An Open-Loop Start-up Method for LLC Resonant Converter with Fixed Frequency and Variable Duty Cycle

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Abstract. An open-loop start-up method with fixed frequency and variable duty cycle for LLC resonant converter is proposed in this paper. The start-up method adopts pulse width modulation (PWM) technology to control LLC resonant converter with fixed switching frequency and variable duty cycle. Compared with conventional start-up method that uses a relative high switching frequency to start-up the converter with closed control loop, the proposed start-up method can reduce the start-up frequency, then the switching loss and driving loss during the start-up process can be reduced. Moreover, the proposed method can fast start-up the converter with low device’s electrical stress. Because high start-up frequency is no need for the proposed start-up method, then the hardware cost of driving chip can be decreased. The theory and the logic of the proposed start-up method is detailed analysed in this paper. The correctness and effectiveness of the proposed start-up method are verified by the built simulation results.

1. Introduction

The advantages of wide soft-switching range [1,2], high power-density [3,4], and high efficiency [5,6] help LLC resonant converter to have wide use in many industrial applications, for example, power supply [7,8], onboard charger [9,10], and computer adapter [11,12], and so on. Before entering the steady working state, LLC resonant converter has a start-up process. LLC resonant converter is generally controlled by pulse frequency modulation (PFM) technology to regulate the output voltage, and a relative high start-up frequency is used to provide high start-up input impedance for decreasing the impulse current during the start-up process, which leads the controlling chip to high cost due to it must operate at short clock period and high clock switching.

Meanwhile, high start-up leads high driving loss and switching loss, and the heatsink needs optimal design to avoid heat breakdown. Moreover, conventional reducing frequency start-up method needs to adjust the switching frequency, which leads to a long start-up time and a slow start-up speed, and causes the devices’ electrical stress impulse that exceeds the normal operating stress.

To solve the above problem, an open-loop start-up method for LLC resonant converter is proposed in this work. The proposed method uses a fixed frequency with variable duty cycle to start-up LLC resonant converter. The start-up frequency is fixed and needs no frequency regulation, then the start-up frequency can be equal to the normal operating frequency, and the clock period of the controlling chip can be longer compared with traditional start-up method. Moreover, the proposed open loop start-up method has faster start-up speed, lower driving loss, and lower devices’ electrical stress compared with conventional start-up method with variable frequency.
2. Characteristics of start-up method

2.1 Topology of FB LLC resonant converter

Fig.1 presents the topology of full-bridge (FB) LLC resonant converter. $U_{in}$ is the input voltage, $u_o$ is the output voltage, $Q_1$~$Q_4$ are the power devices on the primary side, $s_1$~$s_4$ are the triggering signals of $Q_1$~$Q_4$, $L_r$ and $C_r$ are the resonant inductor and resonant capacitor, respectively.

![Figure 1](image1)

Figure 1. Topology of full-bridge LLC resonant converter.

$T$ is the transformer, $L_m$ is the magnetizing inductor of $T$, the transformer’s turn ratio is $n_T=n_p/n_s$, $n_p$ and $n_s$ are the primary-side turn number and secondary-side turn number, respectively. $i_r$ and $i_m$ are the resonant current and the magnetizing, respectively. $D_1$~$D_4$ are the diodes on the secondary side, $C_o$ is the output filtering capacitor, $R_o$ is the load resistor.

2.2 Input impedance analyses

Fundamental harmonic approximation (FHA) is used to analyse the characteristic of FB LLC resonant converter. The ac equivalent circuit of FB LLC resonant converter is depicted in Fig.2, $u_{ab}$ is the square wave on the primary side, $R_{eq}$ is the reflected ac resistor of $R_o$, $R_{eq}$ can be expressed as

$$R_{eq} = \frac{8n_s^2R_o}{\pi^2} = \frac{8n_s^2P_o}{\pi U_o^2}$$  \hspace{1cm} (1)

where $R_o=U_o^2/P_o$, $P_o$ is the output power of the converter.

![Figure 2](image2)

Figure 2. Ac equivalent circuit of FB LLC resonant converter.

The input impedance of FB LLC resonant converter is

$$z_m(\omega_s) = \frac{1}{j\omega C_r} + \frac{j\omega L_m R_{eq}}{j\omega L_m + R_{eq}}$$ \hspace{1cm} (2)

$$\omega_s = 2\pi f_s$$ \hspace{1cm} (3)

where $z_m(\omega_s)$ is the angular frequency, $f_s$ is the switching frequency.

