A New Full Resonant ZCS Forward Converter Having Wide ZCS Domain

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A new full resonant ZCS forward converter intended to improve undesirable performances of the conventional ZCS converter is proposed and many of operational items, such as ZCS domain, amplitude variation, efficiency, dynamic load effect and cross regulation, are successfully confirmed by experiments and theoretical analysis. The converter is possible to get ZCS action exploiting a L-C series resonant circuit putting in parallel with the transformer and a small inductance putting in series with the transformer. It is shown that the new converter is applicable to the power supplies for which good performances with respect to dynamic load effect, noise and efficiency are requested, and has possibilities realizing low noise, high frequency operation and then miniaturization. Furthermore, the simplified design method which is useful on case of early step of designing converter is given.

Key words : Forward converter, Current resonant, Full resonant, ZCS, ZCS domain

1. Introduction

Recently, downsizing of electrical instruments and systems have been advanced and this is true on a field of OA instrument, e.g. personal computer, printer and facsimile, etc.. Therefore, the miniaturization of power supplies is indispensable. In addition to requirements of low noise and high efficiency, the switching power supply is required to have the property that the output voltage can be controlled stably and quickly, even if the load changes rapidly from minimum to maximum or vice versa. The forward converter has been used for the present printer power supply of middle or high power class. It is the reasons that the circuit has a simple structure and the converter is able to take out a large current with small voltage effect and to control the output voltage quickly as the load and the input change rapidly.

The current resonant converter operated under Zero Current Switching (ZCS) has no switching loss and low noise theoretically, which yield high efficiency and high frequency operation and then miniaturization. Many literatures have presented basic characteristics, e.g. ZCS domain, the influence of leakage inductance and the variation of switching peak current, through the steady state analysis and the operation analysis of various converter circuits used ZCS switches1,2,3).

While we have studied to apply the full wave type of current resonant switch resonating on the primary side to the forward converter4), in what follows we call it the conventional ZCS converter and a typical circuit is shown in Fig.1. The conventional one is of full resonant type which has resonant states in both ON and OFF switching periods. We have theoretically and experimentally confirmed that the converter has the following undesirable performances,

1) the amplitude of resonant current becomes small as the output current increases,
2) due to this property, the maximum output current on ZCS and ZCS domain are small.
3) If the impedance \( Z = \sqrt{L_C} \) of \( L_C \) resonant circuit is decreased to get a larger output current, the amplitude of resonant current increases and then the conduction loss increases.

In this paper, to improve these undesirable
performances, we propose a new full resonant ZCS forward converter which is possible to get ZCS action exploiting a $L-C$ series resonant circuit putting in parallel with the transformer and a small inductance putting in series with the transformer. We clear by theoretical analysis and experiments that the proposed converter has the good performances such as; low noise and small switching loss due to ZCS action, Zero Current Zero Voltage Switching (ZCS-ZVS) action at the time of turning off under the critical ZCS condition, wide ZCS domain, small change of amplitude of resonant current at overall loads, small conduction loss at light loads, performance of dynamic load effect, and high efficiency. Furthermore, we give a simple and useful method to determine circuit's parameters.

2. New ZCS Converter

2.1 Main Circuit

To improve undesirable performances of the conventional ZCS converter, we propose a new full resonant ZCS forward converter, shown in Fig.2. The converter consists of a controlled switch $Q$ connected antiparallel diode $D_s$, a transformer coupled forward type rectifier, a $L-C$ series resonant circuit putting in parallel with the transformer and a small inductance $L_2$ putting in series with the secondary side of the transformer. For practical circuits, the leakage inductance of the transformer can be utilized instead of this small inductance $L_2$. Here, the $L-C$ resonant circuit and $L_2$ contribute to ZCS action at turning off and on, respectively.

2.2 Operation Analysis

To analysis the circuit, we assume that

1) the switching devices are ideal,
2) the output choke inductance $L_0$ is large and the output current $I_o$ is constant,
3) the input condenser capacitance $C_i$ is large and the input voltage $V_i$ is constant,
4) a conduction loss is negligible.

