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Soft Switching of Non-Isolated Buck-Type Converter with Common-Ground Switch

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Abstract: A non-isolated buck converter, together with resonance and zero voltage transition to achieve zero voltage switching (ZVS) and zero current switching (ZCS), is presented herein to upgrade the conversion efficiency. In this circuit, the main switch and the auxiliary switch are connected to the common ground so as to make the two switches easily driven. Furthermore, these two switches take time division multiplexing operation. In addition, the pulse width modulation (PWM) control technique is utilized so as to render the output inductor and capacitor easily designed. In this paper, the theoretical derivation is first introduced, and secondly, some experimental results are provided to demonstrate the effectiveness of the proposed topology.

Keywords: buck; resonance; soft switching; zero current switching; zero voltage switching

1. Introduction

The traditional electronic equipment mostly uses the linear power supply, whose large size and poor efficiency performance have been criticized by the world. Therefore, the switching power supply [1,2] has been developed to improve efficiency as well as to reduce the component size by increasing the switching frequency. Generally, the switching power supply uses hard switching, leading to switching loss and noise. In addition, the switch has to withstand relatively great voltage stress, leading to additional switching loss and conduction loss. Since the switching loss is proportional to the switching frequency, the problem becomes worse. As generally acknowledged, the snubber circuits used in the past are connected in series or in parallel with the switch, which can only reduce the noise when the switch is switched and cannot effectively improve the efficiency. Therefore, the soft switching technology was born to improve the efficiency [3,4].

As for the load-resonant converter [5], this converter includes an inductor-capacitor resonance tank, which is connected in series or in parallel with the load terminal. Resonance elements participate in the energy conversion process of the converter throughout the entire process. The resonance voltage or current generated by the resonance tank is used to achieve zero voltage or current switching. The current and power of the load can be adjusted by the resonance tank circuit, and the capacity of the load can be adjusted by the ratio of the switching frequency to the resonance frequency. This load-resonant converter is also called a full resonance converter and is mostly used in half-bridge or full-bridge converters, suitable for high-power applications [6].

As to the switch-resonant converter [7], the converter only uses the resonance generated by resonant elements to provide the voltage or current required for zero voltage or
current switching when the switch is switched. Resonant elements only partially participate in the energy conversion process of the converter, which is also called a semi-resonant converter or quasi-resonant converter [8,9].

As for the zero voltage/current switching, it can be subdivided into two types, full wave and half wave [10], depending on the circuit topology. Since the resonance is in the full wave type, the zero time is short, and it is not easy to accurately control the switch to switch under zero voltage or zero current. If the switch is cut off at the resonant negative current, an auxiliary circuit must be added to keep the current continuous to avoid voltage surges that may damage the switch. In addition, the reverse current flows through the body diode of the switch, causing the conduction loss to be increased. Although the half-wave type does not have this problem, additional components are required, leading to an increase in cost. Currently, diodes are often added to eliminate negative currents, and the length of time, used for zero-voltage, or zero-current switching is increased. At present, most of these converters have been developed to add auxiliary switches, and their working time is shorter than the turn-on time of the main switch, generally about 1/10–1/5 times of $t$, the turn-on time of the main switch, which is used to control the resonance process of resonant elements so as to achieve soft switching as well as to realize pulse width modulation (PWM) control [11,12].

As to the zero voltage/current transition, the converter is featured by working under PWM control, and the auxiliary circuit work before or after the main switch is turned on. The auxiliary circuit mainly transfers the voltage or current stress that the switch bears to other places to realize the soft switching of the switch, but it stops working at other times to reduce the loss of the auxiliary circuit. According to its operation behavior, it can be divided into zero voltage transition [13,14] and zero current transition [15,16]. These two methods can transfer energy without resonance to achieve zero voltage/current switching of the switch, so that the switching components are free from the high voltage or current stress due to resonance, but an auxiliary switch must be added to help achieve this goal and the auxiliary switch still has switching loss. Therefore, if the zero voltage or current switching is applied to the auxiliary switch, then additional components must be used, leading to an increase in cost.

In the traditional buck converter, the main switch is floating and does not share the ground with the system, making it need an isolated driver. Furthermore, the resonant circuit plus the auxiliary circuit becomes more and more complicated, and even more switches or diodes are added, thereby increasing the cost of components and not effectively improving the efficiency.

