A frequency-doubling modulation method for LLC with optimizing thermal balance of power switches

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Abstract

In order to further improve the energy efficiency of power electronic systems, DC-DC converters can increase the power density by increasing the operating frequency to reduce the size and cost. To this end, some scholars have proposed a single-switch frequency-doubling (SS-FD) modulation method, which can make the working frequency of the resonant tank of the converter twice the switching frequency. However, when the full-bridge LLC converter operates under the SS-FD modulation, the conduction time of each switch of the same bridge arm is different, which leads to uneven heating of the switches and reduces the overall life of the device. In order to optimize this problem, this paper proposes a dual-switches time-sharing frequency-doubling (DSTS-FD) modulation. This modulation method ensures that the resonant tank works under the premise of frequency doubling, so that the heating of each switch is more balanced, thereby increasing the overall service life of the equipment. Theoretical analysis is carried out through simulation. Finally, an experimental device of 288 V and 1000 W is built. The proposed modulation method is compared with the traditional modulation method in a stable state, and the experiment verifies the superiority of the proposed modulation method.

KEYWORDS

dual-switches time-sharing frequency-doubling (DSTS-FD) modulation, full-bridge LLC converter, loss equalization optimization, single-switch frequency-doubling (SS-FD) modulation

1 | INTRODUCTION

The increasingly severe energy crisis and environmental pollution have prompted people to look for more energy-saving and environmentally friendly energy supply and consumption patterns. The new grid structures and green power consumption methods are currently the solutions sought by academia and industry, such as new energy technologies, DC distribution systems, micro-grid, and electric vehicles (EVs). To achieve these goals, power electronics technology plays a pivotal role, among which high-performance DC-DC converters are the key power conversion components in the above application fields. Existing DC-DC converters can achieve zero-voltage turn-on and zero-current turn-off, thereby reducing switching losses and achieving high efficiency over a wide load range.[1–4] However, in order to adapt to the above application fields, DC-DC converters need to further improve conversion efficiency to improve energy utilization. Increasing the switching frequency not only increases power density to reduce volume and cost but also provides stable and flexible capacity expansion for high-power conversion applications.[5,6]

In the traditional full-bridge LLC converter, the two switches on each bridge arm work symmetrically, with a duty ratio of 0.5, and the frequency of the full-bridge output square wave is the same as the switching frequency. Previous studies[7–15] apply the single-switch frequency-doubling (SS-FD) modulation strategy to LLC converter, so that the output frequency of inverter is twice the switching frequency and the output voltage is halved. By adjusting the duty ratio of the switch to be 0.25 and 0.75, respectively, and the phase angle to be 180°, the multiplication effect of the operating frequency of the resonant tank is realized. Therefore, in the high frequency and high power density working occasion, a certain working frequency of the resonant tank can be achieved, and the switching frequency of the power device can be halved. In addition, the condition of the soft switch is reduced because the parasitic capacitance of the switch is halved during each switch operation. This method reduces the transformer excitation current and the resonant current of the converter under high-frequency operation, which improves the conversion efficiency and reduces the volume of the resonant element. Based on the frequency doubling modulation strategy, not only the frequency doubling effect of the operating frequency of the resonant tank is achieved but also a high step-down ratio is achieved.