Under the assumptions, the circuit operation of the proposed type is classified into five stages, as shown in table 1, according to the operating conditions of diodes $D_1$, $D_2$ and switch $S_w$ consisted of switching device $Q$ and antiparallel diode $D_s$, and the following four operating modes are considered.

Mode 1: This mode is defined by the cyclic sequence of stages given as $1-2-3-5-1$ in a switching period $T$ and its occurrence is dominated by the polarity of voltage $v_c$ appeared at resonant condenser $C_r$, which is negative / positive at the time of $S_w$ turns on / off.

Mode 2: This mode is defined by the cycle of $1-2-3-5-1$ and its occurrence polarity is negative / negative at the time of turning on / off.

Mode 3: This is a case where diode $D_1$ turns on during OFF period of $S_w$ and the stage 3 appears again during OFF period but its current does not coincide with the value of the output current $I_o$ which may occur due to a low switching frequency and a voltage $v_c$ of resonant condenser which becomes positive value during OFF period due to resonance on $C_r-L_r-L_t$. This mode has the typical cycle of $1-2-3-5-1$.

Mode 4: This mode is the same case as Mode 3 except that the current through $D_1$ coincides with the output current $I_o$ and diode $D_1$ turns off. Thus the stage 4 appears and its typical cycles are $2-3-5-3-4-2$ and $1-2-3-5-3-4-3-1$.

The modes 3 and 4 are unusual ones in the sense that the current flows into the secondary side of transformer during OFF period. Hence we concentrate our attention to Modes 1 and 2. The existence of stage 4 is only a difference between both modes, and its appearance is restricted to near ZCS limits and the time period is short, which results almost same performances. So, here, we discuss the operation of Mode 2.

The equivalent circuits corresponding to stages of Mode 2 are shown in Fig.3, where the output part is treated as a constant current source $I_0'$ converted into primary value on the assumption, and the transformer is replaced by equivalent inductances; an exciting inductance $L_t$ and a small inductance $L_s$ including a leakage inductance, by which we present the following
brief summary of circuit operation to show ZCS action. Let \( v_c, i_{sw}, i_t \) and \( i_{u} \) be the voltage of resonant condenser \( C_r \), the currents through switch \( S_w, L_r - C_r \), resonant circuit, exciting inductance \( L_t \) and \( L_2 \), respectively. These variables were theoretically analyzed using stage by stage state space approach. All state variable equations are not shown for brevity of this paper.

Stage 1 \([t_4, t_1]\) : Suppose \( t = t_0 = 0 \) be the time when \( Q \) turns on and then \( D_t \) turns on provided that \( D_2 \) retains on state. Referring Fig.3(a), \( i_{sw} \) is given by

\[
i_{sw}(t) = i_t + i_s + i_{u} = \frac{V_i}{L_t} t - I_{o} + \frac{V_i}{L_2} t
\]

where \( V_m \) and \( I_{o} \) represent initial values related to \( C_r \) and \( L_r \), respectively. It is seen from Eq.1 that \( i_{sw} \) begins to increase from zero and the switch turns on under ZCS condition, because that the current \( i_{u} \) rises at a gentle slope suppressed by small inductance \( L_2 \). At the time \( t_1 \) when \( i_{sw} \) coincides to \( I_{o} \), \( D_2 \) turns off and enter the next stage.

Stage 2 \([t_1, t_2]\) : Referring Fig.3(b) shows an equivalent circuit of this stage where \( i_{u} \) equals to \( I_{o} \), and \( i_t \) and \( i_{sw} \) have the same form as those of the preceding stage. So we can get

\[
i_{sw}(t) = i_t + i_s + i_{u} = X \sin (\omega t + \varphi) + \frac{V_i}{L_t} t - I_{o} + \frac{V_i}{L_2} t
\]

where \( V_m \) and \( I_{o} \) represent initial values related to \( C_r \) and \( L_r \), respectively. It is seen from Eq.1 that \( i_{sw} \) begins to increase from zero and the switch turns on under ZCS condition, because that the current \( i_{u} \) rises at a gentle slope suppressed by small inductance \( L_2 \). At the time \( t_1 \) when \( i_{sw} \) coincides to \( I_{o} \), \( D_2 \) turns off and enter the next stage.

