Wide gain bidirectional converters for energy storage system of fuel cell vehicles

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Abstract. Fuel-Cell Vehicles have gained reasonable popularity for its low emission, long driving range, and eco-friendly features. A bidirectional DC-DC converter stands between the energy management system and the high voltage bus connected to the load through the inverter. Many converter topologies have been proposed for FCVs can be observed in the Electric vehicle market. Hence, there is a need of assessment of the popular topologies of the bidirectional DC-DC converters required to judge. This paper presents analysis and simulation studies between two converter topologies which employ inherent soft switching technique and set forth the suitable performance observed in PSIM 9.0 simulations.

1. Introduction

The use of non-conventional resources is the need-of-the-hour for every energy utility. Hence, fuel-cell vehicles have paved its way into the vehicle industry. The significance of fuel-cell vehicles is exponentially increasing owing to improved vehicle performance, excellent fuel economy and lowered emissions. When compared to battery-powered electric vehicles with fuel-cell vehicles, the FCVs are more reliable with respect to the emission range, driving comfort and refuelling time [1]. DC-DC Converters are used in two stages in the fuel-cell vehicle model: High gain unidirectional DC-DC boost Converter and Bidirectional DC-DC Converter for ESS.

The research in this area mainly focuses on the isolated Bidirectional DC-DC Converters, this is because, the non-isolated converter topologies suffer with the following problems: a) Diode reverse recovery problem, b) Switching stress, c) Inability to acquire huge gain. Hence the isolated DC-DC converter is preferred as it overcomes the above-mentioned problems, and adds the following advantages: a) Protection to the converter, b) Obtaining multiple outputs c) Achieving huge gain with lesser output duty ratio.

The paper analyses relevant bidirectional DC-DC converter topologies [6]. Fig. 1 illustrates the block diagram of the fuel-cell vehicle model. In FCV, fuel-cell stack generates DC power, which is transferred to the load by the medium of high voltage bus. To match the voltage (boost) of the fuel-cell stack with the bus, we place the above-mentioned high gain unidirectional DC-DC converter between them. Similarly, the bidirectional DC-DC converter is seen of use in the following two cases:

In the absence of the fuel-cell generation, to handle the load, the power is transferred from the Energy Storage System (ESS) to the load, via the high voltage bus. To match the voltage of the ESS with the bus voltage, the DC-DC converter is operated in boost mode (Refer Fig. 2a). The induction motor/electric motor drive in the fuel-cell vehicle, during regenerative braking utilizes the path as shown in Fig. 2b. The bidirectional DC-DC converter bucks the voltage (suitable to the ESS) obtained from the regenerative braking phenomenon and sends the power to the ESS.
Hence, the bidirectional converter has utmost importance in the fuel-cell vehicle as the above mentioned two modes are under operation very frequently. The following are the desired characteristics expected from a bidirectional DC-DC converter:

- **a)** High gain of the converter to meet DC bus voltage requirement
- **b)** High efficiency to improve overall system efficiency
- **c)** Isolated topology for protection
- **d)** Soft switching on both primary and secondary to reduce switching losses, particularly at very high frequencies

The paper analyses precisely two isolated bidirectional DC-DC converter topologies. The advantages and techniques of the respective DC-DC converters are illustrated in Section II. The design parameters and design equations are dealt in Section III. The simulation results and analysis of the converters can be observed in Section IV of this paper.

### 2 Proposed Topologies

#### 2.1 Isolated Current-fed Bidirectional Full-bridge Voltage Doubler DC-DC converter

The converter [2] proposes all the features of the desirable bidirectional DC-DC converter mentioned above. Fig. 3 represents the circuit which adopts the current-fed full bridge voltage doubler topology. The converter as shown in Fig. 3 adopts current-fed topology, as compared to voltage-fed converters, the current-fed converters possesses lower input current ripple, lower high frequency transformer turns ratio, easier current control ability and insignificant diode ringing [3][4]. The circuit employs ‘snubberless’ topology as the snubber circuit absorbs energy by the clamping capacitor and is dissipated on the resistor which leads to decreased efficiency [5][6]. Active clamping leads to higher efficiency which helps in achieving Zero Voltage Switching (ZVS) of switches. The dual half-bridge nature at the secondary side of the circuit is vital in minimizing the number of switching devices [7]. The half-bridge designated mainly to reduce the number of switches and the transformer turns ratio.
2.2 The Isolated Dual Full-bridge Bidirectional DC-DC Converter

The converter [7] as shown in Fig. 4 is also equally competent in all means, as it satisfies the above-mentioned qualities of the required isolated bidirectional DC-DC converter. The topology adopted in this circuit is dual full-bridge.

