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Published in:
Proceedings of IPEC 2018 ECCE Asia

DOI (link to publication from Publisher):
10.23919/IPEC.2018.8507455

Publication date:
2018

Document Version
Accepted author manuscript, peer reviewed version

Link to publication from Aalborg University

Citation for published version (APA):
Full-Bridge T-type Isolated DC/DC Converter with Wide Input Voltage Range

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Abstract—The advent of the silicon carbide (SiC) power device with high voltage stress would simplify the power converter’s circuit structure for high voltage applications since two-level topologies would be possible to instead three-level (TL) based topologies. This paper proposes a full-bridge (FB) T-type isolated DC/DC converter composed of four main power switches with high voltage stress (SiC MOSFET) and four auxiliary power switches with low voltage stress (Si MOSFET). Therefore, comparing with the conventional diode-clamped FB TL isolated DC/DC converter, the proposed converter has fewer circuit components and simpler circuit structure. What is more, a corresponding control strategy is proposed, which can not only realize zero-voltage switching (ZVS) but also achieve wide input voltage range. Finally, simulation and experimental results are both presented for verification.

Keywords—DC/DC converter, Full-bridge (FB), T-type, Wide input voltage range.

I. INTRODUCTION

Although AC distribution system is most widely used distribution system nowadays [1], [2], DC distribution system is a promising solution for the future power distribution system [3], [4] because the increasing applications of EV infrastructure, and renewable energy. The DC/DC converters are responsible for controlling power flow and converting the voltage level in the DC distribution system, so the research about the efficient and reliable DC/DC converters becomes a hot topic [5] - [7]. The three-level (TL) DC/DC converters become attractive because they can withstand the high input voltage and thus reduce the transmission loss. Many studies have been done on the TL isolated DC/DC converters in topics of extending soft switching range [8], [9], balancing voltages on the input capacitors [10], [11], reducing circulating currents [12], [13], minimizing and balancing currents on the input capacitors [14], and balancing currents among power switches [15].

T-type converter is another type of TL converter, which has been widely applied for inverters [16]. References [17] - [19] discussed about the T-type isolated DC/DC converters recently. Comparing with the conventional diode-clamped TL DC/DC converter, T-type converter has fewer circuit components and simpler circuit structure. The T-type DC/DC converters discussed in [17] - [19] belong to the half-bridge (HB) structure, thus they would be unsuitable for high power applications since the power switches’ current stress on in HB structure is twice of that in FB structure. In addition, a major drawback of the T-type converter is that the main power switches’ voltage stress is full input voltage. Fortunately, the advent of SiC power device would result in that the T-type DC/DC converter with SiC power device is possible for the high voltage applications because SiC power device’s drain-source breakdown voltage is much higher than Si power device’s.

In this paper, a FB T-type isolated DC/DC converter with SiC device is proposed for high-power and high-voltage applications. There are four main power switches with high voltage stress (SiC MOSFET) and four auxiliary power switches with low voltage stress (Si MOSFET) in the proposed converter. What is more, a control strategy composed of two modes is proposed, which not only can realize zero-voltage switching (ZVS) for main and auxiliary power switches but also can fulfill wide input voltage range. Finally, both simulation and experimental results are demonstrated for verification.

II. CIRCUIT STRUCTURE

Fig. 1 presents the proposed converter’s circuit structure. In Fig. 1, C₁, C₂ are two input capacitors; V₁, V₂ are two voltages split by C₁, C₂ from input voltage Vᵣᵢᵣ, S₁ - S₄ are four main power switches; S₅ - S₈ are four auxiliary power switches; D₁ - D₄ are body diodes of S₁ - S₄; C₅ - C₆ are parasitic capacitors of S₁ - S₄; Tᵱ is an isolated transformer; Lᵱ is the inductance of series inductor plus leakage inductance of Tᵱ; D₅ - D₈ are four rectifier diodes; Lₒ is an output filter inductor; and Cₒ is an output filter capacitor.

![Fig. 1. Proposed converter’s circuit structure.](image)

In Fig.1, the input voltage is Vᵣᵢᵣ; the voltage between point a and b is Vᵣᵢₒ; the primary current of Tᵱ is iₜᵱ; the current on Lₒ is iₒₒ; the output voltage is Vₒₒ; the output current is iₒₒ; the turns ratio of Tᵱ is n. Table I shows the comparison results about the primary component number
TABLE I
COMPARISON RESULTS ABOUT PRIMARY COMPONENT NUMBER

<table>
<thead>
<tr>
<th>Component</th>
<th>Diode-clamped FB TL DC/DC converter</th>
<th>Proposed FB T-type DC/DC converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power switch</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Clamping diode</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Flying capacitor</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Input capacitor</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

III. OPERATION PRINCIPLE

A ZVS control strategy with two working modes is proposed. Figs. 2(a) and 2(b) show main waveforms of mode I and II respectively, in which \( d_{\alpha1} - d_{\alpha5} \) are driving signals for power switches \( S_1 - S_6 \); \( T_s \) is one switching period; \( d_1, d_2 \) are duty ratios in \( T_s \) and are used for operation mode I and II respectively; \( d_{\text{loss}_I} \) and \( d_{\text{loss}_II} \) are duty ratio losses in \( T_s \) under the operation mode I and II respectively.