Stage 3 \([t_1, t_3]\) : Since \( S_w \) turns off and \( v_c \) is negative, \( D_t \) turns on, so we get an equivalent circuit as shown in Fig.3(c). The switching voltage \( v_{sw} \) begins to oscillate due to resonance on \( L_r - C_r - L_{r} - L_2 \). At the time \( t_3 \) when \( i_{u} \) drops to zero, \( D_2 \) turns off and go to next stage 5.

Stage 5 \([t_5, t_5 + T]\) : Fig.3(d) shows an equivalent circuit of this stage. Then the switching voltage \( v_{sw} \) oscillates due to resonance on \( L_r - C_r - L_{r} \). If \( Q \) is forced to turn on at the time \( t_5 + T \) before the voltage of transformer, which is nearly equal to \( v_c \), returns to zero and \( D_t \) turns on, the switching cycle may be completed.

From the observation stated above, it is cleared that the proposed converter is able to accomplish to ZCS operation exploiting the \( L_r - C_r \) series resonant circuit putting in parallel with the transformer at the time of turning off and to get ZCS action at the time of turning on exploiting the small inductance \( L_2 \) putting in series with the transformer, and acts as a full resonant converter which has resonant states in both switching periods of ON and OFF.

The proposed converter transmits the power to output during stage 2 and the power is given by

\[
w = \frac{1}{T} \int_{0}^{T} n_i V_i d t = \frac{n_i}{T} \left( t_2 - t_1 \right) = \frac{n_i}{T} \left( t_2 - \frac{J_{L_2}}{n_V} \right).
\]

Putting the output be \( V_o \), the output voltage \( V_o \) is equated by

\[
v_o = \frac{n_i V_i}{T} \left( t_2 - \frac{J_{L_2}}{n_V} \right).
\]

3. ZCS Action and Domain

The experimental and theoretical operating wave forms under critical ZCS condition are shown in Fig.4. When the switch turns on, the switch current \( i_{sw} \) begins to increase from zero at a lenient slope because that the
current of $D_1$ rises at a gentle slope suppressed by a leakage inductance of the transformer, which is utilized instead of the small additional inductance $L_2$ on practical circuit. Further, the current $i_{sw}$ becomes zero just as the switch turns off and the switching voltage begins to rise from zero and then the converter acts on ZC-ZVS action. Furthermore, the currents of $D_1$ and $D_2$ begin to rise from zero and these diodes turn off as these currents become zero, and then these diodes operate on ZCS action.

As the results, it is cleared that the proposed converter gets ZCS action and gets also ZC-ZVS action at the time of turning off under critical ZCS condition, and the $D_1$, $D_2$ operate on ZCS, and then the switching loss becomes very small. With respect to $i_{sw}$ and $v_{sw}$ at $t_o$ and $t_s$, we can observe undesirable currents and spike voltages in experimental wave forms but not theoretical ones. These phenomena are due to an existence of a parasitic capacity of the switching device and its charging current flowing during OFF period of $S_w$ even though the switching device has been turned off. But, the behaviors related with ZCS switching operation are almost same.

Experimental and theoretical ZCS domains are shown in Fig.5. Here, the results of conventional ZCS converter are obtained from theoretical analysis and experiments carried out in the same way as the proposed one. The lines present critical ZCS limits obtained by analysis. The critical voltages of conventional one increase linearly as the output current increases, and the left side of this limit line is referred as its ZCS domain. While the critical line of proposed type has the form of convex and its critical voltage related with $I_o$ and switching period $T$ is given from Eq. 6, as

$$V_{con} = \frac{3nV_i T}{4T} - \frac{L_2}{T} I_o$$

using assumption that the ON period of $S_w$ is equal to three fourths of resonant period $T_s$ under critical ZCS condition. Here the switching frequency $f_s(1/T)$ increases as the output current $I_o$ increases and then the graph of Eq. 7 becomes a parabolic curve. As the result, we can get the wide ZCS domain extended over the line. Similar results were obtained from experiments. The ZCS domain can be extended due to reducing the impedance of resonant circuit, but the peak current of $i_{sw}$ and conduction loss increase owing to enlarging the resonant current.

