International Journal of Research
Available at https://edupediapublications.org/journals

e-ISSN: 2348-6848
p-ISSN: 2348-795X
Volume 04 Issue-17
December 2017

Fuel Cell Based Interleaved Four-Phase Voltage Divider Circuit with Uniform Current Sharing

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Abstract

A Novel Fuel Cell based transformer less interleaved high step-down conversion ratio dc-dc converter with low switch voltage stress has been presented. In this converter, two input capacitors are series-charged by the input voltage and parallel discharged by a new two-phase IBC for providing a much higher step-down conversion ratio without adopting an extreme short duty cycle. Based on the capacitive voltage division, the main objectives of the new voltage-divider circuit in the converter are both storing energy in the blocking capacitors for increasing the step-down conversion ratio and reducing voltage stresses of active switches.

As a result, the presented converter topology possesses the low switch voltage stress characteristic. This will allow one to choose lower voltage rating MOSFETs to reduce both switching and conduction losses, and the overall efficiency is consequently improved. Moreover, due to the charge balance of the blocking capacitor, the converter features automatic uniform current sharing characteristic of the interleaved phases without adding extra circuitry or complex control methods. Here interleaved buck converter (IBC) and its operation are discussed. Also comparisons with conventional interleaved buck converter and simulation results are included.

1.INTRODUCTION

Nowadays high performance dc – dc converters are required for increasing high step-down conversion ratio with high output current applications like CPU boards and battery chargers, and distributed power systems [2] – [4]. For non-isolation applications with low output current ripple requirement, an interleaved buck converter (IBC) has received a lot of attention due to its simple structure and low control complexity.

Interleaving technique connects dc-dc converters in parallel to share the power flow between two or more conversion chains it implies a reduction in the size, weight and volume of inductors and capacitors. Also a proper control of the parallel converters increase the ripple frequency and reduces the ripple waveforms at the input and output of the power conversion system, which leads significant reduction of current, voltage ripples and filter capacitor size. Therefore the interleaved buck converters has received a lot of attention in non-isolation applications with low output current ripples.

However, in the conventional multiphase IBC, as shown in active switches are required to use high-voltage devices that are rated above the input voltage. High-voltage- rated devices generally render a number of undesirable characteristics, such as high cost, large on-resistance, large voltage drop, and severe reverse recovery. For high-input low-output voltage regulation applications, operations at higher switching frequencies are required to achieve a higher power density and better dynamics [5]. However, the buck converter with a high step down conversion rate yields a significant switching loss due to its extremely low duty cycle. This fact not only limits the achievable switching frequency, but also complicates its implementation. In addition, the efficiency is further compromised due to the short on- time and long freewheeling time within each switching cycle [6].

To overcome such disadvantages of the conventional IBC, a number of modified IBC structures have been proposed [7]–[14]. A multiphase IBC with extended duty ratio [7], [8]was proposed for high-input low-output voltage regulation applications. Two and four-phase versions of the topology were examined in [7] and [8]. The four-phase extended duty ratio IBC The mechanism of the extended duty ratio lies in the use of highly efficient input voltage dividers which reduce the switching voltage and the associated losses. However, the voltage stress to input switching devices remains rather high.

In this paper, we propose a novel transformer -less dc converter that features low switch voltage stress and automatic uniform current sharing. An interleaved four-phase voltage divider is used to achieve a high step-down conversion ratio. In the proposed converter, series charging of the two capacitors from the input voltage and parallel discharging to the load facilitated by a new four phase IBC. This architecture provides a high step-down conversion ratio and a low output current ripple without requiring an extremely low duty cycle. Based on the capacitive voltage division, the new voltage-divider circuit in the converter achieves two major objectives, i.e., increased voltage conversion ratio, due to energy storage in the blocking capacitors, and reduced voltage stress of active switches. The low switch voltage stress offered by the proposed converter topology allows the use of lower voltage rating MOSFETs to reduce both switching and conduction losses, thereby improving the overall efficiency. Moreover, due to the charge balance of the capacitors, the converter features automatic uniform current sharing of the interleaved phases without adding extra circuitry or complex control methods.