In this paper, the proposed auxiliary resonant circuit, with a small number of components, is applied to a traditional buck converter, which is improved by connecting the main switch to the common ground, thereby making the main switch driven relatively easily. Furthermore, the auxiliary switch is also connected to the common ground. In addition, two switches adopt the time division multiplexing operation and the PWM control scheme, thus rendering the circuit components design relatively easily. Above all, both the main switch and the auxiliary switch have ZVS turn-on and ZCS turn-off.

2. Basic Operating Principle

Figure 1 shows the proposed circuit, including the main power stage and the auxiliary stage, and these two stages are controlled by time division multiplexing. The main power stage is constructed by a buck converter with a main switch $S_1$ having a common ground, an output diode $D_1$, an output capacitor $C$, and an output resistor $R$. The auxiliary power stage is built up by an auxiliary switch $S_2$, an auxiliary diode $D_2$, a resonant inductor $L_r$, and a resonant capacitor $C_r$. The auxiliary diode $D_2$ makes the current flow through the auxiliary switch $S_2$ in a half-wave form. There are six operating states, and Figure 2 shows the relevant waveforms for the circuit operating.
State 0 \((t \leq t_0)\): As shown in Figure 1 and Figure 2, before the switch \(S_2\) is turned on, the current \(I_o\) flows through the diode \(D_1\). During this state, the voltage across \(C_r\) is the input voltage \(V_{in}\). Once the switch \(S_2\) is turned on, the operation goes to state 1. The corresponding equations are shown as follows:

\[
\begin{align*}
    i_{Lr}(t) &= 0 \\
    v_{Cr}(t) &= V_{in}
\end{align*}
\]  

State 1 \((t_0 \leq t \leq t_1)\): As shown in Figure 1, Figure 2 and Figure 3, the main switch \(S_1\) is off but the auxiliary switch \(S_2\) is on, whereas the output diode \(D_1\) and the auxiliary diode \(D_2\) both are on. After the voltage drop across \(S_2\) reaches zero, the current flowing through \(S_2\) gradually rises and, hence, \(S_2\) has ZVS turn-on. Since the resonant voltage \(v_{Cr}\) is clamped at the input voltage \(V_{in}\) and the output diode \(D_1\) is still not cut off, making the
resonant capacitor \( C_r \) open-circuited, the inductor current \( i_{L_r} \) rises linearly. As soon as \( i_{L_r} \) rises to \( I_o \), \( D_1 \) is cut off and the operation proceeds to state 2.

![Figure 3. Equivalent circuit in state 1.](image)

The corresponding initial condition is

\[
\begin{aligned}
i_{L_r}(t_0) &= 0 \\
v_{C_r}(t_0) &= V_{in}
\end{aligned}
\]  

(2)

The corresponding equation based on Figure 3 and Equation (1) can be described as

\[
i_{L_r}(t) = i_{L_r}(t_0) + \frac{1}{L_r} \int_{t_0}^{t} V_{in} d\tau = \frac{V_{in}}{L_r} (t - t_0)
\]  

(3)

At the time instant of \( t_1 \), the result is

\[
i_{L_r}(t_1) = I_o
\]  

(4)

Therefore, based on Equations (3) and (4), the corresponding time elapsed is

\[
T_a = t_1 - t_0 = \frac{I_oL_r}{V_{in}}
\]  

(5)

State 2 \((t_1 \leq t \leq t_2)\): As shown in Figure 1, Figure 2, and Figure 4, the main switch \( S_1 \) is off but the auxiliary switch \( S_2 \) is on, whereas the output diode \( D_1 \) is off but the auxiliary diode \( D_2 \) is on. Since \( S_2 \) continues to conduct, the resonance between the resonant capacitor \( C_r \) and the resonant inductor \( L_r \) begins to occur. Therefore, \( C_r \) begins to send out energy to \( L_r \), making the resonant voltage \( v_{C_r} \) drop and the resonant current \( i_{L_r} \) rise.

