Novel High Step-Up DC–DC Converter for Fuel Cell Energy Conversion System

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***Abstract*—A novel high step-up dc–dc converter for fuel cell energy conversion is presented in this paper. The proposed converter utilizes a multiwinding coupled inductor and a voltage doubler to achieve high step-up voltage gain. The voltage on the active switch is clamped, and the energy stored in the leakage inductor is recycled. Therefore, the voltage stress on the active switch is reduced, and the conversion efficiency is improved. Finally, a 750-W laboratory prototype converter supplied by a proton exchange membrane fuel cell power source and an output voltage of 400 V is implemented. The experimental results verify the performances, including high voltage gain, high conversion efficiency, and the effective suppression of the voltage stress on power devices. The proposed high step-up converter can feasibly be used for low-input-voltage fuel cell power conversion applications.**

***Index Terms*—Coupled inductor, fuel cell, high step-up dc–dc converter, leakage inductor, voltage doubler.**

I. Introduction

THE DEVELOPMENT of "green power" generation has recently become very important to address environmental pollution and the problem of exhaustion of fossil energy reserves. Fuel cells represent one of the most efficient and effective alternative renewable energy sources for many applications, such as hybrid electric vehicles, uninterruptible power supplies, telecom back-up facilities, and portable electronics [1]–[4].

Fuel cells generate electricity via chemical reactions between hydrogen and oxygen. Much research on fuel cells and fuel cell stacks can be found in the literature [5], [6]. The proton exchange membrane fuel cell (PEMFC) is one of the most commonly used fuel cell for low-to-middle power generation systems. The PEMFC transfers hydrogen and oxygen energy into electrical energy and produces water and heat in the surface of catalytic particles. The reactions on the anode and the cathode and the global reaction of the PEMFC can be described as anode reaction

$$H_2 \rightarrow 2H^+ + 2e^- \tag{1}$$

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cathode reaction

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{2}$$

and global reaction

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{heat} + \text{electricity}. \tag{3}$$

Fig. 1 shows a general fuel-cell power generation system. Generally, the output voltage of the fuel cell stacks V_{FC} is varied from 24 to 40 V depending on the output power. In order to obtain a utility ac source (220-V rms at 50/60 Hz) from a fuel cell, a high dc bus voltage (380–400 V) is required at the input of the dc–ac inverter. Therefore, a high step-up dc–dc converter is needed to boost the low voltage at the fuel cell stacks into the high voltage at the dc bus.

In general, a conventional boost converter can be adopted to provide a high step-up voltage gain with a large duty ratio. However, the conversion efficiency and the step-up voltage gain are limited due to the constraints of the losses of power switches and diodes, the equivalent series resistance of inductors and capacitors, and the reverse-recovery problem of diodes [7], [8]. Therefore, a step-up converter with a reasonable duty ratio to achieve high efficiency and high voltage gain is very important for a fuel-cell power generation system.

Isolated converters, such as forward, flyback, half-bridge, full-bridge, and push–pull types, can be used to convert a low voltage into a higher output voltage by adjusting the turn ratio of the transformer. However, the active switch of these converters will suffer very high voltage stress and high power dissipation due to the leakage inductance of the transformer [9], [10]. To reduce the voltage spike, a resistor–capacitor–diode snubber can be employed to limit the voltage stress on the active switch. However, the efficiency will be reduced [11]. Nondissipative snubbers and active clamp techniques have been adopted to recycle the energy stored in the leakage inductor and to suppress the voltage spike across the active switch [12]–[15]. However, the cost will be increased due to the additional power switch, and high side driver is required.

In order to improve the conversion efficiency and to increase the step-up voltage gain without using the isolation transformer, many step-up converters based on a boost converter with a coupled inductor have been proposed [16]–[28]. High step-up converters with a low input current ripple based on the coupled inductor have been developed [16], [17]. The low input current ripple of these converters is realized by using an additional LC circuit with a coupled inductor. However, leakage inductance issues that relate to the voltage spike and the efficiency remain

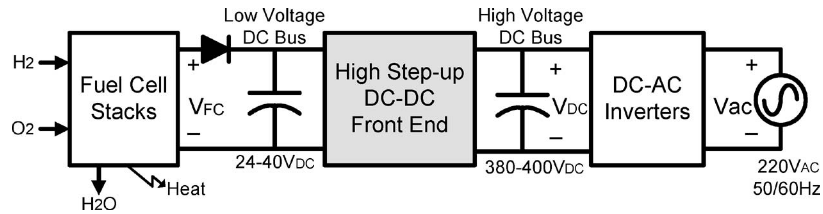

Fig. 1. General fuel-cell power generation system with a high step-up converter.