Mode I and II are applied for low and high input voltage respectively, which can thus achieve the wide input voltage range. As presented in Fig. 2, \( V_o \) is controlled by adjusting \( d_1, d_2 \) under mode I and mode II respectively.

Figs. 3 and 4 present operation circuits for explaining the working operations under mode I and II more clearly.
IV. ANALYSIS OF CHARACTERISTIC AND PERFORMANCE

A. Power Switches: Voltage Stresses

In steady working operations, the voltage stress on main power switches $S_1 - S_4$ are the input voltage ($V_{in}$), and the voltage stress on auxiliary power switches $S_5 - S_8$ are half of the input voltage ($V_{in}/2$).

B. Output Gain

Under mode I and II, the duty ratio losses named $d_{loss,I}$ and $d_{loss,II}$ can be calculated by (1) and (2) respectively.

$$d_{loss,I} = \frac{2 \cdot L \cdot i_a}{n \cdot V_n \cdot T_i} \quad (1)$$

$$d_{loss,II} = \frac{4 \cdot L \cdot i_a}{n \cdot V_n \cdot T_i} \quad (2)$$

Under mode I, the average output voltage $V_{o,I}$ can be obtained by (3).

$$V_{o,I} = \frac{V_n}{n} \cdot (0.5 + d_I - 2 \cdot d_{loss,I}) = \frac{V_n}{n} \cdot (0.5 + d_I - \frac{4 \cdot L \cdot i_a}{n \cdot V_n \cdot T_i}) \quad (3)$$

Under mode II, the average output voltage $V_{o,II}$ can be obtained by (4).

$$V_{o,II} = \frac{V_n}{n} \cdot (d_I - d_{loss,II}) = \frac{V_n}{n} \cdot (d_I - \frac{4 \cdot L \cdot i_a}{n \cdot V_n \cdot T_i}) \quad (4)$$

The average output voltage $V_{o,two}Level$ in the basic FB two-level isolated DC/DC converter utilizing phase-shift control [20] can be calculated by (5).
$$V_{a_{two-level}} = \frac{V_o}{n} \left( 2 \cdot d_{two-level} \cdot \frac{4 \cdot L_i \cdot i}{n \cdot V_o \cdot T} \right)$$

(5)

in which $d_{two-level}$ is the overlap time between the leading and lagging power switch divided by one switching period.

Based on equations (3) - (5) and assuming that the basic FB two-level isolated DC/DC converter and proposed converter have the same circuit parameters ($n=25:8$, $L_i=47.7\mu H$, $f_i=50\text{kHz}$) and secondary circuits, theoretical relations between duty ratio and input voltage in proposed converter and FB two-level isolated DC/DC converter are presented in Fig. 5 under working conditions that $V_o$ is 50 V and output power named $P_o$ is 1 kW.

![Fig. 5. Theoretical relation curves between the input voltage and duty ratio ($V_o=50\text{ V}$, $P_o=1\text{ kW}$, $f_i=50\text{ kHz}$).](image)

Note: Bottom X axis marked by red color represents the duty ratios in proposed converter; and top X axis represents the duty ratio in FB two-level isolated DC/DC converter.

V. SIMULATION AND EXPERIMENTAL VERIFICATION

A. Simulation Verification

For verification, a simulation model is built in PLECS. The built simulation model’s circuit parameters are presented in Table II.

Fig. 6 presents simulations results about $V_{in}$, $V_{ab}$, $V_o$, $I_{L_o}$, $I_p$, and $I_s$ under mode I and II.

![Fig. 6. Simulation results ($V_o=50\text{ V}$, $P_o=1\text{ kW}$). (a) $V_{in}=300\text{ V}$ (Mode I). (b) $V_{in}=600\text{ V}$ (Mode II).](image)

Based on simulation results in Fig. 6, it can be obtained: 1) Mode I is applied when $V_{in}$ is low (300 V) as presented in Fig. 6(a); 2) Mode II is applied when $V_{in}$ is high (600 V) as presented in Fig. 6(b); and 3) the ripple current ($I_{L_o}$) on $L_o$ under mode I is smaller than that under mode II.