2. NOVEL TRANSFORMER-LESS FOUR PHASE BUCK CONVERTER

The proposed converter is shown in Fig. 1, which is derived from the two-phase IBC with an extended duty ratio in [9]. In order to further reduce the output current and output voltage ripples, the converter is divided into four-phase small inductors via an interleaved operation. It is clear from Fig. 1 that the proposed converter consists of four inductors, four active power switches, four diodes, and four capacitors. The proposed converter topology with low switch voltage stress and high step down ratio can only be achieved when the duty cycle is lower than 0.5 and operated in CCM. In addition, when the duty cycle is lower than 0.5, due to the charge balance of the blocking capacitor, the converter enables automatic current sharing so as to obviate any extra current-sharing control circuit. On the other hand, when the duty cycle is higher than 0.5 or when the converter is operates under DCM with a light load, the converter no longer possess the automatic current-sharing capability, and the current-sharing control between each phase should be taken into account.

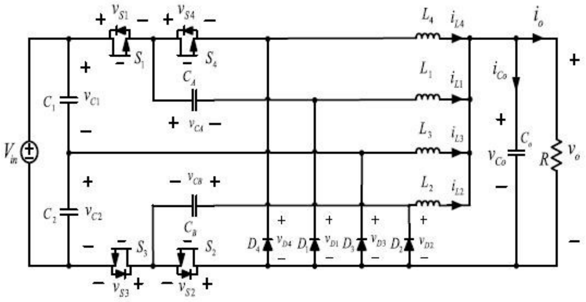

Fig 1. Circuit Diagram of Proposed IBC

3.MODES OF OPERATION

In order to clearly explain the operation principle, the operating duty ratios $0 < D < 0.25$ and $0.25 < D < 0.5$ by the proposed four-phase and two-phase interleaved strategies are, respectively, introduced. Referring to the gate signals shown in Fig. 2, the corresponding operating modes of the proposed converter for condition $0 < D < 0.25$ is discussed next. In first mode, switch $S1$ is turned on, and switches $S2$, $S3$, and $S4$ are all OFF. Hence, diode $D1$ becomes OFF whereas diodes $D2$, $D3$, and $D4$ remain ON. The stored energy of $C1$ is discharged to CA, $L1$, and the output load, whereas current $iL2$, $iL3$, and $iL4$ are freewheeling through $D2$, $D3$, and $D4$, respectively. In the next mode all switches gets off. In this case, $iL1$, $iL2$, $iL3$, and $iL4$ are freewheeling through diodes $D1$, $D2$, $D3$, and $D4$, respectively .In next mode only S2 gets on an all others off.

Corresponding changes as in mode 1 continues.

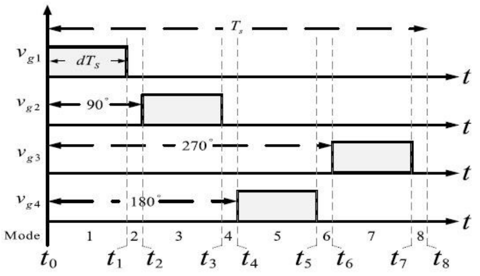

Fig 2. Gate Pulse of four phase strategy

Referring to the gate signals shown in Fig. 3, In first mode two switches S1 and S2 gets on It is observed that *iL*3 and *iL*4 are freewheeling through*D*3 and*D*4 , respectively, and *L*3 and *L*4 are releasing energy to the output load. The stored energy of *C*1 is discharged to *CA*, *L*1 , and the output load, while the stored energy of *CB* is discharged to *L*2 and the output load. In the next mode all switches are off. In this case, *iL*1 , *iL*2 , *iL*3 , and *iL*4 are freewheeling through diodes*D*1 ,*D*2 ,*D*3 , and*D*4 , respectively. During next mode other pair of switches gets on and current flow continues.

