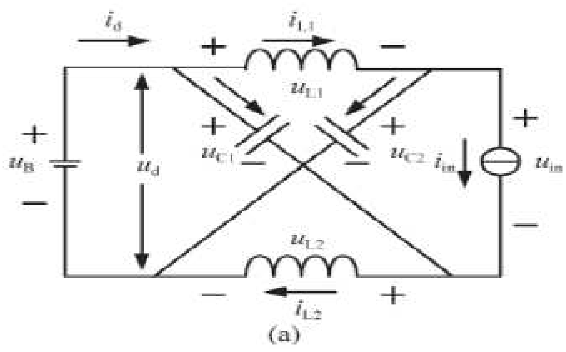


Fig.3 Equivalent circuit of the Non Shoot through

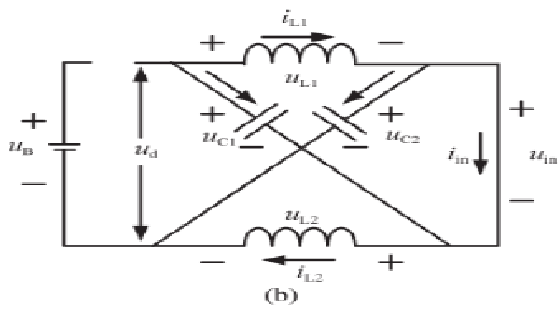


Fig. 3: Equivalent circuit of the Z-source inverter. (a) Nonshoot-through state. (b) Shoot-through state.

$$U_c = \frac{T_1}{T_1 - T_0} U_B \text{ -------------- (7)}$$

Substituting (7) and (4) gives

$$U_{in} = \frac{T_s}{T_1 - T_0} U_B = BU_B \text{ --------- (8)}$$

Where

$$B = \frac{T_s}{T_1 - T_0} > 1 \text{ ------------------ (9)}$$

with *B* being the boost factor. If the voltage across the inductor *L*s is ignored, the output peak voltage is

$$U_{om} = U_{1m} = mU_{in} = mBU_B \text{ ------- (10)}$$

Where u_{1m} is the peak value of fundamental voltage of the H-bridge inverter and *m* is modulation index ($m \leq 1$). Thus, the appropriate selection of the booster factor and the modulation index can obtain the desired ac output voltage regardless of the battery bank voltage.

Control Principle of the Proposed Ups with the Z-Source Inverter: Fig. 4 shows the dual-loop control in the proposed UPS with the Z-source inverter, namely, the control of inductor current *i*L in the inner loop and output voltage *u*o in the outer loop, where *K*PWM/(*sT*s + 1) is the transfer function of the H-bridge inverter and *K*PWM is the average voltage gain viewed from dc link which can be expressed by $K_{PWM} = \frac{1-\frac{T_0}{T_s}}{1-\frac{2T_0}{T_s}}U_B = \frac{1-d}{1-2d}U_B$ ------ (11)

Due to high system switching frequency *f*s(*f*s = 1/*T*s), the capacitor voltage of the Z-source inverter is considered constant in one switching period, which is equal to the average input voltage of the Z-source network *u*d, and thus, the gain *K*PWM is constant as well.

Current Inner Loop: In **Fig. 4**, the output voltage *u*o is regarded as a disturbance to the current inner loop. To smooth the output voltage, a voltage feed forward control is adopted

$$u_0 W_{Fu}(s).\frac{(1-d)u_B}{(1-2d)(sT_s+1)} - u_0 = 0 \text{ -------- } (12)$$

Where *W*Fu(*s*) is the transfer function of the voltage feed forward controller. As the bandwidth of the inner loop (*f*i) is designed to be much lower than the system switching frequency, namely, |*sT*s|*s*=*jω*i << 1, WFu(s) can be found from eq (12) as

$$W_{Fu}(s) \approx \frac{1-2d}{(1-d)u_B} \text{ -------------------------- } (13)$$

On the other hand, the voltage across the inductor *L*s can be written as

$$u_{Ls} = u_1 - u_0 = u_{com}\frac{(1-d)u_B}{(1-2d)(sT_s+1)} - u_0 \text{ -- } (14)$$

Where *u*com is the PWM vectors. According to (13) and (14), the block diagram of the inner loop can be reduced to Fig. 5, and its open-loop transfer function is

$$W_{oi}(s) = W_i(s)\frac{(1-d)u_B}{s(1-2d)(sT_s+1)Ls} \text{ -------- } (15)$$

Where *W*i(*s*) is the transfer function of the inner loop controller. *W*i(*s*) is chosen as the constant value to make *W*oi(*s*) as a type-1 system which has good tracking capability.

