An Electrical Isolated DC Power Supply with Two Ports Based on LLC Resonant Converter

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Abstract. A modified LLC resonant converter is proposed for isolated dc power supply where two ports are needed. The converter can supply different dc voltages for two isolated loads, and the resonant parameters of two LLC channels can be designed as different. The topology of the proposed LLC resonant converter is introduced, the voltage gain is detailed discussed. A simulation model is built to verify the correctness of the proposed LLC resonant converter’s theory. The simulation results verify that the converter can supply two different dc voltages, and the voltages can keep steady even the load states are changed suddenly.

1. Introduction

Due to merits of soft-switching [1,2], high power-density and high efficiency [3,4,5], LLC resonant converter are widely used in many industrial applications, such as onboard charger (OBC) [6], power supply [7], and photovoltaic system [8]. For power supply, it is often to use one circuit to provide two or more ports for loads. However, conventional half-bridge (HB) LLC resonant converter and full-bridge (FB) LLC resonant converter cannot supply two-ports for isolated loads at the same time.

In this paper, a modified LLC resonant converter is proposed for two output ports applications. The modified LLC resonant converter has two LLC channels, each LLC channel can supply power for an independent load with electrical isolation between the primary-side and the secondary-side. The power devices on the primary side can realize zero-voltage switching (ZVS). The diodes on the secondary side are zero-current switching (ZCS). Compared with traditional half-bridge LLC converter, the power devices of the proposed modified LLC converter have better utilization during the whole switching period.

2. Characteristics of modified LLC converter

2.1 Topology of modified LLC converter

The diagram schematic of the modified LLC resonant converter is shown in Fig.1, Uin is input voltage source, Q1 and Q2 are the high-frequency controlled power devices on the primary side, s1 and s2 are the trigger signals of Q1 and Q2, respectively. L₁, C₁ and T₁ are the resonant inductor, the resonant capacitor, and the transformer in the first LLC channel, respectively. L_{m1} is the magnetizing inductor of T₁, L₂, C₂ and T₂ are the resonant inductor, the resonant capacitor, and the transformer in the second LLC channel, respectively. L_{m2} is the...
magnetizing inductor of $T_2$. $D_1$, $D_2$, $D_3$ and $D_4$ are the diodes on the secondary side, respectively. $C_{o1}$ and $C_{o2}$ are the output filtering capacitors of the first and second LLC channels, respectively. $R_1$ and $R_2$ are the load resistors of two LLC channels. $i_{r1}$ and $i_{r2}$ are the resonant currents flowing through the first and the second LLC channels, respectively. $i_{m1}$ and $i_{m2}$ are the magnetizing currents of $T_1$ and $T_2$, respectively. $u_{o1}$ and $u_{o2}$ are the output voltages of two LLC channels, respectively.

**Figure 1.** Diagram schematic of modified LLC resonant converter.

### 2.2 Output voltages of two LLC channels

Based on fundamental harmonics approximation (FHA) method, the output voltage of two LLC channels can be easily obtained and expressed as [9,10,11,12]:

$$u_{o1}(f_s) = U_{in}G_1(f_s)$$  \hspace{1cm} (1)  \\
$$u_{o2}(f_s) = U_{in}G_2(f_s)$$  \hspace{1cm} (2)

$$G_i(f_s) = \frac{1}{2\sqrt{1 + \frac{1}{k_i} - \frac{1}{k_i f_{o1}^2}}} + q_i \left(f_{s,i} - \frac{1}{f_{s,i}}\right)$$  \hspace{1cm} (3)

$$k_i = \frac{L_{m1}}{L_{r1}}$$  \hspace{1cm} (4)

$$q_i = \sqrt{\frac{L_{r1}/C_{r1}}{R_{eq1}}}$$  \hspace{1cm} (5)

$$R_{eq1} = \frac{8\eta_1^2 R_1}{\pi^2}$$  \hspace{1cm} (6)

$$f_{s,i} = \frac{f_s}{f_{r,LLC1}}$$  \hspace{1cm} (7)

$$f_{r,LLC1} = \frac{1}{2\pi\sqrt{L_{r1}C_{r1}}}$$  \hspace{1cm} (8)
\[ G_2(f_s) = \frac{1}{2 \left( 1 + \frac{1}{k_1} - \frac{1}{k_2 f_{s,1}} \right) + q_1 \left( f_{s,1} - \frac{1}{f_{s,2}} \right)} \]  

(9)

\[ k_2 = \frac{L_{m2}}{L_{r2}} \]  

(10)

\[ q_2 = \frac{\sqrt{L_{r2} / C_{r2}}}{R_{eq2}} \]  

(11)

\[ R_{eq2} = \frac{8 n_{f2}^2 R_1}{\pi^2} \]  

(12)

\[ f_{n,2} = \frac{f_s}{f_{r,LLC2}} \]  

(13)

\[ f_{r,LLC2} = \frac{1}{2 \pi \sqrt{L_{r2} / C_{r2}}} \]  

(14)

where \( G_1(f_s) \) is the voltage gain of the first LLC channel, \( G_2(f_s) \) is the voltage gain of the second LLC channel, \( f_s \) is switching frequency. \( k_1 \) is the ratio of \( L_{m1} \) to \( L_{r2} \), \( k_2 \) is the ratio of \( L_{m2} \) to \( L_{r2} \), \( q_1 \) is the quality factor of the first LLC channel, \( q_2 \) is the quality factor of the second LLC channel, \( R_{eq1} \) is the ac equivalent resistor of the first LLC channel, \( R_{eq2} \) is the ac equivalent of the second LLC channel, \( f_{n,1} \) is the normalized frequency of the first LLC channel, \( f_s \) is the switching frequency, \( f_{r,LLC1} \) is the resonant frequency of the first LLC channel, \( f_{n,LLC2} \) is the normalized frequency of the second LLC channel.