The variation of amplitude $I_{sw}$ of resonant current under the constant output voltage condition, which has influence on extent of ZCS domain, is indicated in Fig.6. It is possible to confirm the undesirable performances of the conventional type as following,

1) the amplitude of the conventional type decreases as the output current increases,
2) due to this property, the maximum output current on ZCS and ZCS domain are small,
3) if the impedance of resonant circuit of the conventional type is adjusted to get a large output current, the amplitude increases and then the conduction loss and the duty of switching current increase.

While the amplitude of proposed type increases gradually as the output current increases and the converter with the small amplitude of resonant current, as about 62.5% of conventional one under lights load

![Fig.5 ZCS domains](image-url)
condition, can get the same maximum output current. From Eq. 2, the amplitude of switching current \( i_{sw} \) of the proposed type is evaluated by

\[
I_{sw}=\frac{(V_{in}+V_o)^2}{2L}+I_{on}.
\]  

The absolute values of these initial values \( I_{on}, V_o \) increase gradually as the output current increases and then the amplitude of proposed type increases gradually as experimental one. The amplitudes obtained from theoretical analysis using the state variable equations and Eq. 8 are shown in Fig. 6.

4. Operational Performance

The variation of switching frequency under constant output voltage condition is depicted in Fig. 7. It is seen that the switching frequency increases linearly as the output current increases, the frequency variation of the proposed type is relatively small due to full wave type of current resonant, and a range of \( f_s \) is 180-255kHz on overall loads. The output can be well—controlled excellently at overall loads using pulse frequency modulation control provided that the ON period is fixed by resonant frequency of \( L-C \), and the OFF period is adjusted to get a designed output voltage.

Fig.8 shows the dependency of the efficiencies using testing circuits, from which we can say that

1) the maximum efficiencies more than 80% are attained in the vicinity of respective maximum load,
2) the proposed type has wide range keeping relatively high efficiency than conventional one,
3) the efficiency under light loads condition is higher by 8% than conventional one because that the amplitude of resonant current of proposed type is small at light loads and then the conduction loss due to resonant current is small.

The features that the conduction loss is reduced and then the efficiency at a light load is improved will be favorable for the power supply, such as printer and facsimile, which take a long waiting time.

The dynamic load effect is shown in Fig. 9. It is seen that even if the proposed converter is suffered sudden load changes, we can control the output voltage stably and quickly using a simple feedback control with shunt regulator in such manner that the response time is about 1ms, which satisfies the condition required for
Fig. 9 Dynamic load effect of proposed converter

Fig. 10 Cross regulation effect of the proposed type

-existing power supplies\(^7\), and the output voltage accuracy is kept to good without abnormal oscillations and unstable operations.

The multiple output converter is frequently required for the switching power supply, so we have investigated the performance of cross regulation of the proposed converter having two outputs; one output \(V_1\) is controlled to have constant voltage of 15V under ZCS condition, while the another output \(V_2\) is not controlled but set to the rated output voltage and the constant resistance be 4.5V and 4.5Ω, respectively. The cross regulation effect is shown in Fig. 10. It is observed that the uncontrolled output voltage \(V_2\) increases as the controlled output current \(I_0\) increases and its variation is within the range of ±3% of the rated voltage of uncontrolled output. Its variation obtained from the state space analysis for two output converter is given by

\[
\Delta V_2 = \frac{K R_1 L_1 f_0 + V_d L_2}{R_0 + L_2 f_0} \Delta f_0,
\]

where \(L_1\) and \(L_2\) are small inductances putting in series with each output winding of the transformer, \(K\) is a constant related with combination of the transformer. It is confirmed that the change rate is basically proportional to the frequency effect and is influenced by the inductances \(L_1\) and \(L_2\). Furthermore, these inductances are related to ZCS action at the time of turning on, so we must set adequate values for designing converter.

