VOLUME-1 ISSUE-6
ISSN : 2799-18

ANALYSIS OF AN Alternating Phase Shift Control for Fuel Cell Power System

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Abstract—

This paper investigates a novel PWM scheme for twophase interleaved boost converter with voltage multiplier for fuel cell power system by combining Alternating Phase Shift (APS) control and traditional interleaving PWM control. The APS control is used to reduce the voltage stress on switches in light load while the traditional interleaving control is used to keep better performance in heavy load. The boundary condition for swapping between APS and traditional interleaving PWM control is derived. Based on the above analysis, a full power range control combining APS and traditional interleaving control is proposed. Loss breakdown analysis is also given to explore the efficiency of the converter. Finally, it is verified by experimental results. Also, the reverse recovery problem of all diodes is mitigated and zero-current-switching (ZCS) turn-on operation of the main switches
is established as well. In addition, the passive clamp circuits are employed to suppress the voltage spikes across the main switches during turn-off instants. The operating principles and steady-state analysis of the proposed converter in continuous condition mode are explained. Finally, the simulation and experimental results of prototype 25–400 V circuit with 200 W output power are provided to verify the performance of presented topology.

1. INTRODUCTION

With increasing concern about energy and environment, it is necessary to explore the renewable energy including wind power, solar, fuel cell, etc. Fuel cell is one of promising choices due to its advantages of zero emission, low noise, higher power density and being easily modularized for portable power sources, electric vehicles, distributed
generation systems, etc [1]. The grid-connected power system based on fuel cell is shown in Fig. 1. For a typical 10 kW Proton Exchange Membrane Fuel Cell, the output voltage is from 65 V to 107 V. However, the input voltage of the three phase DC/AC converter needs to be around 700 V, the voltage gain of the DC/DC converter between fuel cell and the DC/AC converter will be from 6 to 11. A high step-up DC/DC converter is needed for the system as shown in Fig. 1. The DC/DC converter will generate a high frequency input current ripple, which will reduce the life time of the fuel cell stack [2-4]. In addition the hydrogen energy utilization decreases with increasing the current ripple of the fuel cell stack output [5]. Therefore the DC/DC converter for the system as shown in Fig. 1 should have high step-up ratio with minimum input current ripple.

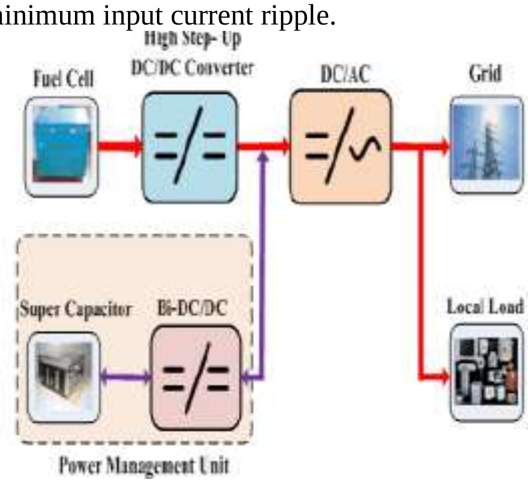

Fig. 1. Grid-connected power system based on Fuel Cell

High step-up ratio can be achieved by combining classical boost converter with switched inductors [6], coupled inductors [7-9], high frequency transformer [10] or switched capacitor (SC). They can obtain high step-up ratio with high efficiency, low voltage stress, and low EMI. In order to reduce output fuel cell stack output current ripple or the DC/DC

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converter input current ripple, either a passive filter or active filter [5] can be used, however, this will increase the complexity of the system. In fact, interleaving the DC/DC converter can reduce the input current ripple of the DC/DC converter. An interleaved boost converter with voltage multiplier was proposed. Its voltage gain was increased up to (M +1) times (M is the number of the voltage multiplier) of the classical boost converter with the same duty-cycle D and lower voltage stress. Besides it has lower input current ripples and output voltage ripples in comparison to the classical boost converter. The interleaving boost converter with voltage multipliers is shown in Fig. 2.
The converter shown in Fig. 2 can achieve low voltage stress in the power devices, which increases the conversion efficiency. However, this is only true in heavy load while the voltage stress of the power devices increases when it works in discontinuous mode (DCM) which occurs when fuel cell only supplies a light local load as shown in Fig. 1. In this case, higher voltage power devices need to be used, and therefore its cost and power loss will be increased. These authors proposed a new PWM control method, named as Alternating Phase Shift (APS), to overcome the problem when the converter operates in light load. High step-up DC–DC converters are employed in
numerous applications, such as renewable energy systems, motor drives, uninterruptible power systems and electric vehicles [1–6]. In these applications, a high step-up converter is required to adapt the low voltage level of batteries or photovoltaic cells to the high-voltage DC bus [7,8]. In order to perform this voltage conversion, various isolated DC–DC converters are presented in which high voltage gain can be achieved by increasing the transformer turns ratio. Nevertheless, these converters suffer from high circulating currents, high voltage stress and low efficiency.

