A Novel Secondary Side Series LCD Forward Converter with High Efficiency and Magnetic Reset

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Abstract: A novel secondary side series LCD forward converter with a high efficiency and a magnetic reset is proposed in this paper. Compared with the traditional forward converter, the proposed converter can transfer excitation energy to the output terminal and achieve a reliable magnetic reset of the transformer with a better working efficiency. Moreover, the proposed converter realizes the low-voltage turn-on of the switch. The operating principle and energy transmission process of the proposed converter is explicitly analyzed. It was concluded that the optimal combined working mode was $L_m$-DCM, $L_1$-CCM and $L_2$-CCM. By analyzing the energy transmission mechanism of the proposed converter in the best working mode, the parameter design scheme of the proposed converter was obtained. Finally, a prototype was built. The simulation and experimental results are presented to verify the correctness of the theoretical analysis and the feasibility of the parameter design scheme of the proposed converter. At the same time, a comparison between the proposed converter and existing converters was conducted to demonstrate the best electrical performance of the proposed converter.

Keywords: secondary magnetic reset; excitation inductance; the optimal operating mode; energy transmission

1. Introduction

Power converters are widely used in various instruments and electrical and electronic equipment. Currently, converters have a trend towards higher efficiency, higher power density, and higher reliability [1–5]. Depending on the circuit structure, the power converter can be divided into a non-isolation or an isolation structure. In common power supply systems, an isolation converter is usually selected. An important part of an isolated converter, the magnetic element can store energy and realize the input–output isolation, which is an essential factor affecting the electrical performance of the converter [6,7]. Common isolated converter topologies mainly include a forward converter and a flyback converter. However, the output power of the flyback converter is greatly limited and its efficiency is not high, so it is mostly used in low-power applications [8,9]. Compared to a flyback converter, the power of a forward converter is not limited by the energy storage capacity of the transformer. It exhibits a high working reliability and a relatively simple structure, and has been widely used in small and medium power fields.

Although forward converters have many advantages, there are still many problems that still need to be solved. The forward converter has no magnetic reset function, and hence, it is likely to cause magnetic core saturation and other problems [10]. Magnetic saturation causes the current flowing through the switch to increase sharply, which greatly limits the promotion of the forward converter. Therefore, it is necessary to consider adding specific magnetic reset circuits to avoid magnetic saturation. In order to further promote the application of the forward converter, it is necessary to solve the problem of magnetic reset
and improve the energy utilization rate. Therefore, it is essential to study new magnetic reset methods.

To solve the problem of magnetic reset, an auxiliary winding reset mode was studied in [11], which returned energy to the input terminal. However, its additional auxiliary windings complicated the structure and design of the transformer and had a small duty cycle range. The switch was required to withstand higher voltages, making it difficult to achieve a large power output. In [12–17], a primary-side RCD magnetic reset mode was studied. The reset mode comprised a simple structure and the range of the duty ratio was greater than 0.5. However, the voltage stress of the switch was large and most of the energy was consumed on the clamping resistor, reducing the efficiency and increasing the difficulty of the heat dissipation design. In [18,19], an active clamp reset circuit was proposed. The advantage of this reset circuit was that it achieved the soft switching of the main and auxiliary switches, thus reducing circuit losses. However, its driving circuit was complex, and when the duty cycle was greater than 0.5, the voltage stress of the switch exceeded twice the input voltage. The reset circuits of the forward converter were located at the primary side of the transformer, and the excitation energy stored in the transformer during the conduction of the switch was either fed back to the input terminal or consumed. This part of the excitation energy was not fully utilized, which did not improve the efficiency of the converter. Based on the above mentioned research, it was necessary to continuously improve the reset mode. The new reset method considers placing the reset circuit on the secondary side of the transformer to improve the energy utilization rate and achieve the goal of continuously optimizing the performance of the forward converter. In [20,21], a four-diode forward-flyback converter was proposed, which realized the transfer of the excitation energy to the load and improved the conversion efficiency of the transformer. However, four diodes were used in the circuit, which increased the cost and circuit loss of the converter. Within the entire dynamic range, the forward inductor only operated in a DCM, which was not suitable for a high power output. In [22], a full-bridge rectifier forward converter with a capacitor on the secondary side was proposed, which solved the issue where the inductor in a four-diode structure was unable to work in a continuous conduction mode. However, compared to the traditional forward converter, this topology increased the circuit loss and the voltage stress of the switch was significant, which was not conducive to the selection of the switch. In [23], a resonant forward reset topology with an auxiliary switch on the secondary side was developed, which reduced the losses of the switches and diodes. However, this topology used two switches, increasing the complexity of the control drive circuit. The secondary reset mode transmitted the excitation energy to the load, but there were still some problems, such as complicated circuit structure, the low output power of the converter, and the high voltage stress of the switch. Therefore, it is of great guiding significance to propose a forward converter that can not only ensure the reliable reset of the magnetic core but also improve the electrical performance.

