High Step-Up Full Bridge DC-DC Converter with Multi-Cell Diode-Capacitor Network

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Abstract—The full bridge boost isolated DC-DC converter achieves high voltage gain by setting the turns ratio of high-frequency transformer. Compared with the transformer, diode-capacitor voltage boost cell is more suitable to achieve high voltage gain with both high efficiency and power density. However, multi-cell diode-capacitor network has inrush current issue and strict LC filter requirement which is not suitable to achieve high efficiency in relatively low switching frequency and large power application. In order to meet high step-up voltage regulation and compulsory electrical isolation due to public safety, this paper proposes a high step-up full bridge isolated DC-DC converter with multi-cell diode-capacitor network which exploits the features of multi-winding transformer and diode-capacitor voltage boost cell. It has the following advantages. 1) increases voltage boost capability and avoid extreme large duty ratio. 2) achieves almost zero output voltage ripples which reducing the inductance in output LC filter, 3) reduces transformer turns ratio and magnetic component volume. Furthermore, it can use the transformer leakage inductor and resonant capacitor to achieve zero-current switching (ZCS), which is beneficial to improve efficiency.

Keywords—Diode-capacitor network; high voltage gain; full-bridge isolated DC-DC converter; multi-winding transformer; zero-current switching (ZCS)

I. INTRODUCTION

Given the efficiency and environmental benefits, solar and fuel cell generation systems have rapidly developed in recent years. In photovoltaic (PV) systems, it is difficult to realize a series connection of PV cells without incurring shading effect [1]. Fuel cell and lightweight battery power supply system are promising in future hybrid electric vehicle, more-electric aircraft and vessel. However, the obvious characteristic of these dc sources is low voltage supply. The basic DC-DC converter has encountered voltage boost limitation due to the parasitic parameters of main circuit. Therefore, high step-up voltage boost capability is the requirement of power converter with low input voltage, high efficiency and high power density. It has been one of the key technical issues in aforementioned renewable energy generation.

Full-bridge isolated boost DC-DC converter shown in Fig.1 have been widely used in solar and fuel cell based medium and high power generation system due to some inherent advantages [2][3]. In order to increase output voltage, the secondary side is replaced with voltage doubler rectifier in Fig.2 [4]. However, the voltage boost ratio is still limited by setting the turns ratio of transformer. Compared with transformer, diode-capacitor voltage boost cell is more suitable to achieve high voltage gain with both high efficiency and high power density. With the increasing number of basic cells, voltage gain can be further increased. Moreover, it does not increase drive and control circuit complexity due to only one fully controllable switch.

Fig.3 shows two typical high step-up DC-DC converters with multi-cell diode-capacitor network [5]-[8]. Fig.3(a) is widely used in low power supply chips such as LT3482, and it operates with high switching frequency such as \( f_s = 1\) MHz. However, in above renewable energy generation system, when \( f_s \) is not high enough, the directly energy charging and discharging between different capacitors causes large inrush current and increases switching loss significantly. For the circuit shown in Fig 3(b), besides the large inrush current, low pass filter is necessary due to pulsed DC voltage generated by diode-capacitor network. In high voltage gain application, the amplitude of pulsed DC voltage is large and output current is relatively small, thus, the large inductance \( L_f \) is required to limit the output current and voltage ripples [9].

In order to overcome the drawbacks of inrush current and strict LC filter requirement, this paper propose a high step-up full-bridge isolated DC-DC converter with multi-cell diode-capacitor network, which exploits the advantages of multi-windings transformer and diode-capacitor voltage boost cell. It
II. OPERATION PRINCIPLE OF HIGH STEP-UP FULL BRIDGE ISOLATED DC-DC CONVERTER WITH MULTI-CELL DIODE-CAPACITOR NETWORK

Fig.4 shows one of the basic voltage boost cells: two-port diode-capacitor network. When \( D_{11} \) and \( D_{12} \) are conducting, \( C_{11} \) and \( C_{12} \) are connected in parallel and the terminal voltage meets:

\[
V_2 = V_{C_{11}} = V_{C_{12}} = V_1 \tag{1}
\]

When \( D_{11} \) and \( D_{12} \) are reversed blocked, \( C_{11} \) and \( C_{12} \) are connected in series and the terminal voltage meets:

\[
V_2 = V_{C_{11}} + V_{C_{12}} = V_1 \tag{2}
\]

Therefore, the \( LC \) filter is added in the output side to obtain the constant DC voltage.

Fig.4 Basic diode-capacitor voltage boost cell.