The switching frequency of two LLC channels are the same, and the output voltage of two LLC channels can be designed from the perspective of the turn ratio of two transformers and the resonant parameters of two LLC channels.

### 2.3 Design Case

In this paper, one case for the application of the converter is shown in Tab. I. The output voltage of the first LLC channel is \( u_{o1}=12V \), and the output power of the first LLC channel is 20W. The output voltage of the second LLC channel is \( u_{o2}=24V \), and the output power of the second LLC channel is \( P_{o2}=30W \).

**Table 1.** Electrical requirements of design case.

| Parameters   | Values | Parameters   | Values |
|--------------|--------|--------------|--------|
| \( u_{o1} \) | 12V    | \( u_{o2} \) | 24V    |
| \( P_{o1} \) | 20W    | \( P_{o2} \) | 30W    |

The transformer’s turn ratio of the first channel is

\[ n_{r1} = \frac{U_{in}}{2u_{o1}} = \frac{400V}{2 \times 12V} = 50:3:3 \]  

(15)

The transformer’s turn ratio of the second channel is
\[ n_{T2} = \frac{U_{in}}{2\mu_{s2}} = \frac{400V}{2 \times 24V} = 25:3:3 \] (16)

Because the powers of two LLC channels are not balanced, then transformers’ turn ratio should be adjusted to regulate the output voltage. In this paper, the turn ratio of transformer \( T_1 \) is adjusted from 50:3:3 to 48:3:3.

Because the switching frequency of \( Q_1 \) is the same as the switching frequency of \( Q_2 \), and the input voltage \( U_{in} \) is a constant, in order to supply a constant output voltage for the first LLC channel, the first LLC channel is designed to work at a fixed frequency \( f_{s1} \), for the same reason, to obtain a constant output voltage for the second LLC channel, the second LLC channel is also designed to work at \( f_{s2} \), therefore, the resonant frequency \( f_{r1} \) should be equal to the resonant frequency \( f_{r2} \), namely, \( f_{r1}=f_{r2} \). To ensure that \( f_{r1}=f_{r2} \) can be satisfied, the following equation should be satisfied.

\[ f_{r1} = f_{r2} = f_r \Rightarrow \frac{1}{2\pi\sqrt{L_{r1}C_{r1}}} = \frac{1}{2\pi\sqrt{L_{r2}C_{r2}}} \] (17)

Form equation (17), the following equation can be easily obtained.

\[ L_{r1}C_{r1}=L_{r2}C_{r2} \Rightarrow \frac{L_{r1}}{L_{r2}} = \frac{C_{r2}}{C_{r1}} \] (18)

The resonant frequency \( f_r \) is set as 200kHz, and \( L_{r1} \) is set as 4\( \mu \)H, namely, \( L_{r1}=4\mu H \). The resonant capacitor \( C_{r1} \) is

\[ C_{r1} = \frac{1}{4\pi^2 L_{r1}f_r^2} = \frac{1}{4\pi^2 \times 4\mu H \times (200kHz)^2} \approx 158nF \] (19)

\( k_1 \) is set as 5, and \( L_{m2}=20\mu H \). \( L_{m2} \) is also set as 4\( \mu \)H, namely, from the equation (18), \( C_{r2} \) can be figured out.

\[ C_{r2} = C_{r1} = 158nF \] (20)

\( k_2 \) is equal to \( k_1 \), then \( L_{m2} \) can be figured out.

\[ L_{m2} = k_2 L_{r2} = k_1 L_{r2} = 5 \times 4\mu H = 20\mu H \] (21)

\( R_1 \) and \( R_2 \) can be calculated and they are

\[ R_1 = \frac{u_{o1}^2}{P_{o1}} = \frac{(12V)^2}{20W} = 7.2\Omega \] (22)

\[ R_2 = \frac{u_{o2}^2}{P_{o2}} = \frac{(24V)^2}{30W} = 19.2\Omega \] (23)

3. Simulation and verification

To verify the theory of the modified LLC converter is correctness, a simulation model of the modified LLC resonant converter is built. Fig.2 gives the model’s diagram. Each transformer has three windings, including one primary-side winding and two secondary-side windings, the secondary-side windings have the same turn numbers.
The control diagram of the modified LLC resonant converter is given in Fig. 3, only $u_{o1}$ is added into the control loop, and the second LLC channel is open. The difference between of $u_{o1}$ and $U_{o,ref}$ is the input of PI controller, $U_{o,ref}$ is the reference of $u_{o1}$. VCO represents voltage-controlled oscillator, the dead time of $s_1$ and $s_2$ are the same, and the dead time is set as 100ns.

