A Coupled Inductor and Switched Capacitor Non-isolated DC/DC Converter

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Abstract. Due to the output voltage characteristics of the photovoltaic cell and other renewable energy generation systems, DC/DC converter with high step-up ratio is commonly needed to raise the voltage. The high gain Boost converter based on coupled inductor with switch capacitor network is presented in this paper. The proposed converter avoid the ultimate duty cycle by designing the ratio of the coupling inductor. As the energy of leakage inductor in the input side can be transferred to the output side, the loss of leakage inductor is reduced. The voltage peak of the switch is inhibited by the switching capacitor, which greatly reduces the voltage stress of the switch, thus the converter improves the transfer efficiency. The working state of the converter is analyzed in detail, the theoretical formula is derived, and the stress of the converter is analyzed in the paper. A simulation circuit is built to verify the theoretical analysis.

1. Introduction

In order to cope with the energy crisis and enjoy the human sustainable development, the renewable energy generation systems are indispensable. In the new energy power generation system, the output voltage is low, and DC/DC converter is needed to raise the voltage. But extraordinary high voltage gain is difficult for a conventional Boost converter \cite{1}.

The Researchers of power electronic technology propose a variety of topologies for high-gain converters. The isolation DC/DC converter achieves high voltage gain through isolation transformer, and is suitable for special occasions requiring electrical isolation. But all of the input side power of isolation converters passes transformer before delivery to the output side, which will cause greater leakage inductor \cite{2}. Boost converter can also improve voltage gain by using switched-capacitor unit. However, as the boost ratio increases, more cell networks are needed, increasing the cost of the converter \cite{3}. An interleaved converter based on a topology-optimized combination can achieve voltage gain up to 2 times of the basic Boost converter \cite{4}. Based on the traditional two phase interleaved converter, a switched capacitor network is added and the converter can achieve 3 times voltage gain in CCM mode \cite{5}. A high gain DC/DC converter is produced by combining the coupled inductor with the Boost converter \cite{6}. However, the leakage inductor of the coupled inductor in this type of converter causes higher voltage stress at ends of the switch tube, resulting in large switching losses. For this reason, the method of active clamp is usually used to suppress the voltage spike of the switch tube, but it increases the complexity of the converter structure and control method.

Based on the research above, aiming at the problem of high gain converter and coupled inductor leakage inductor, this paper proposes a coupled inductor and switched capacitor (CISC) non-isolated
high voltage gain DC/DC converter. This topology does not require additional clamping circuits to reduce the effect of leakage inductor. When the duty ratio is greater than 0.5, the converter can gain a higher voltage gain, and the voltage stress of the switch tube and the diode is smaller. Therefore, the converter can choose the low voltage stress, the small conduction resistance switch tube and the diode, so as to improve the efficiency of the converter. In this paper, the working principle and steady state performance of the converter are analyzed. And through the simulation of the converter, the theoretical analysis is verified.

2. The topology and operation principle of CISC converter

The CISC converter topology is shown as shown in Fig. 1 (a). The converter consists of two phases interlaced. The two phase circuit is connected to the switched capacitor network consisting of capacitor $C_1$, $C_2$, and diode $D_1,D_2$. The voltage stress of the switch tube $S_1$ is clamped by the capacitor $C_2$. The coupled inductor is introduced into the first phase of the converter, and the coupled side of the inductor is coupled to form a flyback loop through a diode and a capacitor, and a new topology is proposed by the output stacking techniques.

![CISC DC/DC converter](image1.png)

(a) CISC DC/DC converter

![Equivalent circuit of the converter](image2.png)

(b) Equivalent circuit of the converter

The coupled inductor can be equivalent to a leakage inductor $L_K$, a magnetizing inductor $L_m$ and an ideal transformer with a turn ratio of $N_1:N_2$, of which $N_1:N_2=1:n$. Fig. 1(b) shows the equivalent circuit of the converter.

![Key waveforms of the converter](image3.png)

Figure 2. The key waveforms of the converter

In order to simplify the analysis of the operation of the converter, all inductors, capacitors, switches, diodes are considered as ideal components, and the impact of parasitic parameters and the leakage inductor of the secondary side of the coupled inductor are not considered. The proposed converter operating in continuous conduction mode (CCM) is only considered. In this paper, we consider the
operation of the converter when duty cycle is greater than 0.5 only.

