Phase Controlled Class E\(^2\) dc/dc Converter with Single RF Choke Core

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Abstract
In this paper, we propose phase controlled class E\(^2\) dc/dc converter that is composed of phase controlled class E inverter and class E rectifier. Moreover, to minimize the circuit scale in phase controlled class E\(^2\) dc/dc converter, we propose reduction of the number of RF choke cores in the converter by coupling two RF choke cores to one. These proposed circuits achieve the output control with fixed frequency and continuous control in the load variations. The measured power conversion efficiency of the converter with single RF choke core is over 84.9% with 5.6W output power at operating frequency of 1.0MHz.

1. Introduction
Class E\(^2\) dc/dc converter [1], [2] that is composed of class E inverter [3] and class E rectifier [4], [5] realizes high power conversion efficiency under high operating frequency (MHz order) because of the realization of class E switching conditions [3] in both inverter and rectifier. One of the disadvantages of this converter is the difficulty of the output control with keeping high power conversion efficiency. Therefore, several control schemes have been proposed. Frequency modulation (FM) control [6] is a method which changes switching frequency. FM control, however, generates a wide and unpredictable noise spectrum, making EMI control more difficult, and poor utilization of magnetic components. As other method, thinned-out method applied to class E\(^2\) dc/dc converter [4]. This achieves fixed frequency operation and high power conversion efficiency in wide range of the load variations. Thinned-out method, however, cannot achieve continuous control.

This paper presents phase controlled class E\(^2\) dc/dc converter. Phase controlled class E\(^2\) dc/dc converter is composed of phase controlled class E inverter [7], [8] and class E rectifier. The proposed circuit is controlled by varying the phase shift between the driving signals of two inverters. The proposed circuit achieves the control with fixed frequency and continuous control in the load variations. Moreover, by reducing the number of RF choke cores, the reduction of circuit scale is possible.

2. Circuit description
2.1. Phase controlled class E\(^2\) dc/dc converter
Figure 1(a) shows a phase controlled class E\(^2\) dc/dc converter. That is composed of a phase controlled class E inverter and a Class E rectifier. The output current of the inverter, namely the input current of the rectifier, \(i = i_1 + i_2\) can be controlled by varying phase shift \(\phi\) between the driving signals \(D_{r1}\) and \(D_{r2}\). As a result, the output power of the dc/dc converter can control by varying \(\phi\).

Moreover, to minimize the circuit scale, we consider reducing the number of RF choke cores in the converter by coupling two RF choke cores to one. Figure 1(b) shows phase controlled class E\(^2\) dc/dc converter with single RF choke core.

2.2. Phase controlled class E inverter
Phase controlled class E inverter consists of identical two class E inverters : inverter 1 and inverter 2. Each inverter is composed of an input direct voltage source \(V_i\), an input inductor \(L_{Cj}\) as work RF choke coil, a switch \(S_j\) with an n-parallel diode, a shunt capacitor \(C_{Sj}\) and a series resonant circuit \(L_{Oj} - C_{Oj}\). The switch is driven by a driving pattern of \(D_{rj}\), where the subscript \(j\) means the number of the inverter, that is, \(j = 1\) or \(2\). \(R\) is a load resistance. The two inverters are driven at the same switching frequency, and have a controllable phase shift between their output current \(i_1\) and \(i_2\) to control the overall output current \(i_1 + i_2\) and the output power. The phase shift between \(i_1\) and \(i_2\) can be controlled by varying the phase shift \(\phi\) between the gate driving voltages \(D_{r1}\) and \(D_{r2}\), which drive the switches \(S_1\) and \(S_2\), respectively. In the state of \(\phi = 0^\circ\), since the switching losses are reduced to zero by the operating requirements of zero and zero slope of switch voltage \((\nu_v = 0\) and \(d\nu_v/dt = 0\)) at the turn on transition, called class E switching conditions, the theoretical efficiency of each class E inverters are 100%. Because of these conditions, high power conversion efficiency under high frequency operation is possible.