Fig.5 shows the proposed high step-up full-bridge isolated DC-DC converter with two-cell diode-capacitor network. The high-frequency transformer can be equivalent as an ideal transformer in parallel connection of magnetic inductor \( L_m \) and then in series connection of leakage inductor \( L_k \). The first winding in the secondary side of transformer is connected to one two-port diode-capacitor cell in normal polarity and the second winding is connected to another two-port diode-capacitor cell in reversed polarity. The output of two diode-capacitor cells is connected in series to achieve high output voltage with essential LC filter.

For simple analysis, it is assumed that \( L_m \) is large enough \((L_k<<L_m)\) and \( i_{km} \) is continuous conduction. In the basic diode-capacitor boost cell, \( C_{i1}=C_{i2} \) \((1\leq i\leq N)\). The detailed operation principles shown in Fig.6 are described as follows:

During \( S_1=S_2=ON, \ S_3=S_4=OFF \) interval, DC source \( V_d \) in series connection with boost inductor \( L \) charges the transformer primary side. The transformer magnetizing current is increasing linearly by ignoring the influence of leakage inductance \( L_k \).
\[ L \frac{di}{dt} = V_{dc} - v_{p(S_1=S_2=ON)} \]  
(3)

The transformer secondary side voltage \(v_{s1}, v_{s2}\) meet:

\[ v_{s1(S_1=S_2=ON)} = \frac{n_1}{n_0} v_{p(S_1=S_2=ON)} \]  
(4)

\[ v_{s2(S_1=S_2=ON)} = \frac{n_2}{n_0} v_{p(S_1=S_2=ON)} \]  
(5)

Where: \(n_0, n_1, n_2\) are the turns ratio of transformer primary and secondary side windings, respectively.

The induced voltage \(v_{s1}\) is positive, and \(D_{11}, D_{12}\) are conducting. \(n_1\) winding and \(C_{11}, C_{12}\) in parallel connection.

\[ v_{s1(S_1=S_2=ON)} = V_{c11} = v_{p(S_1=S_2=ON)} \]  
(6)

The induced voltage \(v_{s2}\) is negative, and \(D_{21}, D_{22}\) are blocked. \(n_2\) winding and two capacitors \(C_{21}, C_{22}\) are connected in series to supply the output side.

\[ v_{s2(S_1=S_2=ON)} = -v_{s2} + 2V_{c21} \]  
(7)

In this interval, the output voltage before filtered is

\[ v_{p(S_1=S_2=ON)} = v_{s1(S_1=S_2=ON)} + v_{s2(S_1=S_2=ON)} = 2V_{c21} + \frac{n_1}{n_0} V_{c11} + V_{c11} \]  
(8)

During \(S_1=S_2=S_3=ON\) interval, the transformer primary side winding \(n_0\) is shorted and \(v_{p}=0\). The DC source \(V_{dc}\) charges the boost inductor.

\[ L \frac{di}{dt} = V_{dc} \]  
(9)

In this interval, the induced transformer secondary side voltage \(v_{s1}=v_{s2}=0\). All the diodes \(D_{11}, D_{12}, D_{21}, D_{22}\) in the transformer secondary side are blocked. The transformer secondary side winding \(n_1\) and \(C_{11}, C_{12}\), \(n_2\) and \(C_{21}, C_{22}\) are connected in series to supply the output side. The output voltage before filtered is

\[ v_{p(S_1=S_2=ON)} = 2V_{c11} + 2V_{c21} \]  
(10)

During \(S_2=S_3=ON\), \(S_1=OFF\) interval, DC source \(V_{dc}\) in series connection with boost inductor \(L\) charges the transformer primary side in reverse direction. The boost inductor current decreases linearly.

\[ L \frac{di}{dt} = V_{dc} - v_{p(S_1=S_2=ON)} = V_{dc} - \frac{n_1}{n_2} V_{c21} \]  
(11)

The induced transformer secondary side voltage \(v_{s1}\) is negative. \(D_{11}\) and \(D_{12}\) are blocked. \(n_1\) winding and \(C_{11}, C_{12}\) are connected in series to supply the output side.

\[ v_{s1(S_1=S_2=ON)} = v_{s1(S_1=S_2=ON)} + 2V_{c11} = \frac{n_1}{n_2} v_{s2(S_1=S_2=ON)} + 2V_{c11} \]  
(12)

The induced transformer secondary side voltage \(v_{s2}\) is positive. \(D_{21}\) and \(D_{22}\) are conducting. \(n_2\) winding charges two capacitors \(C_{21}, C_{22}\) in parallel connection. \(v_{s2}\) is clamped by \(V_{c21}\).