5. Designing Method

In case of designing a converter, it is useful to devise a method for determining values of inductances, condensers and winding ratio of the transformer. From the reasons that the conventional converter has more than one resonant stage during ON period of \(S_w\) and the resonant voltage appears at secondary side, it is necessary to use a computer to aid calculation of the transferred power and determination of values of components. While the proposed type may lead a simplified designing method by which we can determine these values without computer aid, since the resonant state of the proposed one is unchangeable during ON period of \(S_w\) and the voltage appeared at secondary side is similar with that of PWM forward converters.

This method aims to determine the values of resonant elements \(L_r\) and \(C_r\), winding ratio \(n\) of the transformer, small inductance \(L_2\) and the minimum value of exciting inductance \(L_t\) from given electrical rating. In this paper, we use the electrical rating shown in table 2, as a testing example.

At first, the winding ratio \(n\) of the transformer must be determined. If the minimum output current \(I_o\) under the minimum switching frequency \(f_{\text{min}}\) is enough small, the interval of stage 1 is very short and is negligible and then the ON period \(t_1\) can be regarded as being equal to the resonant period \(T_r\) of the \(L_r-C_r\) resonant circuit. Applying the assumption to Eq.6, the winding ratio \(n\) can be determined, as

\[
n = \frac{V_v f_0}{V_i f_{\text{min}}}.
\]

Secondly, with a view to get certainly ZCS action at overall loads, the amplitude \(X\) of resonant current under conditions such as minimum load and minimum switching frequency \(f_{\text{min}}(1/T_{\text{min}})\) condition, on which the

| Input voltage \(V_i\) | 141.4V (ac100V) |
| Output voltage \(V_v\) | 15V (controlled) |
| Output current \(I_o\) | 0.3—7.5A |
| Resonant frequency \(f_r=1/T_r\) | 450kHz |
| Switching frequency \(f_s=1/T_s\) | 180—260kHz |

Table 2 Electrical ratings

\[
V_i=15V, R_2=4.5Ω, L_1=1.5μH, L_2=0.6μH
\]

Input voltage \(V_i\) : 141.4V (ac100V)
Output voltage \(V_v\) : 15V (controlled)
Output current \(I_o\) : 0.3—7.5A
Resonant frequency \(f_r=1/T_r\) : 450kHz
Switching frequency \(f_s=1/T_s\) : 180—260kHz.
amplitude is minimum, is set the maximum value \( n_{\text{max}} \) of the output current observed at the primary side. Considering a minimum load condition where the initial value \( I_{0} \) of resonant inductance \( L_{r} \) is disregarded, the impedance \( Z \) of series resonant circuit can be calculated from Eq. 2, as

\[
Z = \frac{V_{o}}{n_{\text{max}}}.
\]

Here to establish the simple designing method applicable for the early step of designing the converter, put \( V_{o} \) of resonant condenser be an average voltage of the transformer during OFF period of \( S_{w} \) on the assumption that \( L_{r} \) is enough large and then \( V_{o} \) is almost equal to the voltage of the transformer during OFF period and its change is small and furthermore the voltage of the transformer contains no DC component, we have

\[
V_{o} = \frac{V_{T_{o}}}{T_{\text{max}} - T_{o}}.
\]

From Eqs. 11 and 12 and resonant frequency \( f_{s} \), \( C_{r} \) and \( L_{r} \) of resonant circuit are respectively given as

\[
C_{r} = \frac{1}{2 \pi f_{s}} \quad L_{r} = 2 \pi C_{r}.
\]

Next, using the assumption that the critical ZCS condition appears under maximum output condition, which means that the converter operate under maximum switching frequency \( f_{\text{max}}(1/T_{\text{max}}) \) and maximum output current \( I_{\text{max}} \), and at that case the ON period of \( S_{w} \) is equal to three fourths of the resonant period, the small inductance \( L_{2} \) associated with ZCS action at the time of turning on is determined from Eq. 7, as

\[
L_{2} = \frac{V_{o}}{I_{\text{max}}} \left[ \frac{3V_{o}}{4V_{o}} T_{o} - T_{\text{max}} \right].
\]