Based on forward converters that are unable to be magnetically reset, this paper proposes a new type of secondary side series LCD forward converter by studying the magnetic reset technology of secondary winding. The operation mode of the proposed novel forward converter was deeply studied, the optimal operating mode of the proposed converter was obtained, and the energy transmission mechanism under the optimal working mode was analyzed. It was concluded that the proposed converter can not only transfer the excitation energy to the output terminal, achieve a reliable magnetic reset of the transformer, and improve the work efficiency, but also achieve a low-voltage conduction of the switch and reduce the switching loss. According to the influence of the component parameters on the electrical performance of the converter in the best working mode, the corresponding parameter design method was established. Finally, according to the proposed parameter design method, an experimental prototype of the proposed converter was developed, and its working characteristics, output ripple, and efficiency were tested. The experimental results verified the correctness and feasibility of the proposed secondary side reset method.
2. Circuit Composition and Energy Transmission Process of a Novel of Secondary Side Series LCD Forward Converter

2.1. Composition and Principle of a Circuit

The schematic diagram of a novel secondary side series LCD forward converter is shown in Figure 1. Its circuit structure adds an LCD excitation energy transfer path (composed of D3, D4, C2, and L2) to the secondary side of the traditional forward converter. The proposed converter consists of a power switch S, two inductors (forward inductor L1 and auxiliary inductor L2), two capacitors (an output filter capacitor C1 and an additional capacitor C2), four diodes (D1–D4), a transformer T (consists of magnetizing inductor Lm and primary and secondary windings W1 and W2), and one resistive load RL. The magnetizing current coupled to W2 charges C2 through D3. Then, the capacitor C2 exchanges energy with the inductor L2 and the excitation energy is stored in the inductor L2. Finally, the inductor L2 transfers energy to the load through D3, thus realizing the reliable magnetic reset of the transformer.

![Figure 1. Circuit diagram of the proposed converter.](image)

To simplify the analysis of the operating principle of the novel secondary side series LCD forward converter, the following assumptions were made:

1. The switch, diodes, inductors, and capacitors were considered to be ideal.
2. The transformer leakage inductance was minimal, and the energy loss caused by the leakage inductance was not considered.
3. The output voltage was assumed to be constant.

The magnetic reset circuit of the proposed converter can effectively transfer excitation energy to the load, improving the conversion efficiency of the converter. The working process was as follows.

During the switch-on period, the input voltage V1 was applied across the primary winding of the transformer. The energy was transferred to the load through the secondary winding of the transformer and iL1 increased linearly. At the same time, due to the conduction of D2, the capacitor C2 exchanged energy with the inductor L2. When the voltage across C2 dropped to zero and the switch S was still on, diode D4 was naturally turned on. Since diode D3 was not in conduction, the current flow through L2 was naturally turned off. The forward energy continued to be supplied to the load through D2 and L1, and iL1 continued to increase until S was turned off and the stage ended. At this stage, the zero-voltage natural conduction of diode D4 was realized.

During the switch-off period, D3 was forward biased and D4 was reverse biased. The excitation energy was released to the capacitor C2 via D3, the voltage across C2 gradually increased from the minimum value, and the excitation energy was delivered to the capacitor C2, thus realizing the reliable magnetic reset of the transformer core. Meanwhile, the inductor L1 transferred energy to the load through D1, and iL1 gradually decreased. Since diodes D1 and D2 were in on state, iL2 remained unchanged until iL1 decreased to be equal to iL2 and diode D1 was naturally turned off, thus realizing the zero-current turn-off of
D1. After that, if D3 still remained conductive, iL1 and iL2 continued to flow through D3 until the switch was turned on, iL1 and iL2 decreased to the minimum value, the voltage across C2 reached its maximum value, and the excitation current decreased to the minimum value. If the excitation current decreased to zero before the switch was turned on, all the excitation energy of the transformer was released to C2, and the voltage across C2 increased to the positive maximum value. Subsequently, the energy stored in the capacitor C2 was delivered to L2 and W2 through diode D1, and the currents flowing through inductor L2 increased. At the same time, the inductor L1 continued to supply energy to the load via D3 until iL2 increased to be equal to iL1 and the diode D1 was turned off. Then, C2, W2, L1, and L2 supplied energy to the load together. When the voltage across C2 decreased to lower than V0, the excitation inductor generated a voltage with the same polarity as the primary side and the proposed converter achieved a low-voltage turn-on of the switch.

2.2. Analysis of the Working Mode and Energy Transfer Process of the Converter

Depending on whether the excitation current decreases to zero during the switch-off period, the excitation inductance can be divided into a continuous conduction mode (CCM) and a discontinuous conduction mode (DCM). At the same time, according to the working principle of the converter, when iL2 and iL1 are equal, they will jointly supply energy to the load. Therefore, through the analysis of the working principle of the converter, the inductors L1 and L2 can only work in CCM or DCM at the same time. To realize a high power transmission, improve the energy transmission efficiency, and reduce the switching loss, it is necessary to choose the best working mode of the converter.