Fig. 2 shows the key waveforms of the converter in one cycle. \( T \) denotes the switch period of switch tube \( S_1 \) and \( S_2 \), \( D \) denotes the duty cycle, and two switch tubes are interlaced, and the difference of driving signal is 180 degrees. As can be seen from Fig. 2, the proposed converter has seven operating modes in one cycle.

In a switch period, the operating states of the converter, corresponding to the equivalent circuit as shown in Fig. 3. The seven operational modes are described as follows.

Mode 1 \([t_0\sim t_1]\): At \( t=t_0 \), the switch tube \( S_1 \) is turned on, the \( S_2 \) is in the conduction state, the diode \( D_1, D_2 \) and \( D_3 \) are turned off, and the \( D_4 \) is in the conduction state. The energy stored in the magnetizing inductor \( L_m \) provides energy to the output through the secondary side of the coupled inductor. The power supply charges and stores the leakage inductor \( L_K \) and the inductor \( L_2 \).

\[
i_{L_K}(t) = i_{L_K}(t_0) + \frac{nU_{in} + u_{C3}}{nL_K} (t-t_0)
\]

\[
i_{L_2}(t) = i_{L_2}(t_0) + \frac{U_{in}}{L_2} (t-t_0)
\]

Mode 2 \([t_1\sim t_2]\): At \( t=t_1 \), the switches \( S_1 \) and \( S_2 \) are all turned on, and the diode \( D_4 \) is turned off. Input power supply charges leakage inductor \( L_K \), magnetizing inductor \( L_m \) and inductor \( L_2 \).

\[
i_{L_K}(t) = i_{L_K}(t_1) + \frac{U_{in}}{L_K} (t-t_1)
\]

Mode 3 \([t_2\sim t_3]\): At \( t=t_2 \), the switch \( S_2 \) is turned off, \( S_1 \) is in the conduction state, and the diode \( D_2 \) is turned on. The inductor \( L_2 \) and the capacitor \( C_2 \) are connected in series to release energy to the \( C_1 \).

Mode 4 \([t_3\sim t_4]\): At \( t=t_3 \), the switch tube \( S_2 \) is on, and the \( S_1 \) is in the conduction state. The Mode is the same as that of Mode 2.
Figure 3. The operation mode of CISC converter topology in one cycle

Mode 5 \([t_4\sim t_5]\): At \(t=t_4\), the switch tube \(S_1\) is turned off, the \(S_2\) is in the conduction state, and the diode \(D_1\), \(D_3\) and \(D_4\) are turned on. The leakage inductor \(L_K\) releases energy to the capacitor \(C_2\). Leakage inductor \(L_K\) and capacitor \(C_1\) are supplied to the capacitor \(C_0\) and output. And the leakage inductor current \(i_{LK}\) is approximately linearly reduced.

\[
u_{C_2} \approx U_{in} + \frac{U_{C_3}}{n}
\] (4)

\[
u_{C_1} + U_{C_1} = U_{C_0}
\] (5)

Mode 6 \([t_5\sim t_6]\): At \(t=t_5\), the switch \(S_1\) is in the off state, \(S_2\) is in the on state, the diode \(D_3\) is off, and \(D_1\) and \(D_4\) are in the on state. The diode \(D_3\) withstands the reverse voltage and is turned off.

Mode 7 \([t_6\sim t_7]\): At \(t=t_6\), the switch tube \(S_1\) is in the off state, and the \(S_2\) is in the conduction state. The energy in the leakage \(L_K\) has been completely released, so the diode \(D_1\) naturally is turned off.

3. Steady-state performance analysis of CISC converter

In order to obtain the voltage gain of the converter and the voltage stress of each switch tube and diode, the leakage inductor \(L_K\) and the ripple of capacitor are ignored. Due to the time of mode 1 and mode 6 are significantly short, only the operational processes of other modes are considered.

3.1 Voltage gain analysis of CISC converter

According to the volt-second balance of magnetizing inductor \(L_m\) available:

\[
 DTU_{in} - (1 - D)T \cdot \frac{U_{C_3}}{n} = 0
\] (6)

The voltage of the capacitor \(C_3\) is given as:

\[
 U_{C_3} = \frac{nD}{1-D} \cdot U_{in}
\] (7)

According to the volt-second balance of magnetizing inductor \(L_2\) available:

\[
 DTU_{in} - (1-D)T(U_{C_1} - U_{C_2} - U_{in}) = 0
\] (8)