2.3. Class E rectifier
Class E rectifier consists of a diode \(D\) with a shunting capacitor \(C_D\), a low-pass filter \(L_f - C_f\), and load resistance \(R\). In the rectifier, its input is ac current \(i\) supplied from the
inverter and the output current $I_o$. The difference of the input current $i$ and output current $I_o$ flows into the diode $D$ or its shunt capacitor $C_D$ alternatively. While the diode $D$ is off, the current that is expressed as $i_{CD} = C_D \cdot \frac{dv_d}{dt}$ flows through the capacitor $C_D$. When the diode voltage increases to the threshold voltage $v_{th}$, it turns on. In this period, the power dissipation caused in the diode is nearly zero since the diode current $i_D$ is negligible. While the diode $D$ is on, the current $i_D$ flows through the diode. In this period, the power dissipation in the diode is kept small since the diode voltage $v_d$ is equal to the threshold voltage. At the diode turn-off transition, the capacitor current is zero. Therefore, the derivative of the diode voltage $\frac{dv_d}{dt}$ is also zero. This is also characteristic of class E circuits, which reduces the switching losses and noises and enables the rectifier to operate with high power conversion efficiency at high operating frequency. The input current to rectifier is transformed into the direct output current by using the rectifier.

3. The design procedure

3.1. Assumptions

In order to derive the waveforms of the converter, we give the following assumptions.

1) The switching devices, namely diodes and MOSFET’s including anti-parallel diode have zero switching times, infinite off resistance and non-zero on resistance.

2) All passive elements operate as linear elements.

3) The shunt capacitance $C_{S1}, C_{S2}$ include switch device capacitance.

3.2. Parameters

1. $\omega = 2\pi f$ : The operation angular frequency.

2. $\omega_{ij} = 2\pi f_{0j} = 1/\sqrt{L_{ij} C_{0j}}$ : The resonant angular frequency at inverter $j$.  

3. $A_j = f_{0j}/f$ : The ratio of the resonant frequency at inverter $j$ and the operating frequency.

4. $B_j = C_{0j}/C_{Dj}$ : The ratio of the capacitance of a resonant capacitor to a shunt capacitor of the switches at inverter $j$.

5. $H_j = L_{ij}/L_{Cj}$ : The ratio of the inductance of a resonant inductor to a input inductor.

6. $J = C_{01}/C_{D}$ : The ratio of the capacitance of resonant capacitor at inverter 1 to shunt capacitor of the diode.

7. $K_j = \omega L_{ij}/R$ : The parameters for resonant circuits at inverter $j$.

8. $D$ : The switch on duty ratio of the switches. At both switches $S_1$ and $S_2$, these are same.

3.3. Circuit equations

Following above assumptions, the equivalent circuit of the proposed converter is shown in Fig. 2. The circuit equations are expressed as follows:

$$
\begin{align}
\frac{dv_{ij}}{d\theta} &= A_j^2 B_j K_j R \left( i_{ij} - i_j - \frac{v_d}{R_{Sj}} \right) \\
\frac{di_{ij}}{d\theta} &= H_j K_j R \left( v_I - v_{Sj} - r_{Lcj} i_{Cj} \right) \\
\frac{di_j}{d\theta} &= \frac{1}{K_j R} \left( v_{Sj} - v_I - v_d - r_{L0j} i_j \right) \\
\frac{dv_{d}}{d\theta} &= A_j^2 K_j R i_j \\
\frac{dv_d}{d\theta} &= A_j^2 J_k K_j R \left( \sum_{k=1}^{2} i_k - \frac{v_d}{R_D} - i_f \right) \\
\frac{di_f}{d\theta} &= \frac{1}{2\pi f L_f} \left( v_d - v_I - r_{L_f} i_f \right) \\
\frac{dv_f}{d\theta} &= \frac{1}{2\pi f C_f} \left( i_f - \frac{v_f}{R} \right) \quad (j = 1, 2)
\end{align}
$$

Figure 1: Phase controlled class E$^2$ dc/dc converter (a) with two RF choke cores (b) with single RF choke core

Figure 2: Equivalent circuit. (a) The circuit topology of equivalent circuit. (b) The expression of the resistance $R_{Sj}$. 

2. $\omega_{ij} = 2\pi f_{0j} = 1/\sqrt{L_{ij} C_{0j}}$ : The resonant angular frequency at inverter $j$. 

3. $A_j = f_{0j}/f$ : The ratio of the resonant frequency at inverter $j$ and the operating frequency.