When Lm works in the CCM, the secondary winding transfers energy to the capacitor C2 through D3 during the switch-off period, and the voltage across C2 reaches the maximum value when the switch is turned on. Therefore, the voltage stress of the switch in this mode is much higher than the input voltage. When Lm operates in the DCM, the secondary winding W2 delivers energy to the capacitor C2 via diode D3 until the excitation current decreases to zero. The voltage across the capacitor C2 reaches the maximum value. After that, the capacitor C2 transfers energy to the load through L1, L2, and W2 until the voltage across C2 decreases lower than the output voltage. At this time, the voltage at both ends of the secondary winding W2 is changed to a positive direction voltage. Therefore, at the moment when the switch is turned on, the drain source of the switch is lower than the input voltage Vl and the proposed converter can achieve a low-voltage turn-on of the switch. Therefore, in order to reduce the switching loss, Lm was selected to work in the DCM. At the same time, in order to achieve a large energy transmission with the proposed converter, it was necessary to ensure that one of the inductors, L2 or L1, operates in the CCM. Since L1 and L2 can only work in the CCM or DCM simultaneously, L1 and L2 were selected to work in the CCM. Therefore, it was concluded that the optimal working mode of the proposed converter was Lm-DCM, L1-CCM, and L2-CCM.

The waveform of the proposed converter operating in the optimal operating mode is shown in Figure 2. As shown in Figure 2, the working process of the converter can be divided into six stages in one cycle. The energy transmission characteristics of each stage were specifically analyzed as follows.

Phase I [t0-t1]: At t0, the switch S was turned on, and the positive voltage across the secondary side, coupled from Vl through the transformer, was Vl/n. At this time, D2 was forward biased, while D3, D4, and D4 were reverse biased. L1 was magnetized from the voltage of the secondary winding W2 of the transformer and iL1 increased linearly from the minimum value with a slope of (Vl/n − Vl)/L1. Due to the conduction of D2, C2 and L2 resonated through D2, and the capacitor C2 transferred energy to the inductor L2 until the voltage across C2 decreased to zero.

Phase II [t1-t2]: At t2, after the voltage across C2 decreased to zero, diode D4 was naturally turned on as diode D2 continued to be turned on and iL2 remained unchanged. At the same time, the forward energy continued to be provided to the load and the inductor
Figure 2. Key waveforms of the proposed converter.

Phase I [t0~t1]: At t0, S was turned on, D3 was reverse biased, and D4 was forward biased. The secondary winding W2 delivered the excitation energy to the capacitor C2 and the voltage across C2 increased from zero. D4 conducted a freewheeling loop for L1 and its current iL1 was released to W2 via D3, and the current iL2 continued to decrease linearly until iL1 decreased to be equal to iL2. This mode ended at t1 when iL1 reached zero and the transformer core was reset.

Phase II [t1~t2]: At t1, L1 and C2 were connected in a continuous series to supply energy to the load through D3, and iL1 and iL2 decreased linearly. At the end of this mode, the currents flowing through inductors L1 and L2 were equal to the current flowing through C2.

Phase III [t2~t3]: At t2, S was turned off, D3 was forward biased, and D4 was reverse biased. The secondary winding W2 delivered the excitation energy to the capacitor C2 and the voltage across C2 increased from zero. D1 conducted a freewheeling loop for L1 and its current iL1 decreased linearly from the maximum value. D2 was reverse biased due to the conduction of D1 and D3, and iL1 continued to remain unchanged until iL1 decreased to be equal to iL2. This mode ended at t3 when iL1 reached zero and the transformer core was reset.

Phase IV [t3~t4]: At t3, D1 and D3 were connected in a continuous series to supply energy to the load through D3, and iL1 and iL2 decreased linearly. At the end of this mode, the currents flowing through inductors L1 and L2 were equal to the current flowing through C2.

Phase V [t4~t5]: At t4, L1 and L2 were connected in a continuous series to supply energy to the load through D3, and iL1 and iL2 decreased linearly. At the end of this mode, the currents flowing through inductors L1 and L2 were equal to the current flowing through C2.

Phase VI [t5~t6]: At t5, D3 was turned off, the energy stored in capacitor C2 was released to W2 via D3, and the current iL1 and iL2 gradually increased. During this mode, if the voltage across C2 equaled the output voltage V0 and the voltage polarity across the secondary side was changed to the positive direction, C2, L1, L2, and W2 delivered energy to the load simultaneously. At the end of this interval, the voltage stress on the power switch was lower than the input voltage V0; that is, the switch achieved a low-voltage turn-on.

3. Selection and Analysis of the Additional Capacitance Parameters When the Excitation Inductor Works in the DCM

During the switch-off period, the magnetizing current coupled to the secondary winding charged C2 through D3, and the voltage across C2 increased from zero. Its equivalent circuit is shown in Figure 3.
where the value to zero can be obtained as follows.

\[
W = \text{secondary winding}
\]

When the excitation current is decreased to the positive direction, \( W \) increased from zero. Its equivalent circuit is shown in Figure 3.

Figure 3. Equivalent circuit of the transformer excitation energy transfer during the switch-off period.

