Improved Quasi-Y-Source DC-DC Converter for Renewable Energy

Xupeng Fang, Xiaokang Ding, Shixiang Zhong, and Yingying Tian

Abstract—In order to improve the performance of dc-dc converter circuit in renewable energy power generation system, and overcome the problems of input current discontinuity and high inrush current in traditional Y-source converter, an improved Y-source dc-dc boost converter topology is presented in this paper. The voltage gain formula is derived by analyzing the topology and operating principle of the converter circuit. The proposed circuit topology inherits all the benefits of the existing Y-source converter and has several more advantages, including the higher voltage gain, continuous input current and small inrush current. The simulation and the experiments based on the prototype are performed. And the simulation and experimental results verify the rationality and superiority of the circuit topology.

Index Terms—Boost converter, dc-dc converter, improved quasi-Y-source converter, renewable energy.

I. INTRODUCTION

THE rapid development of the human society and the industrial production causes increasing energy consumption, and thus the reserved non-renewable energy declines rapidly, especially for the fossil fuels, has led to a growing supply shortage. At present, renewable energy has become a hot spot for many researchers because of its clean and sustainable development. For new energy generation, such as photovoltaic, wind power and fuel cell power generation, there are disadvantages of low output voltage. Therefore, it is necessary to increase the output voltage to a higher dc voltage by a high voltage gain dc-dc converter.

Although the traditional boost converter has the characteristics of simplicity, high conversion efficiency, due to the low voltage gain, its application in renewable energy systems is limited. This is caused by the following reasons: the conventional boost converter can only obtain a higher output voltage by increasing the duty cycle, which also causes the current peaks of the output diode and the controllable power switch to increase. This will lead to a large conduction loss of the diode and the power switch and an increase of the voltage stress of the capacitor, which reduces the conversion efficiency and the service life of the circuit. The high-boost

gain converters were proposed with the switched inductor unit in [1] and the voltage multiplication unit in [2]. They were designed to increase the voltage gain and the higher the voltage gain need to be obtained, the more cascaded units should be used theoretically. But it increases the cost and complexity of the circuit and affects its conversion efficiency. Prof. F. Z. Peng proposed Z-source inverter topology to overcome the problems of the traditional inverter in 2002 [3]. Subsequently, a quasi-Z-source inverter topology was presented in [4], which reduces the voltage stress of the passive components in the impedance source network and makes the input current continuous compared to the conventional Z-source inverter. Furthermore, the Z-source network can also be applied to dc-dc converters, which also have excellent characteristics [5]. From then on, the Z-source and quasi-Z-source concept have been widely applied in lots of areas such as electric vehicles, photovoltaic generation, and wind power generation, etc.

In order to further increase the voltage gain of the Z-source-based converters, many scholars have applied coupled inductors in impedance source network in recent years[6], [7]. Many new high voltage gain topologies are proposed: high frequency transformer isolated Z-source inverter [8], TZ-source inverter [9], trans-Z-source inverter[10], [11], Γ -source inverter [12], a family of T-source networks [13], [14], Y-source inverter [15], [16] and quasi-Y-source inverter [17], [18]. It is worth noting that the Y-source inverter uses a three-winding transformer to flexibly adjust its voltage gain, and compared with other converters, it can achieve higher boost gain with the same shoot-through duty cycle. The Y-source converter concept could be extended to dc-dc conversion, and the Y-source dc-dc converter topology is shown in Fig. 1. Similar to the Z-source converter, the operating mode of the Y-source converter can also be divided into two states: the shoot-through state and the non-shoot-through state.

The capacitor voltage stress in the Y-source converter is known from [12]:

$$V_{C1} = \frac{1-D}{1 - \frac{N_1 + N_3}{N_3 - N_2}D} V_{in} \quad (1)$$

Where D is defined as the duty cycle of the controllable power switch and N_1 , N_2 and N_3 are the winding turns of the coupled inductors.

Then, the output voltage of the Y-source converter is:

$$V_o = \frac{1}{1-K'D} V_{in} \quad (2)$$

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Fig. 1. Illustration of (a) Y-source dc-dc converter, (b) the equivalent circuit in shoot-through state and (c) the equivalent circuit in non-shoot-through state.

$$\text{where } K' = \frac{N_3 + N_1}{N_3 - N_2}$$

So when diodes D_1 and D_2 are reverse biased, the reverse bias voltages of the two diodes are:

$$V'_{D1} = (1 - K') V_o \quad (3)$$

$$V'_{D2} = V_o \quad (4)$$

Although the Y-source converter has very prominent advantage, it also has many shortcomings. In this paper, an improved quasi-Y-source converter (IQY) is presented for renewable energy generations, using a Y-source and boost impedance network. Compared with the traditional boost converter, the improved Y-source converter not only has higher voltage-gain, continuous input current and no inrush current, but also has flexible selection of the shoot-through duty ratio range and the turns ratio of the coupled inductors. It is more suitable for new energy generation systems.