\[ v_{s2(S_1=S_2=ON)} = V_{c21} = -\frac{n_1}{n_0} v_{p(S_1=S_2=ON)} \]  
(13)

The output voltage in this switching state is

\[ v_{p(S_1=S_2=ON)} = 2V_{c11} + \frac{n_1}{n_2} V_{c21} + V_{c21} \]  
(14)

In steady state, the average voltage across the boost inductor \(L\) should be zero in one switching time period \(T_s\). From (3), (9) and (11), we have

\[ (V_{dc} - \frac{n_1}{n_0} V_{c11})(1-D)T_s + (V_{dc} - \frac{n_1}{n_2} V_{c21})(1-D)T_s \]

\[ + V_{dc}(2D-1)T_s = 0 \]  
(15)

By solving the aforementioned equation, the voltage of the intermediate capacitor can be derived as

\[ (1-D)(\frac{n_1}{n_0} V_{c11} + \frac{n_1}{n_2} V_{c21}) = V_{dc} \]  
(16)

If two secondary side windings have the same turns ratio \(n_1 : n_0 = n_2 : n_0 = n\), all the intermediate capacitors in the transformer secondary side have the same voltage, which can be calculated by solving (16).

\[ V_c = \frac{n}{2} \frac{1}{1-D} V_{dc} \]  
(17)

According to (8), (10), (14) and (17), \(v_{pn}\) has the same voltage and is almost constant.

\[ v_{pn} = \frac{2n}{1-D} V_{dc} \]  
(18)
Two diode-capacitor cells in the transformer secondary side operate in complementary mode to avoid inrush current and achieve zero output voltage ripples. Therefore, \( L_f \) is designed to eliminate the switching noisy and its value can be reduced to large extent.

In steady state, switches \( S_1, S_4 \) or \( S_2, S_3 \) have the same voltage stress, which is the maximum value of transformer primary side voltage \( v_p \). The transformer secondary side voltage is clamped by intermediate capacitor when diodes are conducting. From (17), it can be derived as:

\[
v_{S_{\text{Mos}}} = v_p(S1=S4=ON, S2=S3=OFF) = \frac{n_r V_{C11}}{n_1} = \frac{1}{2} \cdot \frac{1}{1-D} V_{dc} \quad (19)
\]

All the diodes withstand the same voltage stress. The voltage across \( D_{11} \) and \( D_{12} \) during \( S_2=S_3=ON, S_1=S_4=OFF \) interval is the reversed connection with \( v_{C11} \) and \( v_{SL} \). It can be derived as:

\[
v_{S_{\text{Diode}}} = v_{C11} = v_r(S2=S3=ON) = \frac{n_r V_{C11}}{1-D} V_{dc} \quad (20)
\]

With the increasing number of two-port diode-capacitor cells \( (N=2k) \), voltage gain of high step-up full bridge isolated DC-DC converter can be further increased. The main circuit is shown in Fig.7. Using the similar derivation approach, voltage gain, voltage stress of switch and diode can be rewritten as (21), (22) and (23).

\[
G = \frac{V_p}{V_{dc}} = \frac{N \cdot n}{1-D} \quad (21)
\]

\[
v_{S_{\text{Mos}}} = \frac{1}{2} \cdot \frac{1}{1-D} V_{dc} = \frac{G}{2N \cdot n} V_{dc} \quad (22)
\]

\[
v_{S_{\text{Diode}}} = n \frac{V_{C11}}{1-D} V_{dc} \quad (23)
\]

Where: \( n \) is transformer primary, secondary winding turns ratio, \( N \) is the number of two-port diode-capacitor network, \( D \) is the duty ratio of switches.

Fig.8 shows the relationships of voltage gain and boost duty ratio \( D \), transformer turns ratio \( n \), and number of basic diode-capacitor cells \( N \) for high step-up full bridge isolated DC-DC converter with multi-cell diode-capacitor network. Fig.9 and 10 show the voltage stress of switching device and power diode, respectively. With the increasing number of basic diode-capacitor cell, the voltage stress of switch device and power diodes can be further reduced.
III. ZERO CURRENT SWITCHING (ZCS) REALIZATION

The leakage inductor of transformer causes high voltage stress and spikes on the switching devices. In order to absorb the leakage energy and decrease switching loss, ZCS resonant circuit including \( L_k \) and \( C_r \) is provided. It suppresses voltage spikes of power switches and restrains the turn off \( di/dt \) of the secondary side diodes [4][10]. Fig.11 shows the ZCS resonant high-step full-bridge isolated DC-DC converter with two-cell diode-capacitor network \((N=2)\). And Fig.12 shows the key waveforms of different interval in steady state. It includes 8 symmetrical operation modes in one switching time period \( T_s \).