According to Figure 3, we can obtain the following equation.

\[
u_{C2}(t) - u_{W2}(t) = 0
\]

(1)

The currents flowing through the capacitor \( C_2 \) and the secondary excitation winding \( W_2 \) can be written as follows.

\[
i_{C2} = i_{W2} = C_2 \frac{d u_{C2}(t)}{dt}
\]

(2)

The voltage across the secondary side can be obtained from Equation (2).

\[
u_{W2}(t) = -L_{W2}C_2 \cdot \frac{d^2 u_{C2}(t)}{dt^2}
\]

(3)

Substituting Equation (3) into Equation (1), we can derive the following equation.

\[
u_{C2}(t) + L_{W2}C_2 \cdot \frac{d^2 u_{C2}(t)}{dt^2} = 0
\]

(4)

At the moment when the switch is turned off, the current flowing through the secondary winding \( W_2 \) is \( nI_{L,m,\text{max}}' \) and the voltage across \( C_2 \) is equal to zero. Therefore, the initial conditions of \( u_{C2}(0) = 0 \) and \( u_{C2}'(0) = nI_{L,m,\text{max}}'/C_2 \) can be obtained. According to these initial conditions, we can obtain the following by solving Equation (4).

\[
u_{C2}(t) = nI_{L,m,\text{max}}' \sqrt{\frac{L_{W2}}{C_2}} \cdot \sin\left(\frac{t}{\sqrt{L_{W2}C_2}}\right)
\]

(5)

where \( n = N_1/N_2 \) represents the turn ratio of the transformer.

By solving Equation (5), the current flowing through \( C_2 \) can be obtained as follows.

\[
i_{C2}(t) = nI_{L,m,\text{max}}' \cos\left(\frac{t}{\sqrt{L_{W2}C_2}}\right)
\]

(6)

From Equation (6), the time for the excitation current to decreased from the maximum value to zero can be obtained as follows.

\[
t_{Lm} = \frac{\pi \sqrt{L_{W2}C_2}}{2}
\]

(7)

When \( L_m \) works in the DCM, the magnetizing inductor current increases linearly from zero to the maximum value during the conduction of the switch. We can obtain the expressions for \( I_{L,m,\text{max}}' \) using the following equation.

\[
I_{L,m,\text{max}}' = \frac{V_i}{L_m} DT
\]

(8)
Here, $D$ represents the duty cycle.

Substituting Equations (7) and (8) into Equation (5), the maximum voltage across $C_2$ can be calculated using the following equation.

$$V_{C2,max}' = \frac{V_l DT}{\sqrt{L_m C_2}}$$

(9)

where $L_{W2} = L_m / n^2$ is the secondary side inductance.

According to Equation (9), the maximum voltage stress of the switch can be obtained using the following.

$$V_{ds-DCM} = V_i + nV_{C2, max}' = V_i + \frac{nV_l DT}{\sqrt{L_m C_2}}$$

(10)

To ensure that the excitation energy is completely transferred to the capacitor $C_2$ during the switch-off period, the time for the excitation current to decrease to zero should be less than the switch-off time $(1 - D)T$. Therefore, we can obtain the value using the following equation.

$$t_{Lm} \leq (1 - D)T$$

(11)

By substituting Equation (7) into Equation (11), the value range of the capacitor $C_2$ can be calculated using the following equation.

$$C_2 \leq \frac{4n^2 (1 - D)^2}{\pi^2 f^2 L_m}$$

(12)

4. Analysis of the Voltage Characteristics of the Switch and the Selection of the Forward Inductance Parameter

4.1. Analysis of the Turn-Off Characteristics of the Switch

During the switch-on period, $D_2$ was in on state, the inductor $L_2$ and the capacitor $C_2$ resonated in series, and the equivalent circuit is shown in Figure 4.

![Figure 4. Equivalent circuit of Series Resonance of the capacitor $C_2$ and the inductor $L_2$.](image)

According to Figure 4, we can obtain the following equation.

$$u_{C2}(t) + L_2 C_2 \cdot \frac{d^2 u_{C2}(t)}{dt^2} = 0$$

(13)

When the switch is turned on, the current through $C_2$ increases from $I_{L1,10}$ and the voltage across $C_2$ decreases from $V_{C2,0}$. Therefore, the initial conditions $u_{C2}(0) = V_{C2,0}$ and $u'_{C2}(0) = -\frac{I_{L1,10}}{C_2}$ can be obtained. According to these initial conditions, we can obtain the following by solving Equation (13).

$$u_{C2}(t) = V_{C2,0} \cdot \cos \left( \frac{t}{\sqrt{L_2 C_2}} \right) - I_{L1,10} \sqrt{\frac{L_2}{C_2}} \cdot \sin \left( \frac{t}{\sqrt{L_2 C_2}} \right)$$

(14)
Since \( I_{L1,10} \) is approximately zero at the moment when the switch is turned on, by solving Equation (14), the time for the voltage across \( C_2 \) drop to zero can be obtained using the following equation.

\[
l_m = \frac{\pi \sqrt{L_2 C_2}}{2}
\]  

(15)

To ensure that the switch is turned off at a lower voltage, the voltage across \( C_2 \) should be reduced to zero before the switch is turned off. Therefore, \( t_m \) should be less than the switch-on time \( dT \), which can be obtained using the following equation.

\[
\frac{\pi \sqrt{L_2 C_2}}{2} \leq dT
\]  

(16)

According to Equation (16), \( L_2 \) should satisfy the following.