B. Experimental Verification

A 1 kW laboratory prototype is established for verification. The established proposed converter’s circuit parameters are presented in Table II.

Fig. 7 presents the experimental results about $V_{in}$, $V_{ab}$, $V_o$, $I_{L_o}$ and $I_p$.

![Fig. 7. Experimental results about $V_{in}$, $V_{ab}$, $V_o$, $I_{L_o}$, and $I_p$. (a) $V_{in}=300\text{ V}$ (Mode I). (b) $V_{in}=600\text{ V}$ (Mode II).](image)

In Fig. 7, it can be seen: 1) Mode I is applied for the low voltage ($V_{in}=300\text{ V}$) as presented in Fig. 7 (a); and 2) Mode II is applied for the high voltage ($V_{in}=600\text{ V}$)
as presented in Fig. 7 (a).

Figs. 8 and 9 present the power switches’ drain-source voltage. In Figs. 8 and 9, $V_{DS_S1} - V_{DS_S9}$ are drain-source voltages on $S_1 - S_9$. Based on experimental results in Figs. 8 and 9, it can be obtained: 1) main power switches’ voltage stresses are about input voltage; and 2) auxiliary power switches’ voltage stresses are about half of input voltage.

Fig. 8. Experimental results about $V_{DS_S1} - V_{DS_S4}$ ($V_o = 50$ V, $P_o = 1$ kW). (a) $V_{in} = 300$ V (Mode I). (b) $V_{in} = 600$ V (Mode II).

Fig. 9. Experimental results about $V_{DS_S5} - V_{DS_S8}$ ($V_o = 50$ V, $P_o = 1$ kW). (a) $V_{in} = 300$ V (Mode I). (b) $V_{in} = 600$ V (Mode II).

Fig. 10 presents ZVS performances about $S_2$, $S_3$, $S_7$ under mode I when $V_o$ is 50 V, $V_{in}$ is 300 V, $P_o$ is 1 kW. Fig. 11 shows ZVS performances of $S_3$ and $S_6$ under mode II when $V_o$ is 50 V, $V_{in}$ is 600 V, $P_o$ is 1 kW.

Based on experimental results in Figs. 10 - 11, the followings can be obtained: 1) under mode I, main power switches $S_3$, $S_7$ and auxiliary power switch $S_7$ realize ZVS when $P_o$ is 1 kW respectively; and 2) under mode II, the main power switch $S_3$ and auxiliary power switch $S_6$ realize ZVS when $P_o$ is 1 kW. The other main power switches’ and auxiliary power switches’ ZVS performances under mode I and II are similar to that of 1) and 2).

Fig. 10. ZVS performances ($V_{in} = 300$ V, $V_o = 50$ V, $P_o = 1$ kW Mode I). (a) $S_2$. (b) $S_3$. (c) $S_7$. (d) $S_6$. (e) $S_7$. (f) $S_6$. (g) $S_7$.
Fig. 11. ZVS performances \((V_{in} = 600 \, \text{V}, \quad V_{o} = 50 \, \text{V}, \quad P_o = 1 \, \text{kW})\) Mode II. (a) \(S_1\), (b) \(S_2\).

VI. CONCLUSION

A FB T-type isolated DC/DC converter and corresponding control strategy is proposed in this paper. The proposed converter compromises four main power switches with the voltage stress of input voltage (SiC MOSFET) and four auxiliary power switches with the voltage stress of half of input voltage (Si MOSFET). Therefore, it has fewer circuit components and more compact circuit structure when comparing with the diode-clamped FB TL isolated DC/DC converter. What is more, the proposed control strategy not only can realize ZVS but also can fulfill wide input voltage range. Finally, both simulation and experimental results verify the proposed converter with its corresponding control strategy.

APPENDIX

II. PARAMETERS OF SIMULATION MODEL AND EXPERIMENTAL PROTOTYPE

| Main Power Switches \(S_1 - S_4\) | C3M0065090ID |
| Auxiliary Power Switches \(S_5 - S_6\) | SPW47N60C3 |
| Rectifier Diodes \(D_1 - D_4\) | MBR40250TG |
| Turns Ratio of Transformer \(N\) | \(n : 1\) |
| Inductance of Series Inductor plus Leakage \(L\) | \(\mu\)H |
| Input Capacitors \(C_1\) and \(C_2\) | \(\mu\)F |
| Output Filter Capacitor \(C_3\) | \(\mu\)F |
| Output Filter Inductor \(L_1\) | \(\mu\)H |
| Switching Frequency (kHz) | 50 |

REFERENCES