Wu et al[7] proposes a wide output voltage range LLC resonant converter based on the topology reconfiguration method (TRM). As one of the modulation methods, frequency doubling modulation is applied in the converter. Compared with the conventional LLC converter, the converter's gain range is increased in the same switching frequency range. Wei and Mantooth[8] proposes a new combination of full-bridge mode and frequency doubling mode. This method reduces the frequency range of the switch and increases the voltage gain. When the full-bridge LLC converter operates in frequency-doubling mode, the resonant tank operates at twice the frequency of the switch. The inverter output voltage waveform is similar to that of half-bridge mode, so the voltage gain is half that of full-bridge mode. Inam et al[9] applies frequency-doubling control in the Stacked bridge inverter, designed with a wide input and/or output voltage range. This paper analyzes the different modes under the frequency doubling modulation method. Finally, it is proved that the frequency-doubling modulation method can make the resonant tank operating frequency twice the switching frequency. In Wei and Mantooth,[10] a novel LLC topology, which has different operation modes, is proposed for renewable energy system applications and is proposed to satisfy the voltage gain requirement. As an operating mode, frequency-doubling modulation method enables high voltage gain requirements to be realized in the narrow switching frequency operating range. Zhang et al[11] presents control methods that achieve DC-link capacitor voltage balance of a series half-bridge (SHB) LLC resonant converter operating at different modulations. As one of the modulation methods commonly used in SHB LLC converters, the principle of the proposed balance control method is analyzed and studied. Wei et al[12] presents a new control strategy for LLC resonant converters with stacked structures with hold-time operation requirements. In normal operation, the equivalent frequency multiplier is used to achieve high-efficiency conversion. During the holding process, the gate control signal is modified and PWM control is adopted to improve the voltage gain of the converter. Zhang and Barbosa,[13] based on the trajectory analysis in the state plane, proposes a control method for the fast modulation transition of a serial-half-bridge (SHB) LLC resonant converter based on a wide input and/or output voltage range. This control method is based on the frequency-doubling modulation method. By adding the output voltage and output current closed-loop control, the dynamic modulation transition can be realized under the optimal condition. In Lin et al,[14] a new varied-mode control strategy for LLC resonant converter is proposed. The converter circuit operates in three different modes according to different input voltages. When the converter needs to work in a high step-down ratio state, the frequency-doubling modulation mode is selected. This allows the resonant groove to operate at twice the frequency of the switching tube and gives the inverter an output voltage gain of 0.5. Zong et al[15] presents a frequency-doubling LLC resonant converter with high step-down voltage gain for high

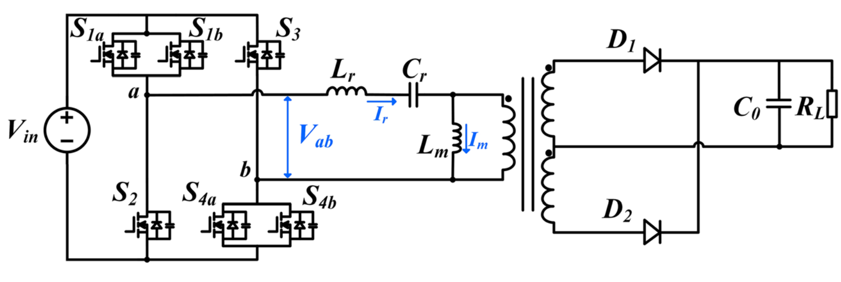

FIGURE 1 DSTS-FD full-bridge LLC converter [Colour figure can be viewed at wileyonlinelibrary.com]

input voltage applications. By using the proposed frequency-doubling modulation method, the operating frequency of the resonant tank is twice that of the switching frequency of the device. This greatly reduces the switching loss and increases the power density of the converter. However, in SS-FD modulation state, the duty cycle of the two switches of the same bridge arm are 0.25 and 0.75, respectively, resulting in different conduction losses of the switches and twice the difference. The service life of the switch with a duty ratio of 0.75 will be shorter than that of the switch with a duty ratio of 0.25, which reduces the overall service life of the equipment.

Aiming at the problem that the losses of each switch of the full-bridge LLC converter are quite different under the SS-FD modulation, this paper proposes a dual-switches time-sharing frequency-doubling (DSTS-FD) modulation method. The newly proposed modulation method is applied to the converter as shown in Figure 1. The duty cycle of the two switches in parallel is 0.375, the switching frequency is the same, and the phase angle is 180°; the duty cycle of the other switch on the same bridge arm is 0.25, and the switching frequency is twice the switching frequency of the parallel switch. In an LLC converter, the losses of a switch are mainly composed of conduction loss and switching loss. The conduction loss of the switch with a duty ratio of 0.375 is still larger than that of the switch with a duty ratio of 0.25, but the switching loss of the switch with a duty ratio of 0.375 is smaller. Therefore, under the newly proposed modulation method, the loss difference of each switch of the converter is very small.

On the premise of realizing the frequency multiplication of the resonant tank, this method makes the heat between switches more balanced and increases the overall life of the device, which is more practical. Finally, the newly proposed modulation method is compared with the SS-FD modulation method by simulation and experiment. And the results verify the superiority of the newly proposed modulation method.