4. $B_j = C_{0j}/C_{Dj}$ : The ratio of the capacitance of a resonant capacitor to a shunt capacitor of the switches at inverter $j$.

5. $H_j = L_{ij}/L_{Cj}$ : The ratio of the inductance of a resonant inductor to a input inductor.

6. $J = C_{01}/C_{D}$ : The ratio of the capacitance of resonant capacitor at inverter 1 to shunt capacitor of the diode.

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\frac{di_{ij}}{d\theta} &= H_j K_j R \left( v_I - v_{Sj} - r_{Lcj} i_{Cj} \right) \\
\frac{di_j}{d\theta} &= \frac{1}{K_j R} \left( v_{Sj} - v_I - v_d - r_{L0j} i_j \right) \\
\frac{dv_{d}}{d\theta} &= A_j^2 K_j R i_j \\
\frac{dv_d}{d\theta} &= A_j^2 J_k K_j R \left( \sum_{k=1}^{2} i_k - \frac{v_d}{R_D} - i_f \right) \\
\frac{di_f}{d\theta} &= \frac{1}{2\pi f L_f} \left( v_d - v_I - r_{L_f} i_f \right) \\
\frac{dv_f}{d\theta} &= \frac{1}{2\pi f C_f} \left( i_f - \frac{v_f}{R} \right) \quad (j = 1, 2)
\end{align}
$$
Table 1: Circuit parameters of converter with two RF choke cores for nominal state

<table>
<thead>
<tr>
<th></th>
<th>Calculated</th>
<th>Measured</th>
<th>Difference</th>
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<tr>
<td>$L_{c1}$</td>
<td>2.39mH</td>
<td>2.65mH</td>
<td>10.4%</td>
</tr>
<tr>
<td>$L_{c2}$</td>
<td>2.39mH</td>
<td>2.51mH</td>
<td>7.3%</td>
</tr>
<tr>
<td>$C_{o1}$</td>
<td>1.36nF</td>
<td>1.36nF</td>
<td>0.0%</td>
</tr>
<tr>
<td>$C_{o2}$</td>
<td>1.36nF</td>
<td>1.36nF</td>
<td>0.0%</td>
</tr>
<tr>
<td>$L_{s1}$</td>
<td>23.9μH</td>
<td>23.6μH</td>
<td>0.4%</td>
</tr>
<tr>
<td>$L_{s2}$</td>
<td>23.9μH</td>
<td>23.6μH</td>
<td>0.4%</td>
</tr>
<tr>
<td>$C_{i1}$</td>
<td>2.25nF</td>
<td>2.25nF</td>
<td>0.0%</td>
</tr>
<tr>
<td>$C_{i2}$</td>
<td>2.25nF</td>
<td>2.25nF</td>
<td>0.0%</td>
</tr>
<tr>
<td>$C_{f1}$</td>
<td>4.24nF</td>
<td>4.23nF</td>
<td>−0.2%</td>
</tr>
<tr>
<td>$C_{f2}$</td>
<td>4.23nF</td>
<td>4.23nF</td>
<td>0.0%</td>
</tr>
<tr>
<td>$R_{D}$</td>
<td>0.47Ω</td>
<td>0.47Ω</td>
<td>0.0%</td>
</tr>
<tr>
<td>$R_{S}$</td>
<td>10Ω</td>
<td>10Ω</td>
<td>0.0%</td>
</tr>
<tr>
<td>$r_{SD}$</td>
<td>0.16Ω</td>
<td>0.16Ω</td>
<td>0.0%</td>
</tr>
<tr>
<td>$r_{D}$</td>
<td>0.5Ω</td>
<td>0.5Ω</td>
<td>0.0%</td>
</tr>
<tr>
<td>$f$</td>
<td>1.0MHz</td>
<td>0.99MHz</td>
<td>−1.0%</td>
</tr>
<tr>
<td>$V_{dc}$</td>
<td>10V</td>
<td>10V</td>
<td>0.0%</td>
</tr>
<tr>
<td>$V_{ref}$</td>
<td>8.00V</td>
<td>7.84V</td>
<td>−2.0%</td>
</tr>
<tr>
<td>$\eta$</td>
<td>90.2%</td>
<td>89.1%</td>
<td>−1.2%</td>
</tr>
</tbody>
</table>