![Figure 4. Equivalent circuit in state 2.](image)

The corresponding initial conditions are

\[
\begin{aligned}
i_{L_r}(t_1) &= I_o \\
v_{C_r}(t_1) &= V_{in}
\end{aligned}
\]  

(6)

The corresponding equations based on Figure 4 can be described as

\[
\begin{aligned}
i_{L_r}(t) &= I_o - i_{C_r}(t) = I_o - C_r \frac{dv_{C_r}(t)}{dt} \\
v_{C_r}(t) &= L_r \frac{di_{L_r}(t)}{dt}
\end{aligned}
\]  

(7)
By taking the Laplace transform of Equation (7), the resulting equations can be shown in Equation (8):

\[
\begin{align*}
    i_{Lr}(s) &= \frac{I_o}{s} - V_{in}C_r - sC_r v_{Cr}(s) \\
v_{Cr}(s) &= s i_{Lr}(s) L_r - I_o L_r 
\end{align*}
\tag{8}
\]

By solving Equation (8) and then taking the inverse Laplace transform of this solution, the resulting time-domain equations can be obtained as

\[
\begin{align*}
    i_{Lr}(t) &= I_o + \left[ i_{Lr}(t_1) - I_o \right] \cos \omega_0(t - t_1) + \frac{\omega_0(t_1)}{Z_0} \sin \omega_0(t - t_1) \\
v_{Cr}(t) &= Z_0 \left[ I_o - i_{Lr}(t_1) \right] \sin \omega_0(t - t_1) + v_{Cr}(t_1) \cos \omega_0(t - t_1) 
\end{align*}
\tag{9}
\]

By substituting the initial values of Equation (6) into (9), the following equations simplified can be obtained as

\[
\begin{align*}
    i_{Lr}(t) &= I_o + \frac{V_{in}}{Z_0} \sin \omega_0(t - t_1) \\
v_{Cr}(t) &= V_{in} \cos \omega_0(t - t_1) 
\end{align*}
\tag{10}
\]

where

\[
\begin{align*}
    Z_0 &= \sqrt{\frac{L_r}{C_r}} \\
    \omega_0 &= \frac{1}{\sqrt{L_r C_r}} 
\end{align*}
\tag{11}
\]

As the resonance starts at the time of \(t_1\), \(i_{Lr}\) continues to rise. When all the energy stored in \(C_r\) is sent to \(L_r\), the maximum value of \(i_{Lr}\) is \(I_o + \frac{V_{in}}{Z_0}\). After this peak value, the energy stored in \(L_r\) is transferred back to \(C_r\) to make \(V_{Cr}\) rise in the opposite direction and \(i_{Lr}\) fall. As soon as \(i_{Lr}\) drops to zero, \(S_2\) is turned off, reaching ZCS turn-off. On the other hand, after \(S_2\) is turned on in state 1, the voltage across \(S_2\) is continuously maintained at zero in state 2, so as soon as the switch \(S_2\) is turned off, the switch \(S_1\) is turned on immediately, making \(S_1\) have ZVS turn-on, and then the operation enters state 3.

At the time instant of \(t_2\), the result is

\[
i_{Lr}(t_2) = 0 \tag{12}
\]

Therefore, based on Equation (10), (11), and (12), the corresponding time elapsed is

\[
T_b = t_2 - t_1 = \frac{\sin^{-1} \left( \frac{Z_0 I_o}{V_{in}} \right)}{\omega_0} \tag{13}
\]

State 3 (\(t_2 \leq t \leq t_3\)): As shown in Figure 1, Figure 2, and Figure 5, the main switch \(S_1\) is on and the auxiliary switch \(S_2\) is off, whereas the output diode \(D_1\) and the auxiliary diode \(D_2\) both are off. \(S_1\) is turned on, taking the role of \(S_2\) to continue the resonance, and \(L_r\) continues to transfer energy to \(C_r\) so that the resonant current \(i_{Lr}\) goes in the negative direction, and the minimum value of this negative current is \(I_o - \frac{V_{in}}{Z_0}\). At the same time, \(C_r\) is charged, making \(v_{Cr}\) continues to rise. Once \(v_{Cr}\) reaches the input voltage \(V_{in}\), the operation goes to state 4.

![Figure 5. Equivalent circuit in state 3.](image-url)
The corresponding initial conditions are
\[
\begin{align*}
\{ & i_{Lr}(t_2) = 0 \\
& v_{Cr}(t_2) = V_{in} \cos \omega_0 (t_2 - t_1)
\end{align*}
\] (14)

The corresponding equations based on Figure 5 can be described as
\[
\begin{align*}
\{ & i_{Lr}(t) = I_o - i_{Cr}(t) = I_o - C_r \frac{dv_{Cr}(t)}{dt} \\
& v_{Cr}(t) = L_r \frac{di_{Lr}(t)}{dt}
\end{align*}
\] (15)