According to the recent studies, non-isolated DC–DC converters are favourable in high step-up application due to lower size, lower circuit cost and higher efficiency than the isolated types. Conventional boost and buck-boost converters theoretically have a high voltage gain. However, due to many limitation factors, such as equivalent series resistance of the passive elements and reverse recovery problem of the output diode, a high step-up gain cannot be achieved in practice. In order to reduce the switches voltage stress in high step-up applications, conventional three-level boost converter can be used. Also, the size of the input inductor is lower than the boost converter. However, the voltage gain is still limited. Conventional cuk, sepic and zeta converters can be employed as a high step-up converter, but they are more complex than the boost converter. Some efforts are made to combine sepic and boost onverters. But despite using further elements, the voltage gain is limited.

2. PROPOSED CONVERTER AND OPERATING PRINCIPLES

The circuit configuration of the proposed converter is shown in Figure 2. This converter is based on two CI boost converter modules, which are interleaved connected at the input and series connected at the output. The input gate signals of the converter switches have a 180-degrees phase shift which causes interleaved operation of two modules. In this topology, inductors L1l

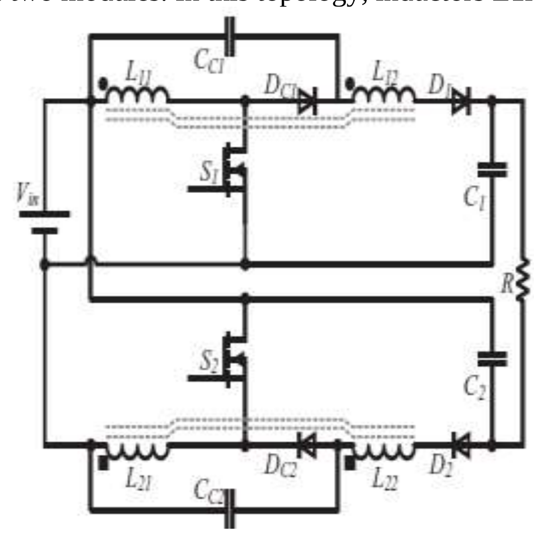

Figure 2. Circuit diagram of the proposed converter.

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and L2l comprise the two coupled inductors. Switches S1 and S2 are the main switches and diodes D1 and D2 are the output-rectifying diodes of the boost converter. Diodes DC1 and DC2 along with capacitors Cc1 and Cc2 comprise two passive clamp circuits which recycle the leakage inductors energy and limit voltage stress on the main switches. In order to simplify the operating principles analysis of the proposed converter, some assumptions are made as follows: - All diodes and MOSFET switches are considered to be ideal.

- All capacitors are large enough. Hence, their voltage ripple can be neglected.
- The operating duty cycle of the main switches S1 and S2 is equal.
- The coupled inductors are modelled as a magnetizing inductor, a leakage inductor and an ideal transformer with n = n12/n11 = n22/n21 turns ratio.

The typical waveforms of the proposed converter at steady-state condition are given in Figure 2. According to the following considerations, the proposed converter has eight operating modes during one complete switching cycle. Owing to the symmetrical operation of switches S1 and S2, only four operating modes of switch S1 are explained. The equivalent circuit of each mode is shown in Figure 3. Before t0, both switches S1 and S2 are ON and the magnetizing inductors LM1 and LM2 are charged through the input. Mode 1 [t0 ¡ t1]: At t0, switch S1 is turned off and clamp diode DC1 starts to conduct. During this mode, a part of magnetizing inductor current iLM transfers to the output via the secondary side of the coupled inductors and diode D1. Also, the leakage energy which stores in Llk1 is absorbed by the clamp capacitor Cc1.