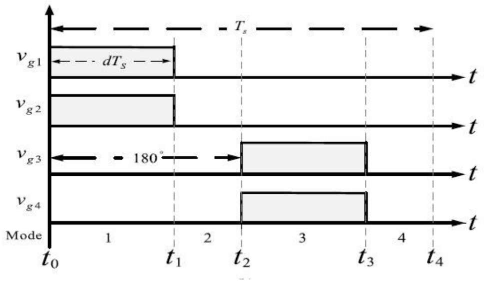

Fig 3. Gate Pulse of two phase strategy

4.DESIGN

From the volt–second relationship on inductors L1 – L4 , it is obtained as

$(V_{C1} - V_{CA} - V_O)D - V_O(1 - D) = 0$

$(V_{CB} - V_O)D - V_O(1 - D) = 0$

$(V_{C2} - V_{CB} - V_O)D - (1 - D)V_O =$

0

$(V_{CA} - V_O)D - (1 - D)V_O = 0$

From the above equation , it can be derived as

$$M_{Step-down} = \frac{Vo}{Vin} = \frac{D}{4}$$

The components are designed based on the assumption that all components are ideal, the capacitors are large enough that the voltage across them can be considered as constant also C1=C2 and CA =

$$CB. Vo = \frac{D}{4} \text{ x } Vin$$

$$_1 = _2 = L_3 = L_4 = \frac{VoTs(1-D)}{\Delta IL}$$

$$C_A = C_B = C1 = C2 = \frac{\Delta ILDTs}{2\Delta Vc}$$

$$Co = \frac{\Delta IL}{8(\Delta Vo - \Delta IL * ESR)fs}$$

5.SIMULATION RESULTS

The closed loop Simulation of the above converter is done in MATLAB simulink using 400 V input and 24 V, 500 W output at 40 KHZ frequency. The Parameters used in Simulation are shown in Table 1

Table 1. Parameters Used in Simulation

Sl.No	Paramers Used	Specification
1	Inductors	250μH
2	Capacitors CA, CB,C1,C2	10μH
3	Output Capacitor Co	220μH
4	Output Resistor	1.152Ω
5	Duty Ratio	24
6	Output Power	500 W
7	Frequency	40KHz
8	Input Voltage	400V
9	Output Voltage	24 V

12 SIMULATION RESULTS

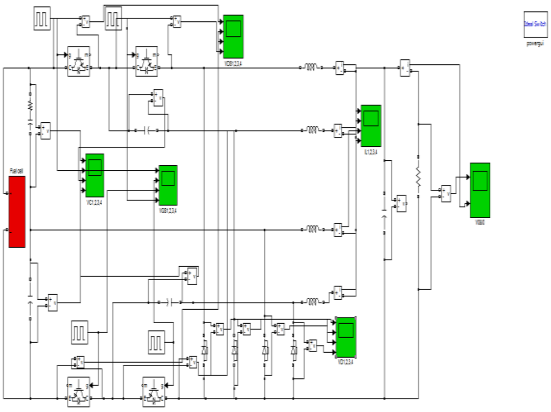

Fig 4. Simulation Diagram of Fuel Cell based IBC

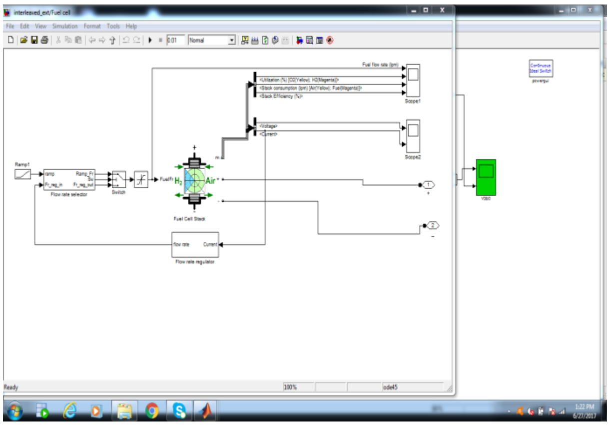

Fig 5. Simulation diagram of fuel cell subsystem.