$$W_i(s) = K_i \text{ ---------------- } (16)$$

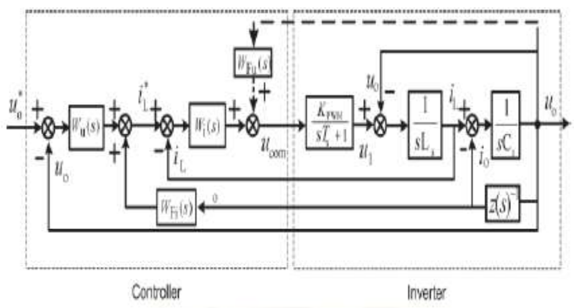


Fig. 4: Control system of the Z-source inverter for the proposed UPS.

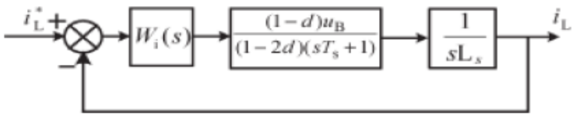


Fig. 5: Block diagram of the inner loop.

Table-3: Step Response of The Inner Loop

K_i	ζ_i	f_{ni} (Hz)	t_s(ms)	σ_i	t_r(ms)	γ_i
0.0429	0.5	1590	0.81	16.3%	0.16	51.8°
0.0296	0.6	1320	0.71	9.3%	0.22	59.3°

Output-Voltage Outer Loop: In Fig. 6, the control of the outer voltage loop has taken the inner current loop into account, where $z(s)$ is equivalent output impedance.

Consider that the current feed forward control of the inner loop has eliminated the load current disturbance

$i_0 W_{Fi}(s) W_{ci}(s) - i_0 = 0$ ---------------- (17)

Where io is the load current, WFi(s) is the transfer function of the current feed forward controller, Wci(s) is the closed-loop transfer function of the inner loop.

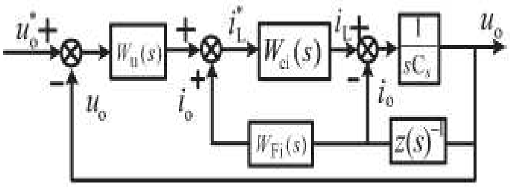


Fig. 6: Block diagram of the outer loop.

Because the bandwidth of the outer loop is designed to be much lower than that of the inner loop, the inner loop has faster tracking capability than the outer loop. As a result, the current gain Wci(s) of the inner loop Can be approximately equal to one

Wci(s) ≈ 1............................ (18)

Substituting (18) into (17) and solving (17)

WFi(s) ≈ 1.............................. (19)

From (18) and (19)

The block diagram of the outer voltage loop can be simplified to Fig. 7, and its open-loop transfer function is

Wou(s) = Wu(s)Wci(s)1/sCs.........(20)

Where Wu(s) is the transfer function of the outer loop

controller. The proportional–integral (PI) controller is adopted to control the outer loop.

Table-4: Step Response of The Outer Loop

K_I	τ_I	ζ_u	f_{nu}(Hz)	t_s(ms)	σ_u	t_r(ms)
0.013	0.0012	0.9	440	3.05	26.6%	0.449

Table-5: Specifications Of A 3kw Ups With Z-Source Inverter

u_B	u_0	$C_1(C_2)$	C_3	$L_1(L_2)$	L_s	C_s
270	300	1500µ F	1000	2.5M H	1. 5	8
170	300	1500µ F	1400	2MH	3	12

Shoot-Through Zero-Vector Control: The shoot-through zero vectors are allowed in the Z-source inverter. These zero vectors can be controlled to boost the capacitor voltage in the Z-source network, maintaining the desired level of the average input voltage of the Z-source inverter. As shown in Fig. 2, when the battery bank voltage drops significantly under heavy load, the capacitor voltage of the Z-source inverter drops significantly as well thus, the voltage difference between the reference *u*□C and the actual capacitor voltage *u*C is sent to the PI controller which generates the shoot-through zero vectors. The PWM signals with the synthesis of the shoot-through zero vectors *u*st's and the PWM vectors *u*com's control the Z-source inverter to achieve the desired ac output voltage *u*o.