Therefore, the leakage inductor current iLlk1 decreases linearly. At t1, iLlk1 reaches zero and this mode ends. During this interval, the equations of the leakage inductor and the magnetizing inductors currents are as follows:

$$i_{L_{lk1}}(t) = I_{L_{m1}}(t_0) - \frac{V_{Cc1} - \frac{1}{1+n}.(V_{C1} - V_{in})}{L_{lk1}}.(t - t_0). \quad (1)$$

$$i_{L_{m2}}(t) = i_{L_{lk2}}(t) = I_{L_{m2}}(t_0) + \frac{V_{in}}{L_{m2} + L_{lk1}}.(t - t_0). \quad (2)$$

Mode 2 [t1 ¡ t2]: At t1, the leakage inductor current becomes zero and the clamp diode DC1 is turned off without any reverse recovery problem. During this mode, the magnetizing inductor current iLM is charging the output capacitor C1 through the secondary side of the coupled inductors. Thus, iLM is decreasing linearly as follows:

$$i_{Lm1}(t) = I_{Lm1}(t_1) + \frac{V_{C1} - V_{Cc} - V_{in}}{L_{m1}}(t - t_1$$

3. CONTROL SCHEME OF ALL POWER RANGE WITH APS AND TRADITIONAL INTERLEAVING CONTROL

According to the principle of APS [25], APS control is proposed to solve the light load problem with duty cycle less than 0.5 as shown in Fig. 4(a). With the load increasing, the duty cycle will be increased as well. When the duty cycle is increased to 0.5, the APS control will be altered to be traditional interleaving control with halved switching frequency as shown in Fig. 4(b). According to previous analysis as shown in Fig. 3, the minimum duty cycle to achieve low voltage stress on switches with traditional interleaving control is less than 0.5. Therefore, it is possible to combine both APS control and traditional interleaving control to control the converter for full power range operation.

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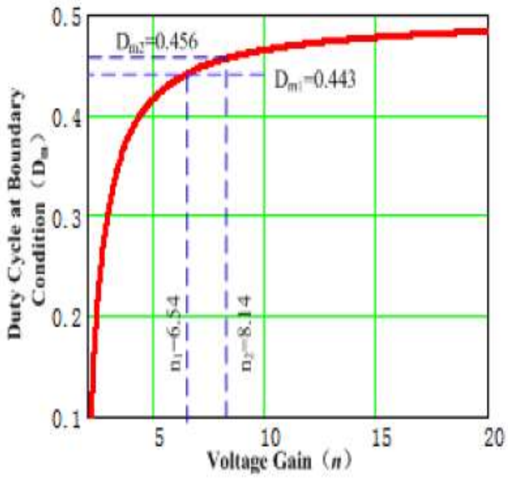
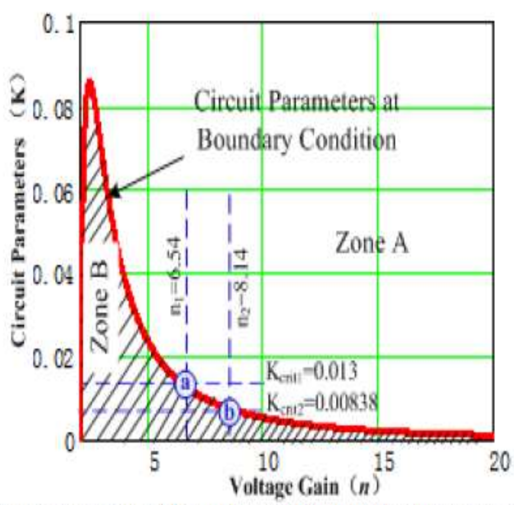


(a) Duty cycle at boundary condition varies with voltage gain



(b) Circuit parameters at boundary condition varies with voltage Gain

Fig. 3. Boundary constraint varies with voltage gain

The boundary constraint with traditional interleaving control decided by equation (14) is shown in Fig. 3. The constraint includes two parts: duty cycle D and the circuit parameters 2 /( ) S K = L R ×T . As the switching period TS and the input inductor L are designed at nominal operation in Continuous Conduction Mode (CCM), the constraint is determined by duty cycle D and the load R. The reason why there are two parts in the boundary constraint is that the duty cycle D varies with the load when the converter operates in Discontinuous Conduction Mode (DCM). For a given application, the voltage gain of the DC/DC converter is determined. And then the minimum duty cycle that can maintain low voltage stress in main power devices with traditional interleaving control will be given by equation (14)-(b) and as shown in Fig. 3(a).