The circuit is designed with current-fed topology, as it advantageous over voltage-fed topology in the following areas:

a) Lower input ripple current  
b) Lower high frequency transformer ratio can be assumed  
c) Insignificant diode ringing  
d) Minor duty cycle loss  
e) Easier current control ability

Natural Commutation is espoused with ZCS of primary devices is attained, hence avoiding the need of passive snubber circuits. Hence, a snubber-less design is embraced in the DC-DC converter.

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**Figure 2.** Power Flow in Boost (a) and Buck (b) modes of the bidirectional DC-DC Converter

**Figure 3.** Isolated Current-fed Bidirectional Full-bridge Voltage Doubler Circuit and Block Diagram of the topology
3 Design of the converters
The converters have been designed meticulously for obtaining reduced switching stress, higher efficiency, reduced inductor ripple currents and improved voltage and current waveforms.

3.1 Isolated Current-fed Bidirectional Full-bridge Voltage Doubler DC-DC converter
The converter has the following design considerations:

Table 1. Specification of proposed converter

| Parameter         | Rating    |
|-------------------|-----------|
| Output Power $P_0$ | 250w      |
| Input Voltage $V_{in}$ | 12v     |
| Output Voltage $V_0$ | 150–300v |
| Switching Frequency $f_s$ | 100kHz |

The following are the design equations presented to determine the components’ rating(s).

i) Average input current
$$I_{in} = \frac{P_0}{nV_{in}} \quad (3.1)$$

ii) Assuming an ideal efficiency $\eta = 95\%$. Therefore, $I_{in} = 21.9$ A

iii) Maximum voltage across the primary switches
$$V_{P(SW)} = \frac{V_0}{2n} \quad (3.2)$$

iv) Input and output voltages are related as
$$V_0 = \frac{n.V_{in}}{1-d} \quad (3.3)$$

Where $d$ is the duty cycle of primary switches. Equation (3.3) is derived by taking into consideration that the body diode conducts for significant short time ensuring ZCS of primary switches without significant increase in the peak current. However, during conditions of light load, the diode conduction time is comparatively large and (3.3) is not valid anymore.

Owing to the extended period of body diode conduction, the output voltage is boosted to higher value when compared to standard boost converter. Hence, for such cases, (3.3) is modified into the following

$$V_0 = \frac{n.V_{in}}{1-d-d'} \quad (3.4)$$

where $d'$ is given by,
$$d' = d - 0.5 - \frac{4.n.I_{in}.L_{lk}.f_s}{2V_0} \quad (3.5)$$
Series inductance $L_{lk}$ is calculated using
\[ L_{lk} = \frac{V_0(d-0.5)}{4nI_{in}f_s} \quad (3.6) \]

The output power can be derived as
\[ P = \frac{4nV_0^2v_{in}(3-4d)}{16nL_{lk}f_s} \quad (3.7) \]

The principal criterion for selecting the transformer turns ratio is based on conduction losses, consisting of conduction losses in the primary switches as they carry higher currents. Increase in the turns ratio shall reduce the maximum voltage across the primary switches allowing low voltage switches with low on-state resistance (from Equation (3.2)). Hence, greater the turns ratio, higher will be the switch RMS current. Voltage regulation caused due to varying input voltage is another matter of interest. An optimum turns ratio $n = 5$ and duty ratio $d = 0.8$ are selected to achieve low overall conduction losses. The output voltage can be regulated from 150V to 300V by varying the duty ratio. Leakage inductance of $L_{lk} = 2.05 \mu H$ is obtained from (3.1.2.5) for the given values.

Value of boost inductor is given by
\[ L = \frac{V_0d(d-0.5)}{\Delta I_{in}f_s} \quad (3.8) \]

where $\Delta I_{in}$ is the boost inductor ripple current. For $\Delta I = 1$ A, $L = 36 \mu H$.

VA rating of each HF transformer is given by
\[ VA_{x-mer} = \frac{V_0I_{in}}{2n} \sqrt{\frac{2.5-4d(1-d)}{3}} \quad (3.9) \]

The calculated value is $VA_{(x-mer)} = 321.9$ VA.