\[
L_2 \leq \frac{4D^2}{\pi^2 f^2 C_2}
\]  

(17)

4.2. Analysis of the Switching Characteristics of the Switch

According to Equation (14), the current flow through the inductor \( L_2 \) can be derived using the following.

\[
i_{L2}(t) = -C_2 \frac{d(V_{C2}(t))}{dt} = I_{L1,10} \cdot \cos \left( \frac{t}{\sqrt{L_2 C_2}} \right) + \frac{V_{C2,10}}{\sqrt{L_2 C_2}} \cdot \sin \left( \frac{t}{\sqrt{L_2 C_2}} \right)
\]  

(18)

The inductor current of \( i_{L2,t1} \) at the switch-off time can be obtained using the following.

\[
i_{L2,t1} = I_{L1,10} \cdot \cos \left( \frac{t_m}{\sqrt{L_2 C_2}} \right) + \frac{V_{C2,10}}{\sqrt{L_2 C_2}} \cdot \sin \left( \frac{t_m}{\sqrt{L_2 C_2}} \right)
\]  

(19)

During the switch-on period, \( i_{L1} \) increases linearly from \( I_{L1,10} \), and reaches the maximum value at the switch-off time. The maximum current of inductor \( L_1 \) can be obtained using the following.

\[
I_{L1,max} = I_{L1,10} + \frac{V_1 - nV_o}{nL_1} \cdot DT
\]  

(20)

Due to the simultaneous conduction of diodes \( D_1 \) and \( D_3 \), the series branches of the inductor \( L_2 \) and diode \( D_4 \) are short-circuited, so \( i_{L2} \) remains unchanged during this process until \( i_{L1} \) decreases to be equal to \( i_{L2} \) and this process ends. In this process, the inductor \( L_1 \) supplies energy to the load through \( D_1 \), \( i_{L1} \) decreases linearly, and the expression of \( i_{L1} \) is shown in Equation (21).

\[
i_{L1}(t) = I_{L1,max} - \frac{V_o}{L_1} \cdot t
\]  

(21)

According to Equations (20) and (21), when \( i_{L1} \) decreases to be equal to \( i_{L2} \), the required time \( t_1 \) can be obtained using the following equation.

\[
t_1 = nL_1 (I_{L1,10} - I_{L2,t1}) + (V_1 - nV_o)DT
\]  

(22)

When \( i_{L1} \) drops to be equal to \( i_{L2} \), \( D_2 \) is naturally turned off. After that, \( L_1 \) and \( L_2 \) deliver energy to the load through diode \( D_3 \). The equivalent circuit is shown in Figure 5.

As shown in Figure 5, \( i_{L1} \) and \( i_{L2} \) decrease linearly from \( I_{L2,t1} \) until the charging voltage across \( C_2 \) increases to the maximum value, \( i_{L1} \) and \( i_{L2} \) decrease to the minimum value, and this process ends. We can obtain the expression for \( i_{L1} \) and \( i_{L2} \) using the following equation.

\[
i_{L1-2}(t) = I_{L2,t1} - \frac{V_o}{L_1 + L_2} \cdot t
\]  

(23)
Figure 5. Equivalent circuit diagram of the inductors $L_1$ and $L_2$ releasing energy to the load.

According to Equations (7) and (22), the time $t_2$ for $L_1$ and $L_2$ to jointly transfer energy to the load can be calculated using the following equation.

$$t_2 = t_{Lm} - t_1 = \frac{\pi \sqrt{L_{W2}C_2}}{2} - \frac{nL_1(I_{L1,0} - I_{L2,1})}{V_o} DT$$

(24)

By substituting Equation (24) into Equation (23), the minimum value of $i_{L1}$ can be obtained using the following.

$$I_{L1,\text{min}} = I_{L2,1} - \frac{V_o}{L_1 + L_2} \left( \frac{\pi \sqrt{L_{W2}C_2}}{2} - \frac{nL_1(I_{L1,0} - I_{L2,2}) + V_o}{V_o} DT \right)$$

(25)

When the voltage across $C_2$ reaches the maximum value, the energy stored in the capacitor $C_2$ is released to inductors $L_1$, $L_2$, and $W_2$, and its equivalent circuit is shown in Figure 6.

Figure 6. Equivalent circuit of the capacitor $C_2$ reverse energy storage release.

According to Figure 6, we can obtain the following equation.

$$-u_{C2}(t) + u_{L2}(t) + u_{L1}(t) + u_{W2}(t) + V_o = 0$$

(26)

The voltage across $L_1$, $L_2$, and $W_2$ can be derived as follows.

$$\begin{cases} u_{L2} = -L_2C_2 \frac{d^2u_{C2}(t)}{dt^2} \\ u_{L1} = -L_1C_2 \frac{d^2u_{C2}(t)}{dt^2} \\ u_{W2} = -L_{W2}C_2 \frac{d^2u_{C2}(t)}{dt^2} \end{cases}$$

(27)

By substituting Equation (27) into Equation (26), we can obtain the following.

$$-u_{C2}(t) - (L_{L2} + L_{L1} + L_{W2})C_2 \cdot \frac{d^2u_{C2}(t)}{dt^2} + V_o = 0$$