By taking the Laplace transform of Equation (15), the resulting equations can be shown in Equation (16):
\[
\begin{align*}
\{ & i_{Lr}(s) = \frac{I_o}{s} - V_{in} C_r - s C_r v_{Cr}(s) \\
& v_{Cr}(s) = s i_{Lr}(s) L_r - I_o L_r
\end{align*}
\] (16)

By solving Equation (16) and then taking the inverse Laplace transform of this solution, the resulting time-domain equations can be obtained as
\[
\begin{align*}
\{ & i_{Lr}(t) = I_o + \left[ i_{Lr}(t_2) - I_o \right] \cos \omega_0 (t - t_2) + \frac{v_{Cr}(t_2)}{Z_0} \sin \omega_0 (t - t_2) \\
& v_{Cr}(t) = Z_0 \left[ I_o - i_{Lr}(t_2) \right] \sin \omega_0 (t - t_2) + v_{Cr}(t_2) \cos \omega_0 (t - t_2)
\end{align*}
\] (17)

By substituting the initial values of Equation (14) into (17), the following equations simplified can be obtained as
\[
\begin{align*}
\{ & i_{Lr}(t) = I_o \left[ 1 - \cos \omega_0 (t - t_2) \right] + \frac{v_{Cr}(t_2)}{Z_0} \sin \omega_0 (t - t_2) \\
& v_{Cr}(t) = Z_0 I_o \sin \omega_0 (t - t_2) + v_{Cr}(t_2) \cos \omega_0 (t - t_2)
\end{align*}
\] (18)

At the time instant of \( t_3 \), the result is
\[
\begin{align*}
\{ & i_{Lr}(t_3) = 0 \\
& v_{Cr}(t_3) = V_{in}
\end{align*}
\] (19)

Therefore, based on Equations (18) and (19), the corresponding time elapsed is
\[
T_c = t_3 - t_2 = \sin^{-1} \left[ \frac{V_{in} - v_{Cr}(t_2)}{Z_0 I_o + \left[ \frac{v_{Cr}(t_2)}{Z_0} \right]^2} \right] / \omega_0
\] (20)

State 4 \((t_3 \leq t \leq t_4)\): As shown in Figure 1, Figure 2, and Figure 6, the main switch \( S_1 \) is on and the auxiliary switch \( S_2 \) is off, whereas the output diode \( D_1 \) is on but the auxiliary diode \( D_2 \) is still off. The resonant voltage \( v_{Cr} \) is clamped at the input voltage \( V_{in} \), making the resonant capacitor \( C_r \) open-circuited and the resonant current \( i_{Lr} \) linearly rising. As soon as \( i_{Lr} \) rises to the output current \( I_o \), the operation goes to state 5.
The corresponding initial conditions are

\[
\begin{cases}
  i_{Lr}(t_3) = 0 \\
  v_{Cr}(t_3) = V_{in}
\end{cases}
\]  

(21)

The corresponding equations based on Figure 6 can be described as

\[i_{Lr}(t) = i_{Lr}(t_3) + \frac{1}{L_r} \int_{t_3}^{t} V_{in} \, dt = i_{Lr}(t_3) + \frac{V_{in}}{L_r} (t - t_3)\]  

(22)

By substituting the initial values of Equation (21) into (22), the following simplified equations can be obtained as

\[i_{Lr}(t) = \frac{V_{in}}{L_r} (t - t_3)\]  

(23)

At the time instant of \(t_4\), the result is

\[i_{Lr}(t_4) = I_0\]  

(24)

Therefore, based on Equations (23) and (24), the corresponding time elapsed is

\[T_d = t_4 - t_3 = \frac{I_0 L_r}{V_{in}}\]  

(25)

State 5: \((t_4 \leq t \leq t_5)\): As shown in Figure 1, Figure 2, and Figure 7, the main switch \(S_1\) is still on and the auxiliary switch \(S_2\) is still off, whereas the output diode \(D_1\) and the auxiliary diode \(D_2\) both are off. The resonant inductor \(L_r\) resonates with the resonant capacitor \(C_r\). \(C_r\) transfers energy to \(L_r\), so the resonant voltage \(v_{Cr}\) falls and the resonant current \(i_{Lr}\) rises. Once \(S_1\) is cut off, the operation proceeds to state 6.