The following formula can be obtained through the analysis of mode 5:

\[
 U_{C_1} + U_{C_2} = U_{C_0}
\] (9)

\[
 U_{C_2} = U_{in} + \frac{U_{C_3}}{n}
\] (10)
Simultaneous (6) ~ (10) can be derived from the following formula:

\[
U_{C1} \approx \frac{1}{1-D} \cdot U_{in}
\]
\[
U_{C2} \approx \frac{1}{1-D} \cdot U_{in}
\]
\[
U_{C3} \approx \frac{3}{1-D} \cdot U_{in}
\]

From (7) to (11), the voltage gain \( M \) of the converter can be obtained:

\[
M = \frac{U_o}{U_{in}} = \frac{3+nD}{1-D}
\]

Fig. 4 is a three-dimensional relation diagram of voltage gain and duty cycle and turn ratio of the proposed converter. It can be seen that when the duty cycle is greater than 0.5, the converter can achieve very high voltage gain.

![Figure 4](image_url)

**Figure 4.** Three-dimensional relation diagram of voltage gain and duty cycle and turn ratio

3.2. Voltage stress analysis of switch devices

By analyzing the operating principle of the converter, the voltage stress on the main switch is expressed as:

\[
U_{ds1} = U_{c2} = \frac{1}{1-D} \cdot U_{in} = \frac{1}{3+nD} \cdot U_o
\]
\[
U_{ds2} = U_{c1} - U_{c3} = \frac{1}{1-D} \cdot U_{in} = \frac{1}{3+nD} \cdot U_o
\]

The voltage stress of the diodes \( D_1, D_2, D_3, D_4 \) is expressed as:
Due to the introduction of a coupled inductor, the voltage stress on the switching tube and the diode is reduced, which will be illustrate in the next section.

### 3.3. Key performance comparison

In order to highlight the advantages of CISC converter, Table 1 shows the number of switches, voltage gain and voltage stress of switching devices for converters and the converters in literatures [7] and [8].

As can be seen from Table 1, the proposed converter has higher voltage gain, lower switch tube voltage stress and diode voltage stress. In addition, the number of switch tubes and diodes is basically the same as the number of the converters in literatures [7] and [8], thus reducing the cost of the converter.

**Table 1.** Converter voltage gain and switch tube, diode voltage stress

|                                | Converter in [7] | Converter in [8] | CISC converter |
|--------------------------------|------------------|------------------|----------------|
| Number of switches             | 2                | 2                | 2              |
| Number of diodes               | 4                | 3                | 4              |
| Voltage gain                   | $\frac{2}{1-D} + nD$ | $\frac{2+nD}{1-D}$ | $\frac{3+nD}{1-D}$ |
| Voltage stress of main switches| $\frac{1}{2+2nD(1-D)} U_o$ | $\frac{1}{2+nD} U_o$ | $\frac{1}{3+nD} U_o$ |
| Maximum voltage stress of diodes| $\frac{n(1+D)}{2+2nD(1-D)} U_o$ | $\frac{n}{2+nD} U_o$ | $\frac{n}{3+nD} U_o$ |

### 4. Simulation research

In order to verify the operating principle and steady-state performance of the proposed converter, the converter simulation circuit is built in MALTAB/SIMULINK.

The simulation parameters are as follows, $U_{in}=23V$, $U_{O}=200V$, $L_m=L_2=470\mu H$, $L_K=3\mu H$, $C_0=C_1=C_2=C_3=100\mu F$, $N_1:N_2=1:2$, Switching frequency $f=20$ KHz.

Fig.5 (a) is the simulated current waveforms of leakage inductor $L_K$ and inductor $L_2$. It can be seen that leakage inductor $L_K$ can completely release energy in every cycle. Figure 5 (b) is the simulation waveforms of capacitor $C_0$ voltage $U_{C0}$ and output voltage $U_O$. And the output voltage $U_O$ is close to 200V. Fig. 5 (c) ~ (e) are waveforms of the withstand voltage of switch tubes and diodes. It is known that switches and diodes suffer from low voltage stress. The simulation results are consistent with the theoretical analysis.
5. Conclusions
A new CISC converter is proposed, and the operating principle and steady state performance are analyzed in detail. The CISC converter avoids the extreme duty cycle and achieves higher voltage gain. Without adding additional loops, the energy of leakage inductor can be transferred to the output, reducing the energy loss on the switch. Besides, the voltage stress of switches and diodes in the topology is quite low, and the control of converter is simple. Therefore, the CISC converter proposed in this paper is suitable for photovoltaic, fuel cell and other new energy generation applications.

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7. References
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