(28)
where \( \lambda \)

Therefore, the voltage stress of the switch \( S \) can be obtained using Equations (31) and (32).

\[
V_{C2,\text{max}} - V_o \cdot \cos \left( \frac{1}{\sqrt{(L_2 + L_1 + L_{W2})C_2}} \right) + V_o
\]

From Equation (7), the time \( t_3 \) for the capacitor \( C_2 \) deliver energy to \( L_1, L_2, \) and \( W_2 \) during the switch-off period can be calculated using the following equation.

\[
t_3 = (1 - D)T - t_m = (1 - D)T - \frac{\pi \sqrt{L_{W2}C_2}}{2}
\]

By substituting Equations (9) and (30) into Equation (29), the voltage across the capacitor \( C_2 \) at the switch-on time can be obtained using the following.

\[
V_{C2-2} = -I_{L1,\text{min}} \cdot \sin \left( \frac{\lambda}{\sqrt{L_1 + L_2 + L_{W2}}C_2} \right)
+ \left( \frac{V_o dT}{\sqrt{V_{W2}C_2}} - V_o \right) \cdot \cos \left( \frac{\lambda}{\sqrt{L_1 + L_2 + L_{W2}}C_2} \right) + V_o
\]

where \( \lambda = (1 - d)T - \frac{\pi \sqrt{L_{W2}C_2}}{2} \).

According to Figure 6, the voltage across the secondary winding \( W_2 \) can be calculated using the following equation.

\[
V_{W2} = (V_{C2-2} - V_o) \frac{L_{W2}}{L_2 + L_1 + L_{W2}}
\]

When the switch is turned on, the voltage across the primary side is \( nV_{W2} \), coupled from \( V_{W2} \) through the transformer, which is opposite to the polarity of the input voltage. Therefore, the voltage stress of the switch \( S \) can be obtained using Equations (31) and (32).

\[
V_{ds} = V_i - nV_{W2}
= V_i + I_{L1,\text{min}} L_m \sqrt{\frac{1}{2C_2(n^2L_1 + n^2L_2 + L_m)}} \cdot \sin \left( \frac{n \lambda}{\sqrt{n^2L_1 + n^2L_2 + L_m}C_2} \right)
- \left( \frac{nV_o dT}{n^2L_1 + n^2L_2 + L_m} \cdot \sqrt{\frac{L_m}{L_2}} - \frac{nV_{W2} L_m}{n^2L_1 + n^2L_2 + L_m} \right) \cdot \cos \left( \frac{n \lambda}{\sqrt{n^2L_1 + n^2L_2 + L_m}C_2} \right)
\]

From the above analysis, we can see that the proposed converter can achieve a low-voltage turn-on of the switch, and the additional LCD can transmit both the excitation energy and the forward energy.

4.3. Parameter Design of the Forward Inductor \( L_1 \)

According to Figure 1, the current across the inductor \( L_1 \) in one cycle is equal to the output average current, which can be drawn as the following.

\[
I_{L1} = I_o
\]

The ripple of the inductor current \( i_{L1} \) can be given as the following.

\[
\Delta i_{L1} = \frac{V_i - nV_o}{nL_1} dT
\]
According to Equations (34) and (35), the maximum current and minimum current of the inductor $L_1$ can be obtained using the following.

$$
\begin{align*}
I_{L1,\text{max}} &= I_0 + \frac{1}{2}\Delta i_{L1} = I_0 + \frac{D(V_i - nV_o)}{2nL_1} \\
I_{L1,\text{min}} &= I_0 - \frac{1}{2}\Delta i_{L1} = I_0 - \frac{D(V_i - nV_o)}{2nL_1}
\end{align*}
$$

(36)

To operate the proposed converter in the best working mode, the minimum current of the inductor $L_1$ should be less than the peak current of the inductor $L_2$. From Equations (18) and (36), $L_1$ should satisfy the following.

$$
L_1 \leq \frac{V_i - nV_o}{2nR - \frac{V_{ds}DT}{\sqrt{L_m(L_2 + L_{W2})}}} - DT
$$

(37)

5. Simulation and Experimental Analysis

5.1. Simulation Analysis

To verify the theoretical analysis, a PSIM simulation was built. The simulation results of the proposed converter were obtained from PSIM to verify the theoretical analysis preliminarily, and the index requirements of the experimental prototype are shown in Table 1.

Table 1. The main design indicators of the experimental prototype.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>AC 165~265 V</td>
</tr>
<tr>
<td>Input frequency</td>
<td>40~60 Hz</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Maximum efficiency</td>
<td>≥90%</td>
</tr>
<tr>
<td>Output ripple</td>
<td>≤1% $V_o$</td>
</tr>
<tr>
<td>Output voltage</td>
<td>48 V</td>
</tr>
<tr>
<td>Output current</td>
<td>10 A</td>
</tr>
<tr>
<td>Load adjustment rate</td>
<td>±2%</td>
</tr>
</tbody>
</table>

According to the index requirements of the experimental prototype, assuming that the maximum duty cycle of the converter was 0.45, the number of turns of the primary winding turns was $N_1 = 30$, the number of turns of the secondary winding was $N_2 = 13$, and the excitation inductor $L_m = 3.5$ mH when the minimum DC input voltage was 198 V. According to Equation (12), we obtained $0 < C_2 < 25$ nF.