![Figure 7. Equivalent circuit in state 5.](image)

The corresponding initial conditions are

\[
\begin{cases}
  i_{Lr}(t_4) = I_0 \\
  v_{Cr}(t_4) = V_{in}
\end{cases}
\]  

(26)

The corresponding equations based on Figure 7 can be described as

\[
\begin{cases}
  i_{Lr}(t) = I_0 - i_{Cr}(t) = I_0 - C_r \frac{dv_{Cr}(t)}{dt} \\
  v_{Cr}(t) = L_r \frac{di_{Lr}(t)}{dt}
\end{cases}
\]  

(27)

By taking the Laplace transform of Equation (27), the resulting equations can be shown in Equation (28):

\[
\begin{cases}
  i_{Lr}(s) = \frac{I_0}{s} - V_{in} C_r - s C_r v_{Cr}(s) \\
  v_{Cr}(s) = s L_r i_{Lr}(s) L_r - I_0 L_r
\end{cases}
\]  

(28)
By solving Equation (28) and then taking the inverse Laplace transform of this solution, the resulting time-domain equations can be obtained as

\[
\begin{align*}
  i_{Lr}(t) &= I_0 + \left[ i_{Lr}(t_4) - I_0 \right] \cos \omega_0(t - t_4) + \frac{v_{Cr}(t_4)}{Z_0} \sin \omega_0(t - t_4) \\
  v_{Cr}(t) &= Z_0 \left[ I_0 - i_{Lr}(t_4) \right] \sin \omega_0(t - t_4) + v_{Cr}(t_4) \cos \omega_0(t - t_4)
\end{align*}
\]  

(29)

By substituting the initial values of Equation (26) into (29), the following equations simplified can be obtained as

\[
\begin{align*}
  i_{Lr}(t) &= I_0 + \frac{V_{in}}{Z_0} \sin \omega_0(t - t_4) \\
  v_{Cr}(t) &= v_{Cr}(t_4) \cos \omega_0(t - t_4)
\end{align*}
\]  

(30)

As the resonance starts at the time of \( t_4 \), \( i_{Lr} \) continues to rise. When all the energy stored in \( C_r \) is sent to \( L_r \), the maximum value of \( i_{Lr} \) is \( I_0 + \frac{V_{in}}{Z_0} \). After this peak value, the energy stored in \( L_r \) is transferred back to \( C_r \) to make \( v_{Cr} \) rise in the opposite direction and \( i_{Lr} \) fall. As soon as \( i_{Lr} \) drops to zero, \( S_1 \) is turned off, achieving ZCS turn-off, the operation enters state 6.

At the time instant of \( t_5 \), the result is

\[ i_{Lr}(t_5) = 0 \]  

(31)

Therefore, based on Equations (30) and (31), the corresponding time elapsed is

\[ T_e = t_5 - t_4 = \frac{\sin \left( \frac{-Z_0 I_0}{V_{in}} \right)}{\omega_0} \]  

(32)

State 6 \((t_5 \leq t \leq t_6)\): As shown in Figure 1, Figure 2, and Figure 8, the main switch \( S_1 \) and the auxiliary switch \( S_2 \) are both off. There is no resonance loop. Hence, there is no energy stored in \( L_r \) and only the input current \( I_0 \) charges the resonant capacitor \( C_r \), making the resonant voltage \( v_{Cr} \) linearly rising. Once \( v_{Cr} \) reaches the input voltage \( V_{in} \), the output diode \( D_1 \) is turned on and the operation goes to state 1 with the next cycle repeated.

![Figure 8. Equivalent circuit in state 6.](image_url)

The corresponding initial conditions are

\[
\begin{align*}
  i_{Lr}(t_5) &= 0 \\
  v_{Cr}(t_5) &= V_{in} \cos \omega_0(t_5 - t_4)
\end{align*}
\]  

(33)

The corresponding equations based on Figure 8 can be described as

\[
v_{Cr}(t) = v_{Cr}(t_5) + \frac{1}{C_r} \int_{t_5}^{t} I_0 dt = v_{Cr}(t_5) + \frac{I_0}{C_r} (t - t_5)
\]  

(34)

By substituting the initial values of Equation (33) into (34), the following simplified equations can be obtained as

\[ v_{Cr}(t) = V_{in} \cos \omega_0(t_5 - t_4) + \frac{I_0}{C_r} (t - t_5) \]  

(35)
At the time instant of $t_6$, the result is

$$v_{Cr}(t_6) = V_{in}$$  \hspace{1cm} (36)

Therefore, based on Equations (35) and (36), the corresponding time elapsed is

$$T_f = t_6 - t_5 = \frac{-C_r \cdot V_{in} \cos \omega_0 (t_5 - t_4)}{I_o}$$  \hspace{1cm} (37)

### 3. Design Considerations

Prior to this section, Table 1 shows system specifications. In the following, the design of the resonant inductor $L_r$ and the resonant capacitor $C_r$ is taken into consideration.