### 3.2 Isolated Dual Full-bridge Bidirectional DC-DC Converter

The following principal specifications are used in the design of this converter:

Duty cycle $D = 0.76$ (at rated load)

| Parameter          | Rating   |
|--------------------|----------|
| Output Power $P_0$ | 180w     |
| Input Voltage $V_{in}$ | 12v   |
| Output Voltage $V_0$ | 250v  |
| Switching Frequency $f_s$ | 100kHz |
| Duty cycle $D$ | 0.76     |

Average input current is, assume the efficiency of the converter is 95%
\[ I_{in} = \frac{P_0}{C_{efficiency} \times V_{in}} = 15.78A \quad (3.10) \]

Primary switches maximum voltage is
\[ V_{swpeak} = \frac{V_0}{n} = 25V \quad (3.11) \]

At rated voltage conversion ratio is
\[ V_0 = \frac{n \times V_{in}}{2(1-D)} = 250V \quad (3.12) \]
Parasitic components create resonance in the circuit. That indicates leakage inductance and capacitance across the switches.

Conduction of ZVS

\[ 2\pi \sqrt{LC} = (1 - D)T_s \]  

Load Resistance

\[ R = \frac{V_o}{P_0} = 347.2 \Omega \]

4 Simulation results of the proposed converter

4.1 Isolated Current-fed Bidirectional Full-bridge Voltage Doubler DC-DC converter

Fig. 5 and Fig. 6 refer to the gate pulses to the switches S1, S4 and S2, S3 respectively. The gate pulses are overlapping to each other. Hence, enabling only either pair of the switches functioning at any instant of time for active power flow from source to load. Fig. 7 and Fig. 8 represents gate signals for switch S5 and S6 respectively; of the voltage doubler (secondary) side. The two switches are clearly complementary in nature. Fig. 9 depicts the current through the leakage inductance of the ‘High Frequency Transformer’. This is a hypothetical representation of the \( X_{\text{leak}} \) of any transformer that is used. It usually is constant with respect to manufacturing of the transformer. The current waveform alternates based on the alternate switching of the primary side switches. Fig. 10 and Fig. 11 clearly show the complementary nature of the primary-side switches. Fig. 12 and Fig. 13 represents secondary switches currents. Fig. 14 is the voltage waveform across primary of the high frequency transformer can observe the voltage varying from +40V and -40V. Fig. 15 is the output voltage waveform of the DC-DC Converter. The waveform is almost ripple free voltage. The magnitude represents the ‘boost operation’ of the converter.

![Figure.5. Gating Signal for switches S1 and S4](image)

![Figure.6. Gating Signal for switches S2 and S3](image)

![Figure.7. Gating Signal for switches S5](image)

![Figure.8. Gating Signal for switches S6](image)
Figure 9. Input current through Leakage Inductance

Figure 10. Current through S2

Figure 11. Current through S1

Figure 12. Current through S6

Figure 13. Current through S5

Figure 14. Voltage across primary of the transformer

Figure 15. Output Voltage
4.2 Isolated Dual Full-bridge Bidirectional DC-DC Converter

Fig. 16 represents the primary side ‘soft-switching’ current waveforms of primary-side switches S1 and S4. One can observe the same soft switching phenomenon in the primary side switches S2 and S3. Fig. 19 shows the secondary side ‘soft-switching’ current waveform of the switches S6 and S7. Fig. 20 represents the input boost inductor current waveform in the primary side of the converter which is of very much less ripple. Fig. 21 depicts the leakage inductor current which is placed in between the primary and secondary side of the DC-DC converter. Fig. 22 is the output voltage waveform of the DC-DC Converter. One can observe almost ripple free output voltage in boost mode.

Figure 16. Primary side Soft switching S1 and S4

Figure 17. Primary side Soft switching S2 and S3

Figure 18. Secondary side S5 and S8 soft switching

Figure 19. Secondary side S6 and S7 soft switching
5 Conclusion
Compared to traditional dual active bridge the proposed voltage doubler converter provides same voltage gain with reduce in number of HF transformer turns ratio, which thereby decreases size and weight of the converter which makes converter even more compact. Because of reduction in transformer turns ratio leakage inductance of the transformer will be less and copper losses of the HF transformer are also less which improves converter efficiency. Also, the primary side switches blocking voltage is reduced, which can yield to use low voltage rating MOSFETs which have usually less Ron, which can even reduce conduction loss Based on the analysis studies, the converters achieve soft switching both on primary side active devices and secondary side active devices without adding additional elements. The efficiency of the converter is improved by obtaining zero current switching on primary side and zero voltage switching at secondary side.

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