Considering the impact of the actual capacitance and the PCB parasitic capacitance, the capacitor $C_2$ was taken as 10 nF in this experiment. According to Equation (17), we obtained $0 < L_2 < 162.5$ µH. Considering its volume and winding loss, $L_2 = 45$ µH was selected in this experiment. Under the condition that the inductor $L_2$ was already present, the inductor $L_1$ was taken as 50 µH, according to Equation (37).

Figure 7 shows the key waveforms of the proposed converter with the output currents of 2 A, 5 A, and 10 A, respectively. As shown in Figure 7a, the inductor current waveforms $i_{L1}$ and $i_{L2}$ affirmed that the inductor $L_1$ and $L_2$ operated in the CCM. The voltage waveform $V_{ds}$ affirmed that the voltage across the capacitor $C_2$ increased first and then decreased during the switch-on period, indicating that $L_m$ operated in the DCM. Using the voltage waveform of $V_{ds}$, we concluded that the proposed converter achieved a low-voltage turn-on of the switch. Similarly, as shown in Figure 7b,c, it can be concluded that the inductor $L_1$ and $L_2$ also worked in the CCM, and the voltage stress waveform of $V_{ds}$ also increased first and then decreased during the switch-on period. Therefore, the excitation inductor $L_m$ worked in the DCM, which was in good agreement with the theoretical results.
Figure 7. Simulated waveforms of the main components of the converter with different output loads. (a) Waveforms of $V_{gs}$, $V_{ds}$, $i_{L1}$, and $i_{L2}$ when $I_o = 2$ A; (b) Waveforms of $V_{gs}$, $V_{ds}$, $i_{L1}$, and $i_{L2}$ when $I_o = 5$ A; (c) Waveforms of $V_{gs}$, $V_{ds}$, $i_{L1}$, and $i_{L2}$ when $I_o = 10$ A.

5.2. Experimental Analysis

In order to verify the performances and simulations further, we considered the following factors, such as the circuit power, efficiency, and output voltage ripple. The experimental prototype was developed, as shown in Figure 8. The key parameters were same as the simulated parameters. According to the working principle of the proposed converter and the existing equipment and safety practices in the laboratory, the selected parameters of the model are given in Table 2.

In order to verify the correctness of the optimal operating mode of the converter and its parameter design method, when the input voltage was DC300V, the waveforms of $V_{gs}$, $V_{ds}$, $i_{L1}$, and $i_{L2}$ with output currents of 2 A, 5 A, and 10 A, respectively, were tested using the experimental prototype, as shown in Figure 9.
In order to verify the correctness of the optimal operating mode of the converter and its parameter design method, when the input voltage was DC 300 V, the waveforms of $V_{gs}$, $V_{ds}$, $i_{L1}$, and $i_{L2}$ with output currents of 2 A, 5 A, and 10 A, respectively, were tested using the experimental prototype, as shown in Figure 9.

![Figure 8. Experimental prototype.](image_url)

<table>
<thead>
<tr>
<th>Components</th>
<th>Part Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power switch $S$</td>
<td>80R280P7</td>
</tr>
<tr>
<td>Diodes $D_1$–$D_4$</td>
<td>MM60F060PC</td>
</tr>
<tr>
<td>Transformer core $T$</td>
<td>EE/42/21/15</td>
</tr>
<tr>
<td>Control chip</td>
<td>UC3845</td>
</tr>
</tbody>
</table>

![Figure 9. Cont.](image_url)
As shown in Figure 9, the voltage waveform of $V_{ds}$ first increased in a curve and then decreased in a curve during the switch-off period, indicating that $L_m$ operated in the

**Figure 9.** Waveforms of the main components of the converter with different output loads. (a) Waveforms of $V_{gs}$ (10 V/div), $V_{ds}$ (400 V/div), $i_{L1}$ (2 A/div), and $i_{L2}$ (2 A/div) when $I_o = 2$ A; (b) Waveforms of $V_{gs}$ (10 V/div), $V_{ds}$ (400 V/div), $i_{L1}$ (10 A/div), and $i_{L2}$ (2 A/div) when $I_o = 5$ A; (c) Waveforms of $V_{gs}$ (10 V/div), $V_{ds}$ (400 V/div), $i_{L1}$ (10 A/div), and $i_{L2}$ (2 A/div) when $I_o = 10$ A.

As shown in Figure 9, the voltage waveform of $V_{ds}$ first increased in a curve and then decreased in a curve during the switch-off period, indicating that $L_m$ operated in the
DCM. However, the inductor currents $i_{L1}$ and $i_{L2}$ were greater than zero throughout the entire switching period, indicating that the inductors $L1$ and $L2$ both operated in the CCM, which proves that the proposed converter operated in the optimal operating mode. At the same time, it can be seen in Figure 9 that when the output current of the converter was significant, the voltage stress on the power switch was equal to the input voltage at the switch-on moment. When the output current of the converter was minimal, the voltage stress of the switch was obviously lower than the input voltage at the switch-on moment. The above analysis shows that the proposed converter achieved a low-voltage turn-on of the switch. Therefore, the correctness of the above mentioned optimal working mode and its parameter design method was verified. Meanwhile, by comparing the experimental waveform with the simulated waveform, it can be seen that they were generally consistent.