Fig.11 ZCS resonant high step-up full-bridge isolated DC-DC converter with two-cell diode-capacitor network.

Mode 1 \((t_0-t_1)\): before \( t_0 \) instant, \( S_1=S_2=OFF \), \( S_3=S_4=ON \), diodes \( D_{21} \) and \( D_{22} \) are conducting. The resonant inductor current is the same as boost inductor current \( i_{L_k}=i_L \). At \( t_0 \) instant, \( S_1, S_2 \) are turned on, the drain source voltage \( v_{s1} \) and \( v_{d4} \) decrease to zero immediately. \( S_1, S_3, S_k, D_{21} \) and \( D_{22} \) are conducting. \( L_k, C_r \) and \( L_m \) form resonant circuit. The voltage of capacitor \( C_r \) is clamped to \( v_{C21} \). \( i_{L_k} \) is decreasing linearly by the rate of \( v_{C21}/(nL_k) \). The current of switch \( S_1, S_4 \) increases and the current of \( S_2, S_3 \) decreases. During this interval, the state equations in time domain are:

\[
v_{C_1}(t) = -\frac{1}{n} v_{C21} \tag{24}
\]

\[
i_{L_k}(t) = \frac{V_{C21}}{nL_k} (t-t_0) - i_L \tag{25}
\]

\[
i_{S_1}(t) = i_{L_k}(t) - \frac{1}{2} i_L + (-i_{L_k}(t)) \tag{26}
\]

\[
i_{S_2}(t) = i_{L_k}(t) + \frac{1}{2} i_L + (-i_{L_k}(t)) = i_L - \frac{V_{C21}}{2 nL_k} (t-t_0) \tag{27}
\]

When the leakage inductor current decreases to zero \( i_{L_k}=0 \) at \( t_1 \), diodes \( D_{21} \) and \( D_{22} \) are turned off. From (25), the time interval for mode 1 is

\[
T_{i0} = t_1 - t_0 = \frac{n i_L L_k}{V_{C21}} \tag{28}
\]

Mode 2 \((t_1-t_2)\): at \( t_1 \) instant, all the diodes in the transformer secondary side are turned off. \( L_k \) and \( C_r \) form the resonant circuit. The initial voltage of \( C_r \) is \(-V_{C21}/n\). The leakage inductor current \( i_{L_k} \) and the capacitor voltage \( v_{C_1} \) are:

\[
i_{L_k}(t) = \frac{V_{C21}}{nL_k} \sin(\omega \tau (t-t_1)) \tag{29}
\]

\[
v_{C_1}(t) = -\frac{V_{C21}}{n} \cos(\omega \tau (t-t_1)) \tag{30}
\]

Where: \( \omega = 1/\sqrt{L_k C_r} \) is the resonant frequency. \( Z_r(t) = \sqrt{L_k / C_r} \) is the impedance of resonant network.

The current of switch \( S_2 \) and \( S_3 \) continue to increase and the current of \( S_2 \) and \( S_3 \) continue to decrease.

\[
i_{S_3}(t) = i_{L_k}(t) = \frac{1}{2} (i_L + i_{L_k}(t)) = \frac{1}{2} \left( i_L + \frac{V_{C21}}{nZ_r} \sin(\omega \tau (t-t_1)) \right) \tag{31}
\]

\[
i_{S_2}(t) = i_{L_k}(t) = \frac{1}{2} (i_L - i_{L_k}(t)) = \frac{1}{2} \left( i_L - \frac{V_{C21}}{nZ_r} \sin(\omega \tau (t-t_1)) \right) \tag{32}
\]

The leakage inductor current increases and it equals to the boost inductor current \( i_{L_k}=i_L \) at \( t_2 \). From (29), the time interval for mode 2 is

\[
T_{i2} = t_2 - t_1 = \frac{1}{\omega \tau} \arcsin\left( \frac{nZ_r}{V_{C21}} \right) \tag{33}
\]
Mode 3 \((t_2-t_3)\): At \(t_2\) instant, the current of switches \(i_{k2}, i_{k3}\) decrease to zero and increase reversely. The resonant inductor current \(i_{Lk}\) increases to maximum value \(i_p\) and the resonant capacitor voltage \(v_{C}\) decreases to zero. From (31), the maximum value of resonant inductor current \(i_p\) and the time interval for mode 3 are

\[
i_p = |i_{Lk}(t)|_{\text{max}} = \frac{v_{C21}}{nZ_r} \quad (34)
\]

\[
T_{Lk} = t_3 - t_2 = \frac{\pi/2 - \omega L k r}{\omega r} \quad (35)
\]

Apparentnly, the condition of ZCS for \(S_2\) and \(S_3\) is: the leakage inductor current peak value should be larger than the boost inductor current \(i_p\).