**Table 1. System Specifications.**

| Parameters                             | Specifications |
|----------------------------------------|----------------|
| System operating mode                  | CCM            |
| Input rated voltage ($V_{in}$)         | 48 V           |
| The output voltage ($V_o$)             | 24 V           |
| Output rated current ($I_o$)           | 5 A            |
| Rated output power ($P_{o,rated}$)     | 120 W          |
| Minimum output power ($P_{o,min}$)     | 12 W           |
| System switching frequency ($f_s$)     | 250 kHz        |
| Output Inductor ($L$)                  | 50 µH          |
| Output Capacitor ($C$)                 | 10 µF          |

As it is well recognized, the resonant behavior occurs at the resonant radian frequency $\omega_0$ and on the condition of ZCS turn-off is $I_o \leq V_{in}/Z_0$, namely, $Z_0 \leq V_{in}/I_o$. Therefore, the choice of $\omega_0$ and $Z_0$ should be determined first.

Since the voltage conversion ratio $V_o/V_{in}$ is 0.5, then the corresponding duty cycle $D$ is ideally 0.5, meaning that each duty cycle for $S_1$ and $S_2$ is ideally 0.25 due to time division multiplexing operation between the two switches. Accordingly, the resonant frequency $f_0$ is larger than 1 MHz, which is equal to 250 kHz divided by 0.25. Finally, the value of $f_0$ is chosen to be 1.1 MHz.

After determination of $f_0$, the choice of $Z_0$ follows. From [17], it is assumed that $Z_0' = V_{in}/I_{r,rated} = 48/5 = 9.6\Omega$ and the value of $Z_0$ locates between 0.2$Z_0'$ and 0.7$Z_0'$ so as to avoid the internal impedance effect. Finally, the value of $Z_0$ is chosen to be $0.5Z_0'$, equal to 4.8Ω. In addition, the inequality equations of $L_r$ and $C_r$ are

$$\begin{align*}
L_r &\leq \frac{Z_0}{2\pi f_0} \\
C_r &\geq \frac{1}{2\pi f_0 Z_0}
\end{align*}$$  \hspace{1cm} (38)

Therefore, the value of $L_r$ is smaller than 0.69 µH and the value of $C_r$ is larger than 30 nF. Eventually, the value of $L_r$ is 0.65 µH and the value of $C_r$ is 35 nF.

### 4. Control Strategy

As shown in Figure 9, the resonant buck converter is powered by the input voltage. In the feedback block (VFB), a high-voltage operational amplifier is used to feedback the output voltage. However, because the load and the circuit do not share the same ground, a photocoupler should be used to isolate the two. The feedback signal is sent to the control integrated circuit (IC), named UC3842, to obtain a suitable PWM control signal. Afterwards, this signal is sent to the gate driver to drive the switch so that the output voltage is regulated at the prescribed value.
5. Experimental Results

The following waveforms are measured at rated load. Figure 10 shows the resonant current $i_{Lr}$ and the resonant voltage $v_{Cr}$. Figure 11 shows the gate driving signals $v_{g1}$ and $v_{g2}$ for $S_1$ and $S_2$, respectively. Figure 12 shows the gate driving signal $v_{g1}$ for $S_1$, the voltage across $S_1$, called $v_{ds1}$, and the current flowing through $S_1$, called $i_{ds1}$. Figure 13 shows the zoom-in of Figure 12 for ZVS turn-on of $S_1$. Figure 14 shows the zoom-in of Figure 12 for ZCS turn-off of $S_1$. Figure 15 shows the gate driving signal $v_{g2}$ for $S_2$, the voltage across $S_2$, called $v_{ds2}$, and the current flowing through $S_2$, called $i_{ds2}$. Figure 16 shows the zoom-in of Figure 15 for ZVS turn-on of $S_2$. Figure 17 shows the zoom-in of Figure 15 for ZCS turn-off of $S_2$. Figure 18 shows the efficiency comparison between with and without the proposed soft switching strategy.