SIMULATION AND EXPERIMENTAL RESULTS

The simulation model and the experimental setup of a 3-kW UPS with the Z-source inverter have been developed to confirm its validity. The technical specifications of the proposed UPS are shown in **Table 5.**

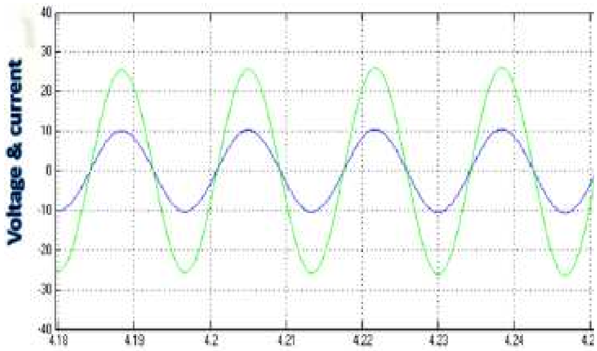
Simulation Results: Fig. 8(a) and (b) shows the output voltages and currents, respectively, of the proposed UPS with the Z-source inverter when both pure resistive and nonlinear loads.

It should be noted that the capacitor voltage of the Z-source inverter can be much higher than the battery bank voltage by controlling the shoot-through zero vectors.

The proposed UPS with the Z-source inverter when both pure resistive and nonlinear loads are suddenly applied. In the steady state, the total harmonic distortion (THD) of the output voltage is less than 1% under the pure resistive load, whereas the THD of the output voltage is less than 3% under the nonlinear load

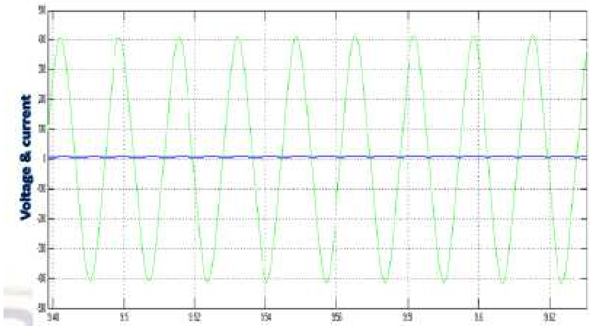
Simulation results of the Proposed UPS

(a) Pure resistive load:



Time in sec Fig (a)

(b) Non Linear load

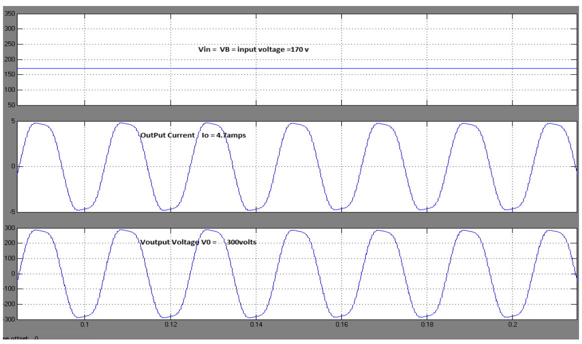


Time in sec Fig (b)

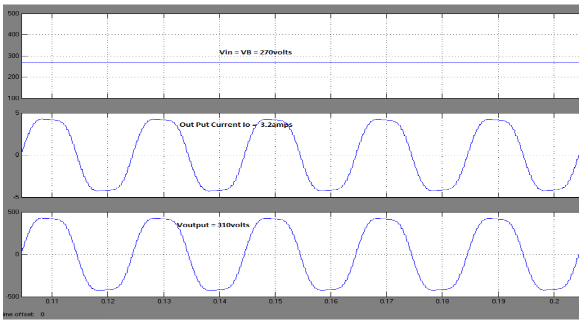
EXPERIMENTAL RESULTS

Fig. 9(a) and (b) shows the output voltages for both the proposed UPS with the Z-source inverter for different input voltages 170v and 250v respectively, when the battery bank voltage declines by 20% of its normal voltage. The waveform distortion can be observed for the traditional UPS, whereas the sinusoidal waveform can be kept for the proposed UPS.

When UB = Uin = 170v



When UB = Uin = 270v



CONCLUSION

In this Project, a new topology of the UPS with the Z-source inverter has been presented. The Proposed UPS System placing a Z-source inverter in the circuit. It is a unique impedance network to couple the inverter to the dc source. Here proposed UPS system simulation is done by taking two different input voltages i.e. 170V and 270V. Hence output voltage 'Vo' is achieved desired constant voltage 300V. The proposed UPS shows the strong regulation capability to maintain the desired ac output voltage at voltage sag of the battery bank with high efficiency, low harmonics and reduces cost. All these advantages were verified by simulation in MATLAB.

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