2 | ANALYSIS OF TOPOLOGY AND MODULATION METHOD

2.1 | Topology and modulation method

The SS-FD full-bridge LLC converter is shown in Figure 2. S_1 and S_2 form the left half bridge arm, and the right half bridge arm consists of S_3 and S_4. The two switches of each bridge arm conduct complementary conduction, and the capacitances at both ends of S_1, S_2, S_3 and S_4 are the equivalent parasitic output capacitances of the four switches, respectively. Since the selected four switches are the same, it is assumed that the four parasitic capacitances are also equal. C_r, L_r, and L_m are the resonant inductance and the primary side excitation inductance, respectively, which constitute the resonant tank. The specific modulation method is shown in Figure 3. The duty ratios of the two switches of each bridge arm are 0.25 and 0.75, respectively, and the two half-bridge modules have a phase difference of 180°.

Under SS-FD modulation, the duty cycle of two switches on the same bridge arm is 0.25 and 0.75, respectively. The conduction loss of switches with a duty cycle of 0.75 is three times that of switches with a duty cycle of 0.25. Therefore, the switch with a duty cycle of 0.75 is more likely to be damaged, reducing the overall service life of the equipment. In order to make the heat of each switch as balanced as possible and increase the service life of the equipment, the following two modulation methods are conceived. Then the two methods are analyzed, respectively, to select the most appropriate modulation method.

(1) A switch with a duty cycle of 0.75 (frequency $= f$) is replaced by three parallel switches ($D = 0.25$, frequency $= f/3$) with alternating conduction.

The conduction loss of each parallel switch tube is only 1/3 that of the switch with a duty cycle of 0.75. Similarly, the switching loss is also 1/3 that of a switch with a duty cycle of 0.75. The conduction loss of each parallel switch is the

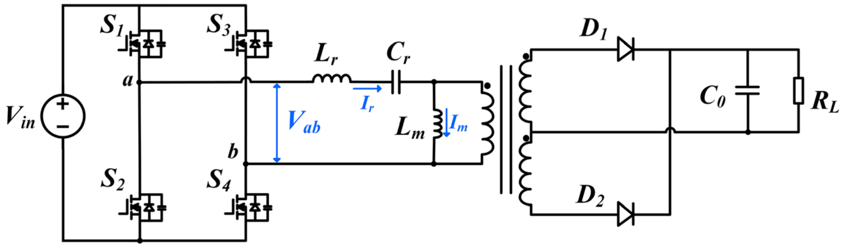

FIGURE 2 SS-FD full-bridge LLC converter [Colour figure can be viewed at wileyonlinelibrary.com]

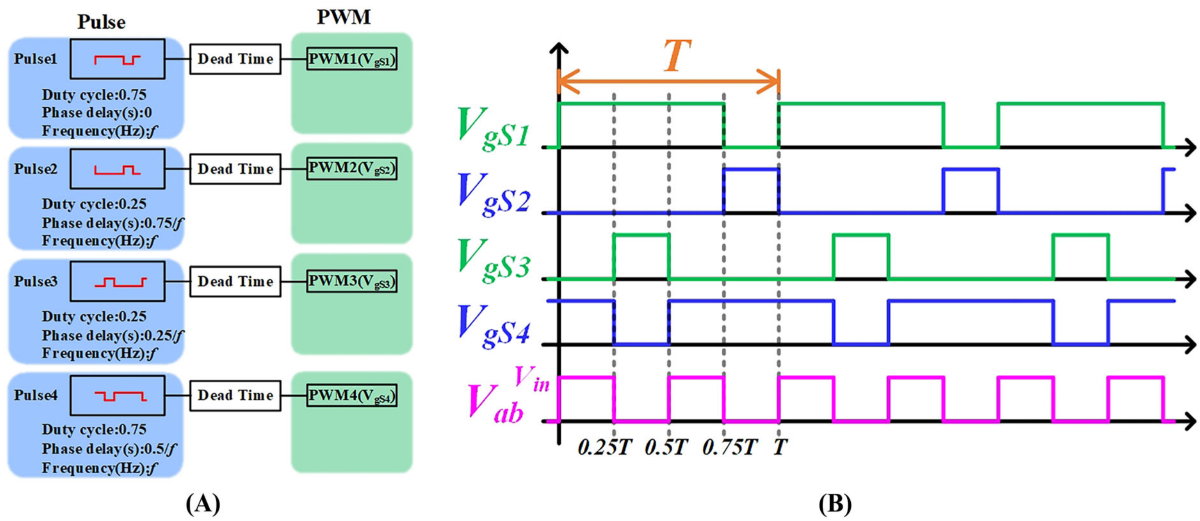

FIGURE 3 SS-FD modulation. (A) Block schematic of gate generation logic. (B) Waveforms (dead time = 0) [Colour figure can be viewed at wileyonlinelibrary.com]