II. PROPOSED TOPOLOGY AND OPERATING STATES

The proposed dc-dc converter is shown in Fig. 2, which consist of a quasi-Y-source dc-dc converter combined with a boost converter. The input of the converter is V_{in} , which can come from a photovoltaic power generation system or other dc source. Same as Z-source converters, the proposed converter also has two operating states: (1) SW_1 is on, SW_2 is off, and (2) SW_2 is on, SW_1 is off. Given that the switching cycle is T , T_0 is the turn-on time of SW_1 , T_1 is its turn-off time, apparently $T = T_0 + T_1$, so the duty cycle of SW_1 is $D = T_0 / T$. And the equivalent circuits during two operating states are shown in Fig. 3(a) and (b), respectively.

Fig. 2. Illustration of the proposed dc-dc converter.

Fig. 3. Equivalent circuits of improved quasi-Y-source converter : (a) SW_1 is on, SW_2 is off and (b) SW_2 is on, SW_1 is off.

In the turn-on time of SW_1 , the diode D_0 is turned on and the diode D_1 is in reverse bias state. By applying Kirchhoff's voltage law (KVL) in this mode, the voltage equations in this state are:

$$-V_{in} + V_{L0} = 0 \quad (5)$$

$$-V_{C0} + V_{L1} - V_{C1} = 0 \quad (6)$$

$$V_{C2} + V_{N2} - V_{N3} = 0 \quad (7)$$

$$N_1 : N_2 : N_3 = V_{N1} : V_{N2} : V_{N3} \quad (8)$$

where N_1 , N_2 and N_3 are the winding turns of the coupled inductors. By inserting (8) in (7), we have:

$$V_{N2} = \frac{N_2}{N_3 - N_2} V_{C2} \quad (9)$$

In the turn-off time of SW₁, the diode D₀ is in reverse bias and the diode D₁ is turned on. From the equivalent circuit diagram, Fig. 3(b), one has:

$$-V_{in} + V'_{L0} + V_{C0} = 0 \quad (10)$$

$$-V_{C0} + V'_{L1} - V_{C1} - V_0 = 0 \quad (11)$$

$$-V_{C0} + V'_{L1} + V'_{N1} + V'_{N2} + V_{C2} = 0 \quad (12)$$

$$V_{C1} + V'_{N1} + V'_{N3} = 0 \quad (13)$$

By replacing (8) in (13) we will have:

$$V_{C1} + \frac{N_1}{N_2} V'_{N2} + \frac{N_3}{N_2} V'_{N2} = 0 \quad (14)$$

Thus:

$$V'_{N2} = -\frac{N_2}{N_1 + N_3} V_{C1} \quad (15)$$

By applying voltage-second balance principle to the inductors L_0 , L_1 and windings of transformer, the average voltage over the inductor is equal to zero, hence:

$$DV_{L1} + (1-D)V'_{L1} = 0 \quad (16)$$

$$DV_{L2} + (1-D)V'_{L2} = 0 \quad (17)$$

$$DV_{L0} + (1-D)V'_{L0} = 0 \quad (18)$$

By inserting (9) and (15) in (18), we will have:

$$\frac{V_{C1}}{V_{C2}} = \left(\frac{N_1 + N_3}{N_2 - N_3} \right) \left(\frac{-D}{1-D} \right) \quad (19)$$

Then by combining (6), (8), (12), (15) and (19) in (17), we have:

$$V_{C0} = \frac{DN_1 + (1-D)N_2 - (1-2D)N_3}{(1-D)(N_2 - N_3)} V_{C2} \quad (20)$$

By replacing (6), (11) and (20) in (17), we will have:

$$V_0 = \frac{N_2 - N_3}{DN_1 + (1-D)N_2 - (1-2D)N_3} V_{C0} \quad (21)$$

Defining $K = \frac{N_3 + N_1}{N_3 - N_2}$, so equation (21) can be rewritten as (22).