According to the performance index requirements of the prototype, under an input voltage of 220 VAC, the output voltage was tested using different load conditions. Table 3 shows the experimental results of the proposed converter.

Table 3. Output voltage under different load conditions.

<table>
<thead>
<tr>
<th>Load (A)</th>
<th>Output Voltage (V)</th>
<th>Load (A)</th>
<th>Output Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48.14</td>
<td>6</td>
<td>48.01</td>
</tr>
<tr>
<td>2</td>
<td>48.11</td>
<td>7</td>
<td>47.99</td>
</tr>
<tr>
<td>3</td>
<td>48.08</td>
<td>8</td>
<td>47.97</td>
</tr>
<tr>
<td>4</td>
<td>48.06</td>
<td>9</td>
<td>47.94</td>
</tr>
<tr>
<td>5</td>
<td>48.03</td>
<td>10</td>
<td>47.91</td>
</tr>
</tbody>
</table>

Table 3 presents the maximum variation when the output voltage was 0.23 V. Therefore, the load adjustment rate of the experimental prototype was obtained as the following.

$$U = \frac{\Delta V_o}{V_o} = \frac{48.14 - 47.91}{48} = 0.47\%$$  \hspace{1cm} (38)

From Equation (38), it can be seen that the load adjustment rate of the developed experimental prototype met the design requirements.

The output ripple was an important technical index of the converter. According to the design index of the prototype, the output ripple voltage should be less than 1% $V_o$, that is, the output ripple voltage should be less than 480 mV. The waveform of the output ripple voltage was tested using full load conditions, as shown in Figure 9.

As shown in Figure 10, the peak-to-peak output voltage ripple of the proposed converter was 200 mV, which was less than 1% $V_o$. Therefore, the prototype designed in this paper met the index requirements of the converter.

![Figure 10. Waveform of the output ripple voltage.](image-url)
To verify the working efficiency of the proposed converter, the efficiency of the experimental prototype was tested using changing output current conditions, and the measured efficiency is plotted in Figure 11.

![Efficiency curve of the prototype [18,21] and the proposed converter.](image)

Figure 11. Efficiency curve of the prototype [18,21] and the proposed converter.

Figure 11 shows that the proposed converter had a higher efficiency than the other converters under the medium and high power conditions, and the highest experimental efficiency reached was 93.5%, which met the index requirements of the converter. The energy of the converter was effectively utilized.

The comparison between the proposed converter and the other existing converters is presented in Table 4. The efficiency of the proposed converter was obviously higher than the efficiency of the other types, such as the converters proposed in [17,21]. The proposed converter utilized a lower number and the same number of components, respectively. In comparison with the converter proposed in [17,18], the number of active switches was fewer, which denoted that the complexity of the control circuit and the number of gate drivers was reduced due to the lower number of power switches. In comparison with the converter in [21], the voltage stress of the power switch of the proposed converter was adjustable with the change of the additional capacitor $C_2$. In comparison with the converter in [17,18], the proposed converter transmitted excitation energy and forward energy to the load end, which improved the conversion efficiency of the transformer. In summary, the proposed converter exhibited the best electrical performance.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Switch</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Inductors</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Diodes</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Voltage stress of the Switch</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Adjustable</td>
</tr>
<tr>
<td>Low-voltage turn-off</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Excitation energy</td>
<td>Consumed</td>
<td>Input</td>
<td>Output</td>
<td>Output</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
</tr>
</tbody>
</table>

Table 4. Comparison between the existing converters.

6. Conclusions

This paper proposed a new secondary side series LCD forward converter. The principal operation and energy transmission process of the proposed converter were presented, and it was concluded that the optimal operating mode of the proposed converter was $L_m$-DCM, $L_1$-CCM, and $L_2$-CCM. The value range of the capacitor $C_2$ in the best working
mode of the converter was analyzed, combining the analysis of the turn-on and turn-off characteristics of the switch, and the parameter design scheme of the converter was obtained. Finally, the proposed converter was implemented and tested in the best working mode and its performance was verified through the experimental results. The experimental results showed that its maximum efficiency was 93.5%, the output ripple voltage was less than 1% \( V_o \), and the voltage adjustment rate was 0.47%. It was proved that the proposed converter possessed the merits of transferring excitation energy to the output terminal, the reliable magnetic reset of the transformer and an improvement in the working efficiency, and the realization of the low-voltage turn-on of the switch. This converter can be a good complement for the existing forward converters and an appropriate candidate for industrial applications.

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References
4. Ghorbanian, M.; Maghsoudi, M.; Esteki, M.; Farzanehfard, H. Forward converter using a resonant auxiliary circuit to provide soft-switching and reset the magnetic core. *IET Power Electron.* 2022, 15, 1713–1724. [CrossRef]

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