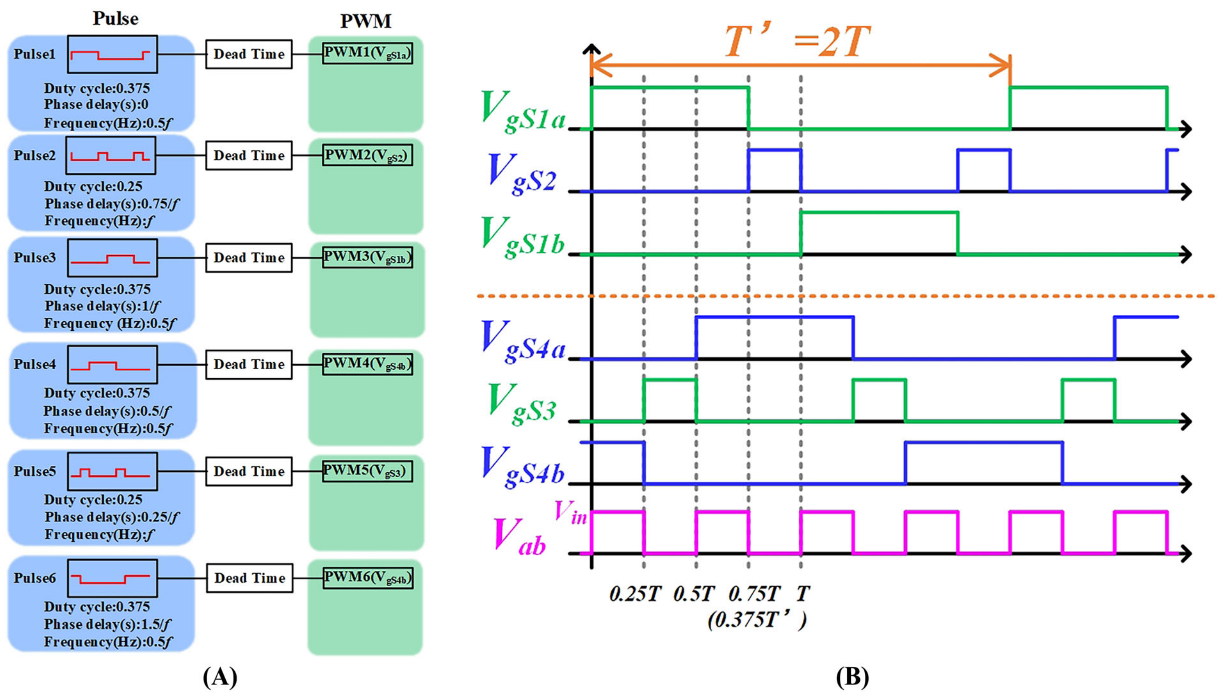

FIGURE 4 DSTS-FD modulation. (A) Block schematic of gate generation logic. (B) Waveforms (dead time = 0) [Colour figure can be viewed at wileyonlinelibrary.com]

same as that of the switch with a duty ratio of 0.25. However, the switching loss per parallel switch tube is 1/3 that of a switch tube with a duty cycle of 0.25 (frequency $= f$). To sum up, the total loss (conduction loss + switching loss) of a switch with a duty cycle of 0.25 must exceed the total loss of each parallel switch. In addition, this method requires four switches and corresponding drive circuits, which greatly increases the cost and space.

(2) A switch with a duty cycle of 0.75 (frequency $= f$) is replaced by two parallel switches ($D = 0.375$, frequency $= f/2$) with alternating conduction.