![System configuration block diagram](image)

**Figure 9.** System configuration block diagram.

![Resonant waveforms](image)

**Figure 10.** Resonant waveforms: (1) $i_{Lr}$; (2) $v_{Cr}$.
Figure 11. Gate driving signals for $S_1$ and $S_2$: (1) $v_{g1}$; (2) $v_{g2}$.

Figure 12. Waveforms relevant to $S_1$: (1) $v_{g1}$; (2) $v_{ds1}$; (3) $i_{ds1}$.

Figure 13. Zoom-in of Figure 12 for ZVS turn-on of $S_1$. 
Figure 14. Zoom-in of Figure 12 for ZCS turn-on of $S_1$.

Figure 15. Waveforms relevant to $S_2$: (1) $v_g2$; (2) $v_{ds2}$; (3) $i_{ds2}$.

Figure 16. Zoom-in of Figure 15 for ZVS turn-on of $S_2$. 
Figure 17. Zoom-in of Figure 15 for ZCS turn-on of $S_2$.

Figure 18. Efficiency comparison between with (real line) and without (dotted line) the proposed soft switching strategy.

From Figure 10, it can be seen that the peak value of $i_{Lr}$ is 14 A, which is smaller than 15 A ($=I_o + V_{in}/I_{o,\text{rated}}$), and the peak value of $v_{Cr}$ is 45 V, which is smaller than the input voltage of 48 V. From Figure 11, it can be seen that the switch-on instant for $S_2$ is prior to that for $S_1$ and time division multiplexing operation between $S_1$ and $S_2$ holds. From Figure 13, Figure 14, Figure 16, and Figure 17, it can be seen that the proposed soft switching strategy based on time division multiplexing can make $S_1$ and $S_2$ both have ZVS turn-on and ZCS turn-off. From Figure 18, it can be seen that the maximum efficiencies with and without the proposed soft switching are 92.8% and 90.7%, respectively, and the maximum difference in efficiency between the two is about 2.1%.

6. Comparison

The comparison between the buck-type circuits and the proposed circuit is shown in Table 2, in terms of soft switching features, auxiliary circuit components, output power, output voltage, switching frequency, soft switching strategy, maximum efficiency, and common-ground auxiliary switch. From these comparison items, the proposed circuit has some characteristics: (i) under the smallest number of auxiliary circuit components used, both the main and auxiliary switches have ZVS turn-on and ZCS turn-off; (ii) only the proposed auxiliary circuit has a common-ground auxiliary switch; and (iii) the average performance of the maximum efficiency is mainly due to the highest switching frequency used.
Table 2. Circuit Comparison.

| Comparison Items                  | [2] | [3] | [4] | [8] | [13] | Proposed |
|-----------------------------------|-----|-----|-----|-----|------|----------|
| **Soft switching features**       |     |     |     |     |      |          |
| Main switch                       | ZVS | ZVS | ZVS | ZCS | ZVS  | ZVS/ZCS  |
| Auxiliary switch                  |     | ZVS | ZVS |     | ZVS/ZCS | ZVS/ZCS |
| **Auxiliary circuit components**  |     |     |     |     |      |          |
| Diode                             | 2   | 2   | 2   | 0   | 2    | 1        |
| Magnetic element                  | 3   | 2   | 2   | 0   | 1    | 1        |
| Capacitor                         | 0   | 2   | 2   | 0   | 1    | 1        |
| Isolated gate driver              | 0   | 2   | 2   | 0   | 1    | 0        |
| **Output power (W)**              | 1500| 240 | 300 | 10  | 150  | 120      |
| **Output voltage (V)**            | 130 | 12  | 48  | 36  | 24   | 24       |
| **Switching frequency (kHz)**     | 50  | 75  | 100 | 100 | 100  | 250      |
| **Maximum efficiency (%)**        | 94.0| 90.3| 93.6| 92.5| 93.5 | 93.3     |
| **Common-ground auxiliary switch**|     |     |     |     |      | No       |

7. Conclusions

The proposed circuit has several merits described as follows:

1. The converter adopts an auxiliary circuit with fewer components to realize that both the main and auxiliary switches have ZVS turn-on and ZCS turn-off.
2. These two switches take the time division multiplexing operation plus the width modulation (PWM) control technique so that the circuit components are designed easily.
3. The main and auxiliary switches are connected to the common ground so that the two switches are driven easily.
4. From the experimental results, it can be seen that the maximum efficiencies with and without the proposed soft switching are 93.3% and 90.7%, respectively, and the maximum difference in efficiency between the two is about 2.6%.

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