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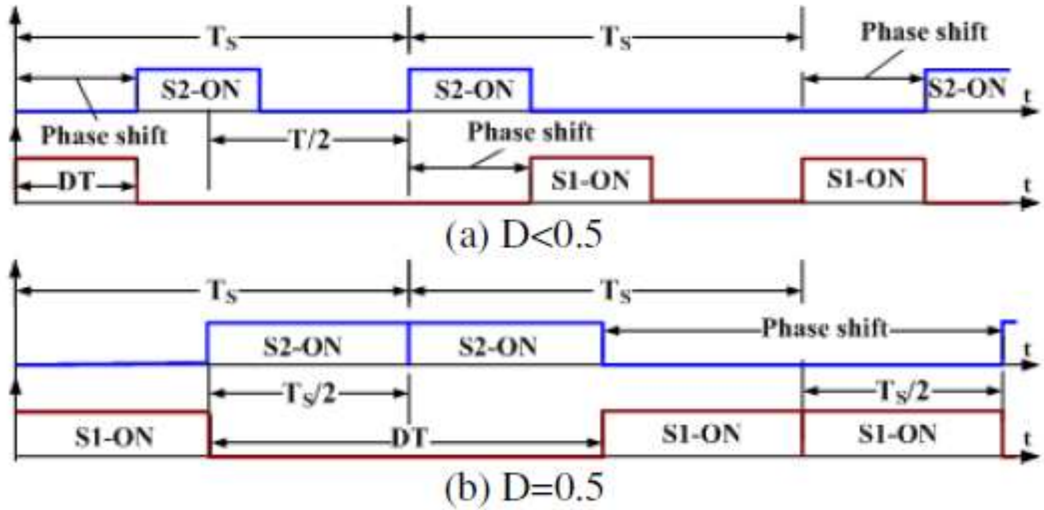

Fig. 4. PWM waveform of APS with D<0.5 and D=0.5

Conclusion

In this paper, a new interleaved high step-up DC–DC converter based on the floating-output capacitors technique was introduced. The steadystate analysis and derived equations represent that the voltage gain of the proposed converter is much higher than the conventional interleaved boost converter. In this topology, the voltage stress on the main switches and diodes is very low. Consequently, low-voltage, high-performance MOSFET switches and scotty diodes can be used. Also, the output and clamp diodes turn off under ZCS condition. Moreover, the leakage inductors energy is recycled into the circuit, so the voltage spikes across the main switches are avoided. At last, the proposed converter was simulated and a 200 W prototype circuit was implemented to prove the validity of the steady-state analysis.

REFERENCES

[1] N. Sammes, Fuel Cell Technology:Reaching Towards Commercialization. London: Spring-Verlag, 2006.

[2] G. Fontes, C. Turpin, S. Astier, and T. A. Meynard, "Interactions Between Fuel Cells and Power Converters: Influence of Current Harmonics on a Fuel Cell Stack," Power Electronics, IEEE Transactions on, vol. 22, no. 2, pp.
670-678, March 2007.

[3] P. Thounthong, B. Davat, S. Rael, and P. Sethakul, "Fuel starvation," *Industry Applications Magazine, IEEE*, vol. 15, no. 4, pp. 52-59, July-Aug. 2009.

[4] S. Wang, Y. Kenarangui and B. Fahimi, "Impact of Boost Converter Switching Frequency on Optimal Operation of Fuel Cell Systems," in *Vehicle Power and Propulsion Conference, 2006. VPPC '06. IEEE*, Windsor, 2006, pp. 1-5.

[5] S. K. Mazumder, R. K. Burra and K. Acharya, "A Ripple-Mitigating and Energy-Efficient Fuel Cell Power-Conditioning System," *Power Electronics, IEEE Transactions on*, vol. 22, no. 4, pp. 1437-1452, July 2007.

[6] B. Axelrod, Y. Berkovich and A. Ioinovici, "Switched- Capacitor/Switched-Inductor Structures for Getting Transformerless Hybrid DC-DC PWM Converters," *Circuits and Systems I: Regular Papers, IEEE Transactions on*, vol. 55, no. 2, pp. 687-696, March 2008.

[7] Z. Qun and F. C. Lee, "High-efficiency, high step-up DC-DC converters," *Power Electronics, IEEE Transactions on*, vol. 18, no. 1, pp. 65-73, Jan. 2003.

[8] H. Yi-Ping, C. Jiann-Fuh, L. Tsorng-Juu, and Y. Lung-Sheng, "A Novel High Step-Up DC-DC Converter for a Microgrid System," *Power Electronics, IEEE Transactions on*, vol. 26, no. 4, pp. 1127-1136, April 2011.