Mode 4 \((t_3-t_4)\): At \(t_3\) instant, the resonant inductor current \(i_{Lk}\) starts to decrease and the capacitor voltage \(v_{C}\) continues to increase. Until \(t_4\) instant, \(i_{Lk}\) decreases to \(i_0\). The freewheeling diodes of \(S_2\) and \(S_3\) are turned off. The current commutation is completed. Thus, in order to achieve ZCS, \(S_2\) and \(S_3\) should be triggered off between \(t_3\) and \(t_4\).

Seen from Fig.12, the half of resonant period should be slightly larger than the on-state interval of power switches in one switching time period.

\[
\frac{1}{2} T_r \geq (D - 0.5) T_s \quad (36)
\]

Where: \(D\) is the on-state duty ratio of main switch in the transformer primary side \((0.5 \leq D \leq 1)\). \(T_r = 1/f_r\) is the switching time period. \(T_s = 1/f_s = 2\pi\sqrt{L_k/C_r}\) is the time period of resonant circuit.

After \(t_4\) instant, \(S_1=S_2=ON; S_3=S_4=OFF\), DC source in series with boost inductor charges the resonant capacitor \(C_r\). \(v_{C}\) increases immediately and diodes \(D_{11}, D_{12}\) are conducting. The voltage of resonant capacitor \(C_r\) is clamped by \(C_{12}\) and \(C_{11}\) \((v_{C} = n_0 C_{12} V_{C12} = n_0 V_{VC12})\). Because the energy stored in \(L_k\) is much higher than that of \(C_r\), this charging interval is very small.

Until \(t_0\) instant, \(S_2\) and \(S_3\) are turned on. The circuit enters into a new time period.

In order to achieve ZCS of main switches, \(L_k\) and \(C_r\) should be designed to meet \(i_p > i_0\) in (34) and (36).

IV. Simulation Verification

Numerical simulations using MATLAB/Simulink have been performed to verify the theoretical analysis and operation principles. The main circuit parameters are: \(V_{DC}=48V, V_o=540V, L_m=400uH, L_k=8.6uH, C_{1}=15uF, C_{11}=C_{12}=C_{21}=C_{22}=25uF, L_k=5uH, C_p=250uF; T_s=50\mu s, n_1=n_0=n_2=n_0=n=2\).

Fig.13 shows the waveforms of high step-up full bridge isolated DC-DC converter with multi-cell diode-capacitor network \((N=2)\) when \(V_{DC}=48V, V_o=540V, n=2, R_{load}=300\Omega\). It includes the boost inductor current \(i_p\), leakage inductor current \(i_{Lk}\), transformer primary side voltage \(v_o\) and the output voltage \(v_{o}\). In steady state, the duty ratio is \(d_{on}=0.65\). The measured voltage gain and voltage stress of power devices are almost consist with the theoretical value.

Fig.14 shows the corresponding waveforms for ZCS resonant high step-up full bridge isolated DC-DC converter. As shown in Fig.14, before main switch is triggered off, the current across MOSFET is smaller than zero. Thus, when MOSFET is turned off, the current is flowing through the freewheeling diode. Then, it is resonant to zero. All the main switches in the transformer primary side achieve ZCS. The unfiltered output voltage \(v_{o}\) just contains some small switching frequency noise. Thus, the volume of output LC filter can be reduced to large extent.

![Fig.13 Waveforms of high step-up full bridge DC-DC converter with multi-cell diode-capacitor network](image-url)
V. CONCLUSION

The full bridge boost DC-DC converter achieves high voltage gain by setting the turns ratio of high-frequency transformer. Conventional boost derived converters with multi-cell diode-capacitor network have inrush current issue and strict LC filter requirement. In order to overcome these drawbacks, this paper proposes a high step-up full-bridge isolated DC-DC converter with multi-cell diode-capacitor network which exploits the features and advantages of multi-winding transformer and diode-capacitor network. It avoids inrush current issue and achieves almost zero output voltage ripples which reducing the inductance in output LC filter. Meantime, the reduced magnetic component volume contributes to high power density. Furthermore, it can use the leakage inductor of transformer and resonant capacitor to achieve ZCS, which is beneficial to increase efficiency. With improved performance, the new topology is more promising in solar and fuel cell generation system where high step-up voltage boost capability is one of the key requirements.

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