During the start-up process, $U_o$ is close to 0V, then it can be seen that the load is open from the converter, and $R_o=\infty$, then the input impedance can be approximately expressed as
\[ z_{\text{in, start}}(\omega) = \left| j\omega L_c + \frac{1}{j\omega C_r} + j\omega L_m \right| \]  \hspace{1cm} (4)

For conventional start-up method, at \( t=0s \), a high start-up frequency \( f_{\text{start}} \) is set, and \( f_{\text{start}} \) is relative higher than the resonant frequency \( f_r \), namely, the condition \( f_{\text{start}} > f_r \) should be satisfied. The resonant frequency \( f_r \) is

\[ f_r = \frac{1}{2\pi \sqrt{L_c C_r}} \]  \hspace{1cm} (5)

The circulating current at \( t=0s \) is

\[ i_{\text{start}} = \frac{\sqrt{2}U_{\text{in}}}{z_{\text{in, start}}(\omega_{\text{start}})} \]  \hspace{1cm} (6)

Fig.3 shows the curve of relationship between \( f_{\text{start}} \) and \( z_{\text{in, start}} \), it can be seen that \( z_{\text{in, start}} \) increases as the increase of \( f_{\text{start}} \), that is to say, in order to obtain high input impedance in the start-up process, the start-up frequency should be set as a higher value.

Fig.4 shows the curve of relationship between \( i_{\text{start}} \) and \( f_{\text{start}} \), \( i_{\text{start}} \) decreases as the increase of \( f_{\text{start}} \), which means that higher \( f_{\text{start}} \) is useful to reduce the impulse of start-up current. As Fig.4 shows, if \( f_{\text{start}} \) is set as 100kHz, this value is even higher than \( f_r \approx 92 \text{kHz} \), the impulse of start-up current is higher than 100A, which is too high for the current handling ability of power devices on the primary side.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig3.png}
\caption{Curves of relationship between \( z_{\text{in, start}} \) and \( f_{\text{start}} \) for \( n_T=1 \), \( U_{\text{in}}=400V \), \( u_o=400V \), \( L_r=40\mu \text{H} \), \( L_m=320\mu \text{H} \), \( C_r=75\text{nF} \).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig4.png}
\caption{Curves of relationship between \( i_{\text{start}} \) and \( f_{\text{start}} \) for \( U_{\text{in}}=400V \), \( n_T=1 \), \( u_o=400V \), \( L_r=40\mu \text{H} \), \( L_m=320\mu \text{H} \), \( C_r=75\text{nF} \).}
\end{figure}

To reduce start-up current, a relative high value is set to \( f_{\text{start}} \), for example, as shown in Fig.4, if \( f_{\text{start}} \) is set as 300kHz, \( i_{\text{start}} \) is almost 8.25A, if lower \( i_{\text{start}} \) is needed, higher \( f_{\text{start}} \) should be set. Furthermore, if \( f_{\text{start}} \) is set as 500kHz, the value of \( i_{\text{start}} \) can be reduced to 4.66A.

From the above analyses, a conclusion can be easily obtained, that is, conventional start-up method needs a very high start-up frequency to increase the input impedance to reduce the impulse of the start-up current. However, if start-up frequency is too high, the driving loss and the switching loss will be increased, and the hardware cost of driving chip are also increased.

2.3 Variable duty cycle and fix frequency start-up method

The operational principle of the proposed start-up method is shown in Fig.5.
To solve the problem that conventional start-up method needs a relative high start-up frequency, which leads high switching loss, driving loss and increased hardware cost of driving chip to LLC resonant converter, an open loop start-up method with fixed frequency and variable duty cycle is proposed.

The waveform of $s_1$ is the same as the waveform of $s_4$, the waveform of $i_2$ is the same as the waveform of $s_3$. There is a phase difference between $s_1$ and $s_2$. At the same switching period, $s_1$~$s_4$ has the same duty cycle, and the duty cycle $d$ is 0 at $t=0s$, as time goes on, the duty cycle gradually increases from 0 to 0.5. The frequency during the start-up process is fixed at the normal switching frequency $f_{s,nor}$. When the start-up process finished, the duty cycle is fixed at 0.5, and the frequency is fixed at $f_{s,nor}$.

3. Simulations and verifications

To verify the correctness and the effectiveness of the proposed open loop start-up method, a simulation model is built.