where, subscript $j$ means the number of the inverter and $\theta = \omega t$ represents angular time. The resistance of the switches $R_{Sj}$ is given as follows:

$$R_{Sj} = \begin{cases} 
    r_s & S_j \text{is in on state.} \\
    r_{SD} & S_j \text{is in on state and } v_{Sj} < 0 \\
    \infty & S_j \text{is in off state and } v_{Sj} \geq 0
\end{cases} \quad (2)$$

where, $r_s$ is the on resistance of switch and $r_{SD}$ is the on resistance of antiparallel diode in the switch. On the other hand, resistance of the diode $R_D$ is given as follows:

$$R_D = \begin{cases} 
    r_D & \text{for } v_d \leq v_{th} \\
    \infty & \text{for } v_d > v_{th}
\end{cases} \quad (3)$$

where $v_{th}$ and $r_D$ are the threshold voltage and on resistance of the diode, respectively.

By using (1)-(3) and numerical calculations presented in [2], design values of the circuit are derived.

4. Design example

At first, the following specifications are given: the operating frequency $f = 1.0$MHz, the input voltage $V_i = 10.0V$, the output voltage $V_o = 8.0V$, the output resistance $R = 10\Omega$, the switch on duty ratio $D = 0.5$, $H = 0.01$, $K = 15$, $L_f = 2.39$mH, $C_f = 0.47\mu$F. Moreover, $r_s = 0.16\Omega$, $r_{SD} = 0.5\Omega$, $r_D = 0.5\Omega$ and $v_{th} = 0.0V$ are given since IRF530 MOSFET is used as switches, and Shottky barrier diode 11DQ04 is used. And design parameters are derived that $A_1 = A_2 = 0.884$, $B_1 = B_2 = 0.604$, $J = 0.321$. Therefore, the element values are acquired as Tab. 1.

In case of reduction of RF choke core, inductor must wind together on a same core. And if input inductor bear enough inductance for working as choke coil with mutual inductance, reducing the number of turns is possible.

As coupling input inductor, the mutual inductance of input inductor $M_C$ is expressed as follows:

$$M_C = k \sqrt{L_{c1} \times L_{c2}} \quad (4)$$

where $k$ is the coupling factor. Therefore, inductances of coupled inductor $X_{Cj}$ expressed as follows:

$$X_{C1} = L_{c1} + M_C \frac{i_{c2}}{i_{c1}}$$
$$X_{C2} = L_{c2} + M_C \frac{i_{c1}}{i_{c2}} \quad (5)$$

5. Experimental results

Figure 3(a) shows the nominal waveforms of phase controlled class $E^2$ dc/dc converter with two RF choke cores for $\phi = 0^\circ$. Figure 3(b) shows the nominal waveforms of converter with single RF choke core for $\phi = 0^\circ$. The element values of the experimental circuit are shown in Tab. 1. From Fig. 3, we can find that both converters satisfy class $E$ switching conditions. In this case, measured efficiency 89.1% with
Although, inverter 1 can achieve zero voltage switching in both converters can not satisfy class E switching conditions. The converter with two choke cores maintains output voltage from 100% to 23%, keeping over 50% power conversion efficiency. On the other hand, at the converter with single choke core, the phase shift control can reduce the output voltage from 100% to 51%, keeping over 50% power conversion efficiency as a function of load resistance $R/R_{nom}$.

From Fig. 5 and 6, phase controlled class E$^2$ dc/dc converter achieves continuous control with keeping high power conversion efficiency. In addition, control range of the converter with single choke core is narrow with same power conversion efficiency that of two choke cores type. Although, the converter with single choke core can minimize the circuit scale.

### 6. Conclusion

In this paper, we have proposed phase controlled class E$^2$ dc/dc converter. Moreover, to minimize the circuit scale in phase controlled class E$^2$ dc/dc converter, the reduction of the number of RF choke cores in the converter by coupling two RF choke core to one have also been proposed. These proposed circuits achieve the output control with fixed frequency and continuous control in the load variations. The measured power conversion efficiency of converter with single RF choke core is over 84.9% with 5.6W output power at operating frequency of 1.0MHz.

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### References