Fig. 4 The theoretical voltage gain of the proposed converter for different winding factors K .

$$V_o = \frac{1}{1 - (1 + K)D} V_{C0} \quad (22)$$

Similarly, by inserting (5) and (10) in (16), we will have:

$$V_{C0} = \frac{1}{1 - D} V_{in} \quad (23)$$

Now, using (21) and (23), the voltage gain is obtained as follow:

$$V_o = \frac{1}{[1 - (1 + K)D](1 - D)} V_{in} \quad (24)$$

So when the diode D₁ is in reverse bias state, using (7), (8) and (19), the voltage over D₁ is:

$$V_{D1} = \left(\frac{D}{1 - D} - 1 \right) K V_o \quad (25)$$

When the diode D₂ is in reverse bias state, the voltage over D₂ is:

$$V_{D2} = V_o \quad (26)$$

The overall gain can be varied by changing D (the shoot-through duty cycle) and K (turn ratios), in order to better illustrate the boosting performance of the proposed converter, which can be depicted in Fig. 4. It will be shown that high transfer gains can be achieved with small shoot-through (ST) duty cycle by increasing the turn ratio K . It can be seen from Fig. 4 that the improved quasi-Y-source converter has a higher voltage gain than the conventional Y-source converter. Different winding turns ratios (N_1 : N_2 : N_3) have been collectively summarized in Table I. The same winding factor K , voltage gain and range for D have been given in each of these groups.

From (2) and (24), we can know that the voltage gain of the proposed topology is higher than the conventional Y-source converter. As shown in Fig. 5, in order to more intuitively observe the difference between the two topologies, let $K = K' = 3$, and plot the voltage gain curves of the two

TABLE I
GAIN OF PROPOSED CONVERTER VERSUS WINDING FACTOR AND TURNS RATIOS

K	Range of D	Voltage Gain	Possible Turns Ratios $N_1: N_2: N_3$
1	$0 < D < 1/2$	$1/(1-2D)(1-D)$	1:1:3, 2:1:4, 1:2:5, 3:1:5 4:1:6, 1:3:7
2	$0 < D < 1/3$	$1/(1-3D)(1-D)$	1:1:2, 3:1:3, 2:2:4 1:3:5, 4:2:5
3	$0 < D < 1/4$	$1/(1-4D)(1-D)$	2:1:2, 1:2:3, 4:2:4 5:1:3, 8:1:4
4	$0 < D < 1/5$	$1/(1-5D)(1-D)$	3:1:2, 2:2:3, 1:3:4 7:1:3, 6:2:4

Fig. 5 Theoretical voltage gain of the proposed converter and Y-source converter when the winding factors $K = K' = 3$.

topologies.

From [12], we can know the range of variation for K' and D can be determined as $K' \geq 2$, $D \leq \frac{1}{K'}$. Under the same output voltage, the voltage stress of the diode D_2 of the IQY is as large as the Y-source converter, however, the voltage stress of the diode D_1 of the IQY is much smaller than the Y-source converter. From (3) and (25), we have:

$$\begin{aligned}
 K \geq 1, D \leq \frac{1}{1+K} &\Rightarrow \begin{cases} 0 < \frac{D}{1-D} < 1 \\ K' > 1+K \end{cases} \\
 \Rightarrow -1 < \frac{D}{1-D} - 1 < 0 &\Rightarrow |V_{D1}| < |KV_o| < |V'_{D1}|
 \end{aligned} \quad (27)$$

Where V_{D1} is the voltage stress of the diode D_1 of the IQY, V'_{D1} is the voltage stress of the diode D_1 of the Y-source converter.

It is worth noting that the leakage inductance between the coupled inductors can't be ignored, which can cause large switching transients and reduce the effective switching duty cycle, resulting in a reduction in the system's voltage gain and efficiency. Therefore, the leakage inductance should be reduced as much as possible.

In summary, in order to better understand the difference

TABLE II
THE DIFFERENCE BETWEEN IMPROVED QUASI-Y-SOURCE CONVERTER AND Y-SOURCE CONVERTER

	B	$V_{D1}(V'_{D1})$	Inrush current	Input current
Y-source	$1/(1-KD)$	high	high	Discontinuous
I-QY source	$1/[1-(1+K)D](1-D)$	low	low	Continuous

Fig. 6 Control block diagram of the switches.

between the Y-source converter and the proposed topology, we list the advantages and shortcomings between both of them in the Table II.

A double closed loop structure is used in the controller to adjust the output voltage to follow the given. Its inner loop is a current loop that allows the output current to follow the input quickly. The outer voltage loop adopts PI controller to meet the requirements of output stability, and the current inner loop adopts P controller to meet the requirements of rapidity. Besides, the controller also reduces the influence of leakage inductance on the duty cycle. The structure diagram of the controller is shown in Fig. 6. The PWM pulse generated by the controller is used to control the on and off of the switches.

III. SIMULATION AND EXPERIMENTAL RESULTS

Simulation is performed in MATLAB/Simulink environment, using the parameters listed in Table III, which are also the parameters of the experimental prototype.