significant. An integrated boost–flyback converter based on a coupled inductor with high efficiency and high step-up voltage gain has been presented [18], [19]. The energy stored in the leakage inductor is recycled into the output during the switch-off period. Thus, the efficiency can be increased, and the voltage stress on the active switch can be suppressed. Many step-up converters, which use an output voltage stacking to increase the voltage gain, are presented [20]–[23], [31]. A high step-up dc–dc converter with an integrated coupled inductor and a common mode electromagnetic interference reduction filter is presented [20]. A Sepic–flyback converter with a coupled inductor and an output voltage stacking is developed [21]. A high step-up converter, which utilizes a coupled inductor and a voltage doubler technique on the output voltage stacking to achieve a high step-up voltage gain, is introduced [22]. A high step-up boost converter that uses multiple coupled inductors for the output voltage stacking is proposed [23]. High voltage gain can also be obtained with a tapped secondary winding of the transformer and input–output voltage cascoded for the extended forward-type converters of the high step-up converters [31]. However, extra devices, such as diodes and output capacitors, are needed for these converters. Additionally, step-up converters, which use a voltage lift, are introduced [24], [25]. Since the switch must suffer high current during the switch-on period, this technique is appropriate for low-output-power applications. High step-up converters with low voltage stress on the active switch can be realized by using the integrated coupled inductor and the voltage-lift technique [26]–[28]. Since the low voltage rating and the low conducting resistance $r_{ds(\mathrm{on})}$ of the power switch are used for these converters, the high conversion efficiency can be achieved. However, the requirement for a coupled inductor with a high coupling coefficient will result in manufacturing difficulty and cost increment. A high step-up converter, which uses a three-state switching cell and a voltage multiplier stage based on capacitors, can achieve high step-up gain [29], [30]. The voltage gain can be raised by adding the voltage multiplier stages of the capacitors. Since the two switches operate as interleaved operation, the size of the inductor can be reduced because the operating frequency of the inductor is double of the switching frequency. Moreover, the conduction losses can be reduced due to the current share of the active switches. Thus, this converter is suitably used for high-power applications. However, two switches are needed for the interleaved operation of this high-voltage-gain boost converter.

This paper presents a novel high-efficiency high step-up dc–dc converter, which has only one active switch. The proposed converter uses a three-winding coupled inductor and a voltage doubler on the output to achieve a high dc voltage. The proposed converter has the following features:

1) high step-up voltage gain;
2) energy stored in the leakage inductor is recycled to increase efficiency;
3) voltage stress on the active switch is clamped; thus, a power switch with a low voltage rating and a low on resistance $r_{ds(\mathrm{on})}$ can be adopted.

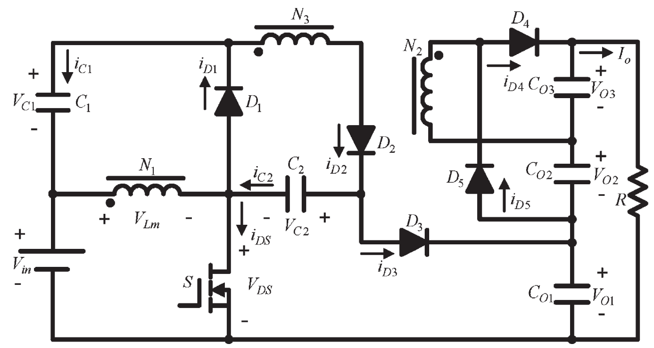

Fig. 2. Circuit configuration of the proposed converter.

II. Operation Principle of the Proposed Converter

Fig. 2 shows the circuit configuration of the proposed converter. This converter consists of a dc input voltage V_{in}, one power switch, one three-winding coupled inductor, five diodes, and five capacitors. The dc input voltage V_{in} and the circuit components N_1, S, D_1, and C_1 are operated as a boost converter with an input voltage cascode. The energy stored in the leakage inductor can be recycled. Thus, the efficiency can be improved. Also, the voltage across switch S is clamped effectively. The voltage doubler is composed of N_2, D_4, D_5, C_{O2}, and C_{O3}, which is stacked on the output to increase the voltage gain. The three-winding coupled inductor is used to provide high step-up voltage gain by adjusting the turn ratios of the windings.

To simplify the circuit analysis, the following conditions are assumed.

1) Capacitors C_1, C_2, C_{O1}, C_{O2}, and C_{O3} are large enough. Thus, V_{C1}, V_{C2}, V_{O1}, V_{O2}, and V_{O3} are considered as constant in one switching period.
2) The power MOSFET and the diodes are treated as ideal, but the parasitic capacitance of the power switch is considered.
3) The turn ratios of the coupled inductor are $n_2 = N_2/N_1$ and $n_3 = N_3/N_1$.