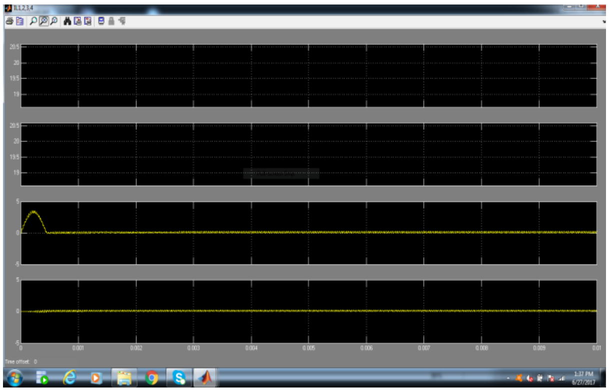

Fig 6. Wave forms of interleaved extension of IL1, IL2, IL3, IL4.

Fig 7. Wave forms of Interleaved extension in voltage stress $V_{DS1,2,3,4}$, (10 μS/div)

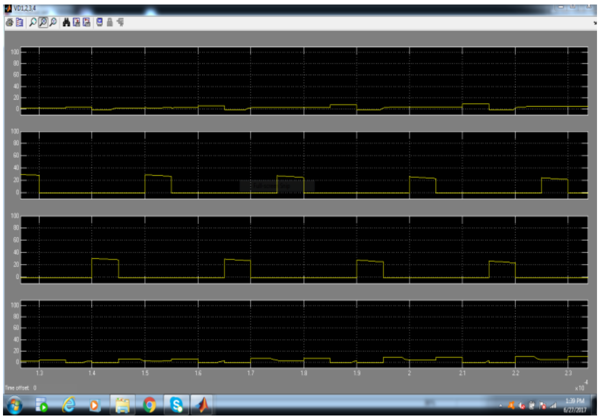

Fig 8. Wave forms of interleaved extension in Voltage stress $V_{D1, 2, 3, 4}$,(10 µs/div).

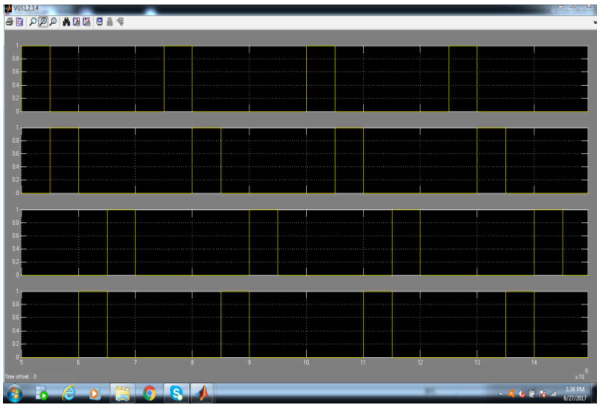

Fig 9. Wave forms of Inter leaved extension gate signals in $V_{GS1, 2, 3, 4}$.

Fig 10. Output Voltage & Current wave forms of interleaved extension.

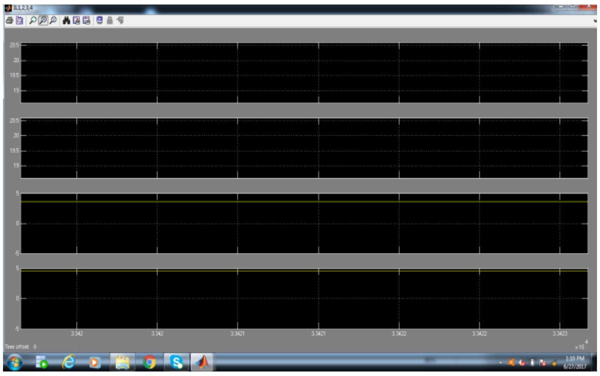

Fig 11. Wave forms of interleaved in $I_{L1, 2, 3, 4}$.