Fig. 4 shows the simulation results of $u_{o1}$ and $u_{o2}$ during the start-up process at the normal load state. At steady state, $u_{o1}$ and $u_{o2}$ are 12V and 24V, respectively. This means that the converter has ability to supply steady voltages for two independent loads with electrical isolation by two LLC channels.

Fig. 5 shows the simulation waveforms of $i_{r1}$ and $i_{r2}$ at the normal load state for steady state case. The frequencies of two resonant currents are the same, and the peak values of two resonant currents are also almost equal, this characteristic is good for the selections of power devices, because the same power devices can be used for each channel, which is good for the reduction of hardware cost.
Figure 5. Simulation waveforms of $i_{r1}$ and $i_{r2}$ at normal load state and steady state.

Fig.6 depicts the simulation waveforms of $u_{o1}$ and $u_{o2}$ when the load percentage decreases from 100% to 70%. In this case, $u_{o1}$ and $u_{o2}$ still keep balanced states, which means that the converter has good dynamic regulation ability. When 100% load percentage is set, the voltage ripples of two channels are about 0.1V. When 70% load percentage is set, the voltage ripples of two output ports are about 0.5V. If the load percentage is smaller, the output voltages’ ripple will be lower. Larger capacitors at the output ports can be also used to reduce the output voltages’ ripple.

Figure 6. Simulation waveforms of $u_{o1}$ and $u_{o2}$ when load factor decreases from 100% to 70%.

When the first LLC channel’s load is open, the second LLC channel can also work normally. Fig.7 shows the simulation waveforms of $u_{o1}$ and $u_{o2}$ when the first LLC channel’s load is open. $u_{o2}$ is about 24V, which is the same as the value of $u_{o2}$ at the normal load state, however, $u_{o1}$ is about 24V, which is higher than the value of $u_{o1}$ at the normal load state, the reason for this can be explained as follows, because the load of the upper channel is open, and the load resistor is equal to infinite, then the quality factor of the first LLC channels is equal to zero, and the voltage gain of the first LLC channel is increased, then $u_{o1}$ is higher than that at the normal load state.
Based on the above simulation results, a conclusion can be drawn, to ensure that the converter’s secondary-side diode can safely work, the voltage stress of the secondary-side diode should be doubled compared with its normal voltage stress. To reduce secondary-side diodes’ voltage stress and keep the output voltage steady, another method can be used, that is, paralleling an extra load resistor at the output port of the first LLC channel. Fig.8 presents the simulation waveforms of \( u_{o1} \) and \( u_{o2} \) when an extra resistor is paralleled with the output port of the first LLC channel. Without paralleled extra resistor, the output voltage of the first LLC channel is about 24V, this voltage is almost twice its needed value, which not satisfies the requirement. However, if an extra resistor is paralleled, the output voltage of the first LLC channel is reduced from about 24V to 12V, and the output voltage can satisfy the voltage requirement. This means that paralleled extra resistor is helpful to keep the output voltage at its required value. The extra resistor can be selected as a high value to reduce the power loss when the first LLC channel, especially at no load state.

4. Conclusions
A modified LLC resonant converter with two LLC channels is proposed for the applications where two electrical isolated dc ports are needed. The operational principle of the proposed converter is detailed discussed. A design case is used to verify the correctness of the proposed converter by the established simulation. In the future study, the experimental prototype will be developed based on the parameters of the design case in this paper.
5. References
[1] Y. Li, S. Shao, H. Chen, et al., CPSS Trans. Power Electro. App., 5, 63-73 (2020).
[2] J. Zeng, G. Zhang, S. S. Yu, et al., CNS J. Electri. Eng., 6, 73-84 (2020).
[3] A. Kumar, A. Awasthi, O. Salari, et al., APEC, 17-21 (2019).
[4] B.-C. Kim, K.-B. Park, C.-E. Kim, et al., IEEE Trans. Ind. Electro., 25, 2248-2252 (2010).
[5] A. Elrayyah. ECCE, 11-15 (2020).
[6] C. Shi, H. Wang, S. Dusmez, et al., IEEE Trans. Ind. App., 53, 501-511 (2017).
[7] M.-H. Park, Y. Jeong, D.-K. Kim, et al., ECCE, (2019).
[8] Y. Zhuang, F. Liu, X. Zhang, et al., ECCE, (2019).
[9] Y.-K. Tran, F. D. Freijedo, D. Dujic. CPSS Trans. Power Electro. App., 4, 171-179 (2019).
[10] I.-O. Lee, G.-W. Moon. IEEE Trans. Power Electron., 29, 13-16 (2014).
[11] X. Tan, X. Ruan. IEEE Trans. Ind. Electro., 63, 2112-2123 (2016).
[12] J. Deng, S. Li, S. Hu, et al., IEEE Trans. Veh. Tech., 63, 1581-1592 (2014).

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