Fig.6 presents the simulation model of FB LLC resonant converter and the open loop control diagram. ESR is the equivalent series resistor of the circuit. The MOSFETs are anti-parallelled by diodes. The simulation condition are as follows: $U_{in}=400V$, $ESR=1m\Omega$, $C_1=72nF$, $L_r=41\mu H$, $L_m=160\mu H$, $n_T=32:32$, $C_o=5\mu F$, $f_{start}=f_r=92kHz$. The normal output power $P_o$ is set as 2kW. At the full load state, $R_o=160\Omega$, at the half load state, $R_o=320\Omega$.

Fig.7 shows the simulation results of $d$, $U_o$ and $i_r$ at none load state. At $t=0s$, $d=0$ $U_{in}=0V$, and $i_r=0A$. As time goes on, $d$ is gradually increasing from 0 to 0.5, and $U_o$ is gradually increasing from 0V to 415V, the output voltage at stable state with none load is higher than the normal output voltage 400V. However, none load state is not common for the actual applications, and the 15V overvoltage can be acceptable for many industrial applications.
From Fig.7, it can be seen that the resonant current $i_r$ has a fluctuation during $0s \leq t \leq 10ms$, but the resonant peak current during this fluctuation is still much lower than the resonant current peak at the stable state. Moreover, $U_o$ and $i_r$ only use about 10ms to reach their stable state, which means that the proposed open loop start-up has a rapid start-up speed, and this characteristic is useful for the application where fast startup is needed.

Fig.8 shows the waveforms of $U_o$, $i_r$ and $d$ with half load state. As shown in Fig.8, at half load state, the start-up time is about 30 ms, which is longer than the start-up time in Fig.7. The start-up process as shown in Fig.8 is more smoothly than that in Fig.7, and there is no fluctuation for resonant current. At half-load state, the time of $d$ increasing from 0 to 0.5 is 50ms, which is also longer than that in Fig.7, which means that shorter time of duty cycle increasing from 0 to 0.5 is useful the start-up speed, but not helpful for the smoothness of the start-up process. $U_o$ at half load state is equal to $400V$, which is equal to $U_{in}/n_T$.

Fig.9 presents the simulation waveforms of $d$, $U_{in}$ and $i_r$ at with full-load condition, the time of $d$ increasing from 0 to 0.5 is 50ms, and the time of the converter from $t=0s$ to the steady state is about 33ms, which is longer than that in Fig.8, this simulation results verify that heavier load state leads longer start-up time to the converter.
As Fig. 9 shows, there is a fluctuation for resonant current during the start-up of the converter, at \( t=21\text{ms} \), the peak value of \( i_r \) is about 8.0A, which is little higher than the peak value of \( i_r \) at the full load steady state, the peak value at steady state is about 7.8A, this means that the overcurrent is only 0.2A and acceptable. Compared with the waveforms of \( U_o \) in Fig.7 and Fig.8, the waveform of \( U_o \) in Fig.9 is more smoothly.

Table I shows the comparisons of the start-up characteristics of FB LLC converter at different load states using the proposed open loop control method. The start-up time at none load state is the shortest among the three loads states in Table I. At none or full load states, \( i_r \) has some fluctuations, but the fluctuations are no harm or little harm to the power devices on the primary side. At full load state, the smoothness of the output voltage in the start-up process is the best.

Because the proposed open loop method uses fixed frequency to startup LLC resonant converter, and the fixed frequency can be set as a relative lower value compared with the conventional method using a very high start-up frequency, then the switching loss and the driving loss of the proposed start-up method can be reduced, moreover. Because a relative high start-up frequency is no longer needed for the proposed start-up method, then the hardware requirement of controlling chip and driving chip can be reduced.

### Table 1. Characteristics for different load states.

| Items       | None load | Half load | Full load |
|-------------|-----------|-----------|-----------|
| Start-up time | 26 ms     | 30 ms     | 33 ms     |
| Impulse of \( i_r \) | None     | None     | None     |
| Impulse of \( U_o \) | None     | None     | None     |

4. Conclusions
An open loop start-up method with variable duty cycle and fixed frequency is proposed and used for LLC resonant converter. The basic operation and characteristics of the proposed start-up method is detailed analysed and verified by the built simulation model. The proposed start-up method can be used to reduce the switching loss and the driving loss of LLC resonant converter during the start-up, moreover, the hardware requirements of driving chip and controlling chip can be also reduced with using the proposed open loop start-up method.

5. References
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Acknowledgments
This work is supported by National Key Research and Development Program of China (2017YFE0132100) and Natural Science Foundation of Ningxia (2020AAC03483).