The rise rate of switching current \( i_{sw} \) at the time of turning on is influenced by \( L_{r} \) and is obtained from Eq. 1, as

\[
\frac{di_{sw}}{dt} = \left[ \frac{T}{L_{r}(T - T_{o})} + \frac{1}{L_{2}} \right] V_{i}.
\]

Therefore, \( L_{2} \) must be set an adequate value from Eqs. 14 and 15. If the rise rate is steep, the maximum switching frequency is changed to more higher value and then \( L_{2} \) must be stepped up.

At last, in order that neither Mode 3 nor 4 appear at light loads condition, the half of resonant period of \( C_{r} - L_{r} - L_{t} \) must be extended longer than the OFF period \( T - T_{o} \). So the minimum exciting inductance \( L_{t} \) is given by

\[
L_{t} = \frac{(T - T_{o})^{2}}{n^{2}C_{r}} - L_{r}.
\]

For practical circuits, its value is better to set to be about twice of the minimum value.

The values obtained from the designing method and minimum and maximum frequencies obtained from experiments and state space analysis are shown in Table 3, from which it is possible to confirm that this designing method is useful on case of early step of designing the converter, although the frequencies are slightly different from rating frequencies.

### 6. Conclusions

From discussions stated above, the following results are obtained.

1. To improve undesirable performances of conventional type, we have proposed the new full resonant ZCS forward converter having a series resonant circuit putting in parallel with the transformer and presented its operation modes and operation stages by theoretical analysis. As the results, it is cleared that the converter acts on ZCS and the output is given by Eq. 6.

2. From the observation of the ZCS domain, the variation of amplitude of resonant current and operating wave forms, the following performances are confirmed;
   a) the converter has a small amplitude variation, which increases gradually as the output current increases, and get the same maximum output current of conventional one in spite of using small amplitude of resonant current,
   b) due to this property, the ZCS domain is considerably wider than conventional one,
   c) the converter get ZC-ZVS action at critical ZCS. (3) From verifying the operational performance, it is confirmed that the proposed converter has high efficiency and small conduction loss at light loads and the withstanding performance for practical use

### Table 3 Estimation of designing method

<table>
<thead>
<tr>
<th>Designed Values</th>
<th>Theoretical</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n )</td>
<td>0.273</td>
<td>0.272</td>
</tr>
<tr>
<td>( L )</td>
<td>40.6\mu H</td>
<td>40.6\mu H</td>
</tr>
<tr>
<td>( C )</td>
<td>3.08nF</td>
<td>3.08nF</td>
</tr>
<tr>
<td>( L_{2} )</td>
<td>1.00\mu H</td>
<td>1.00\mu H</td>
</tr>
<tr>
<td>( Z )</td>
<td>114.8 \Omega</td>
<td>114.8 \Omega</td>
</tr>
<tr>
<td>( L_{r} )</td>
<td>L_{\text{min}}=325\mu H</td>
<td>620\mu H</td>
</tr>
<tr>
<td>( f_{s} )</td>
<td>450kHz</td>
<td>450kHz</td>
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<tr>
<td>( f_{\text{max}} )</td>
<td>180kHz</td>
<td>184kHz</td>
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<tr>
<td>( f_{\text{max}} )</td>
<td>260kHz</td>
<td>260kHz</td>
</tr>
</tbody>
</table>

The maximum and minimum output currents are attained at \( f_{\text{max}} \) and \( f_{\text{min}} \), respectively and ZCS action is accomplished.
converter is applicable for practical power supplies and has possibilities realizing low noise, high frequency operation and then miniaturization.

Acknowledgement

The authors wish to acknowledge Mr. Kouzou Ogita of Shihen Technical Corp., the persons concerned in this study of Ehime Univ. for argument and trial support, and the reviewers who read the manuscript critically and made valuable suggestions.

(Manuscript received Sep. 22, 1994, revised Feb. 6, 1995)

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