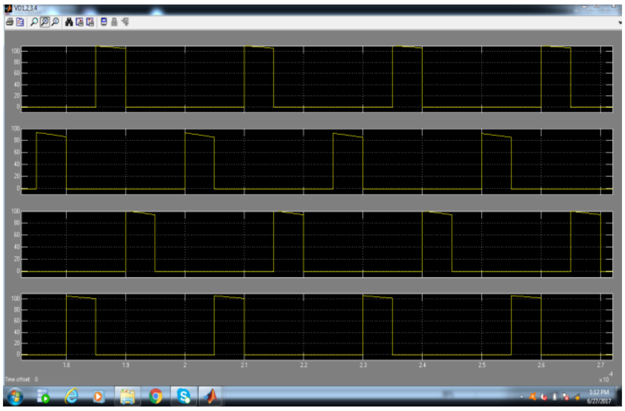

Fig 12. Wave forms of interleaved in $V_{D1, 2, 3, 4}$,(10 µs/div).

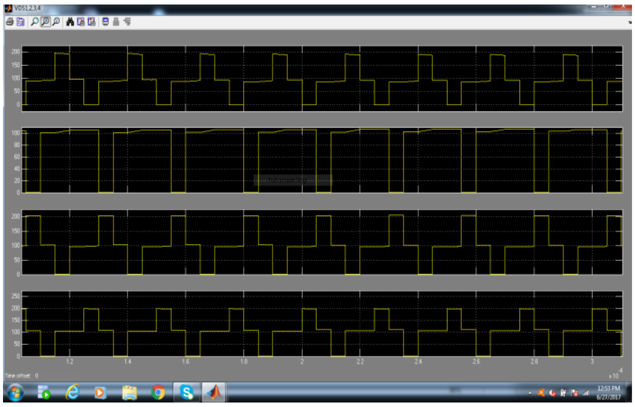

Fig 13. Wave forms of interleaved voltage stress $V_{DS1, 2, 3, 4}$,(10 µs/div).

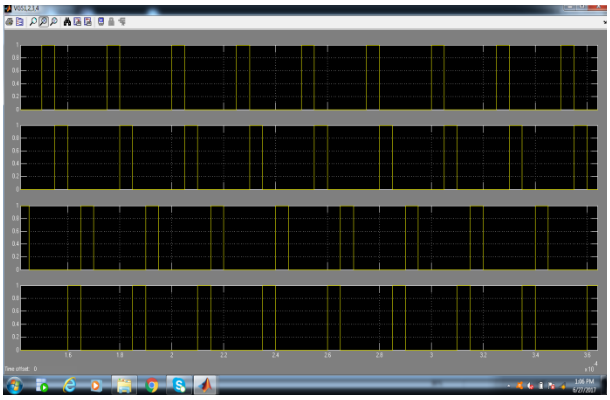

Fig 14. Wave forms of interleaved voltage gate signals $V_{GS1, 2, 3, 4}$.

6. CONCLUSION

In this paper, an interleaved Fuel Cell based high step-down conversion ratio dc–dc converter with low switch voltage stress has been proposed. In the proposed converter, two input capacitors are series-charged by the input voltage and parallel discharged by a new four-phase IBC for providing a much higher step-down conversion ratio without adopting an extreme short duty cycle. Based on the capacitive voltage division, the main objectives of the new voltage divider circuit in the converter are both storing energy in the blocking capacitors for increasing the step-down conversion ratio and reducing voltage stresses of active switches. As a result, the proposed converter topology possesses the low switch voltage stress characteristic. This will allow one to choose lower voltage rating MOSFETs to reduce both switching and conduction losses. Moreover, due to the charge balance of the blocking capacitor, the converter features automatic uniform current sharing characteristic of the interleaved phases without adding extra circuitry or complex control methods. The operation principles and relevant analysis of the proposed converter are presented in this paper.

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