According to (24) derived above, when $D = 0.15$ and $V_{in} = 36$ V, the output voltage of the improved quasi-Y-source is theoretically $V_o = 105.9$ V. It can be seen from Fig. 7 that the simulation results are basically consistent with the theoretical values. In addition, it shows that the improved quasi-Y-source converter has high voltage gain, no inrush current and continuous input current.

In order to verify the correctness of the theoretical analysis, a low-power open-loop test prototype is set up in the laboratory. Use the DSP TMS320F2812 to output a set of complementary PWM pulse signals to control the on and off of the switches. Fig. 8 shows a three-winding coupled inductor and a physical circuit diagram. To reduce leakage

TABLE III
PARAMETERS AND COMPONENT VALUES OF THE CONVERTER

Parameter/Description	Value/Part Number
Maximum output power	105 W
Input voltage V_{in}	36 V
Output voltage V_o	105 V
Switching frequency f_s	20 kHz
Turns ratio of coupled inductor	1:3:5 (10:30:50)
Winding factor K	3
Permitted ranges of D	$0 < D < 0.25$
Inductor L_0 and L_1	500 μ H
Capacitor C_1	100 μ F/100 V
Capacitor C_0 and C_2	470 μ F/160 V
Switching devices SW ₁ and SW ₂	$V_{DS} = 1200$ V, $I_{DS} = 20$ A H20R1203
Diode D ₀ and D ₁	STPSC20H12-Y-Silicon Carbide Schottky Diode

Fig. 7 Simulation results of improved quasi-Y-source converter at $D = 0.15$ and $K = 3$ when $V_{in} = 36$ V. (a) I_{L0} , I_{L1} . (b) V_{C0} , V_{C1} , V_{C2} . (c) V_{SW1} , V_{SW2} . (d) V_{D0} , V_{D1} . (e) Output voltage V_o .

Fig. 8 The experimental setup of proposed converter and three-winding coupled inductor.

inductance, an E-core instead of a toroidal core is used, and a flyback winding is chosen when make the coupled inductor. In this way, the leakage inductance of each winding of the coupled inductor can be controlled within 10 μ H. Although the proposed new topology has small leakage inductance, there are still surge voltages and currents. In order to get better output voltage and current waveforms, and protect the controllable power switch, a RCD snubber circuit is added to the circuit, where the parameters of the resistor and capacitor are $R = 50 \Omega$ and $C = 10 \mu$ F, and the diode uses a fast recovery diode.

When $D = 0.144$ and $K = 3$, the experimental waveforms of each inductor current, capacitor voltage, the voltages of the controllable switches and the diodes, and output voltage at steady state are shown in Fig. 9. From the experimental

(a)

(b)

(c)

(d)

(e)

(f)

(g)

Fig. 9 Experimental results. (a) The pulse signal of switch SW_1 . (b) The current of L_0 and L_1 . (c) The voltage of C_0 and C_2 . (d) The voltage of C_2 . (e) The voltage of D_1 . (f) The voltage of SW_1 . (g) Output voltage V_o of the improved quasi-Y-source converter when $K = 3$, $D = 0.144$.

waveforms, it can be concluded that the measured values are consistent with the theoretical values and the simulation results.

Fig. 10 shows the measured efficiency and voltage gain of the converter at $K = 3$, where D changes to keep the output voltage constant at 105 V. It can be seen from this figure that the recorded efficiency is the highest when $D = 0.05$, which is 96.2%. At $D = 0.2$, it drops to 89.9%. The drop in efficiency may be related to a large breakdown current, which can cause large leakage current and reduce the

Fig. 10 The measured efficiency of the Y-source converter and IQY converter when $K = 3$ and $0.05 \leq D \leq 0.2$.

effective switching duty cycle, resulting in a reduction in the system's voltage gain and efficiency, which can be reduced by using better wire or bus-bar to reduce the parasitic parameters and the stray losses. As for the efficiency of the Y-source converter, it becomes lower at higher duty cycles because it is more affected by the leakage inductance.

IV. CONCLUSIONS

In this paper, a new type of improved quasi-Y-source dc-dc converter based on the traditional quasi-Y-source structure is introduced, which own all the benefits of the existing Y-source dc-dc converter, such as extremely high boost gain and flexibility in designing winding magnetics. In addition, the converter has higher voltage gain, continuous input current and small starting inrush current. Undoubtedly, it is better than the quasi-Y-source converter for renewable energy systems. The mathematical derivation and experimental results for verification clearly demonstrates the expected performance of the proposed dc-dc converter and its practicality.

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