The DSTS-FD full-bridge LLC converter is shown in Figure 1. S_{1a} and S_{1b} are connected in parallel with S_2 to form the left half bridge arm, and the right half bridge arm is formed by S_{4a} and S_{4b} connected in parallel with S_3. The capacitances at both ends of $S_{1a}, S_{1b}, S_2, S_3, S_{4a}$, and S_{4b} are the equivalent parasitic output capacitances of the six switches, respectively. Likewise, the six parasitic capacitances are all equal. The resonant tank is composed of the resonant inductance L_r, the resonant capacitor C_r, and the primary side excitation inductance of the transformer L_m. The specific modulation method is shown in Figure 4. Switches S_{1a} and S_{1b} have a duty ratio of 0.375, switching frequency of $f/2$ (Hz), and phase delay of 0 (s) and $1/f$ (s), respectively. Switch S_2 duty cycle is 0.25, switching frequency is f, and phase delay is $0.75/f$ (s). Switch S_3 has a duty cycle of 0.25, a switching frequency of f (Hz), and a phase delay of $0.25/f$ (s). Switches S_{4a} and S_{4b} have a duty ratio of 0.375, switching frequency of $f/2$ (Hz), and phase delay of $0.5/f$ (s) and $1.5/f$ (s), respectively. The conduction loss of each parallel switch is 0.5 times that of the switch with a duty cycle of 0.75. Similarly, the switching loss is also 0.5 times that of the switch, with a duty cycle of 0.75. The conduction loss of each parallel switch is 1.5 times that of the switch with a duty cycle of 0.25. However, the switching loss per parallel switch is 0.5 times that of a switch with a duty cycle of 0.25 (frequency $= f$). Under this modulation method, the total loss (conduction loss + switching loss) ratio between each parallel switch and the switch with a duty ratio of 0.25 must be less than 1.5 or even close to 1. The theoretical loss analysis and experiments below confirm this conclusion. This method only needs to add two switches and the corresponding drive circuits. Compared with the first method, the cost and the space required by the converter are smaller.

Through the above analysis, both modulation methods reduce the heat difference between the switches and increase the service life of the device. But the second modulation method is relatively simple, and the corresponding converter is low-cost and small in size. So the second modulation method (DSTS-FD modulation) is of great significance in optimizing the heat imbalance of switches.

2.2 | Modal analysis of DSTS-FD full-bridge LLC converter

The resonant tank has two resonant frequencies[15]:

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{1}$$

$$f_m = \frac{1}{2\pi\sqrt{(L_r + L_m)C_r}} \tag{2}$$

f_r is the resonant frequency of the resonant inductor and capacitor, and f_m is the resonant frequency of the resonant inductor, excitation inductor, and resonant capacitor. The operating frequency f_s of the resonant tank should always be higher than f_m to ensure that the input impedance of the resonant tank is inductive and the ZVS of the transistor is softly turned on. When the operating frequency f_s of the resonant tank is equal to f_r, if the transformation ratio of the transformer is not considered, the voltage gain of the LLC converter is 1. At this time, the efficiency of the converter is the highest.[16]

With FHA, all voltages and currents are represented by their fundamental components. The secondary side variables are reflected in the primary side, resulting in the approximate circuit shown in Figure 5.

The DC output voltage of the inverter is $V_{in}/2$, so the transformer turns ratio is chosen as

$$n = \frac{V_{in}}{2V_{out}} \tag{3}$$

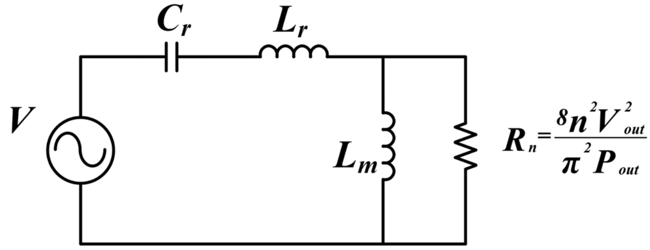

FIGURE 5 Fundamental harmonic model of the LLC converter

The L_m/L_r ratio (referred to as k) has a recommended range of 3 to 10. The smaller the k value, the narrower and steeper the gain curve, but the higher the magnetization current, the greater the loss. The value of k can be optimized for a narrower frequency range or a higher efficiency depending on the intended application. The maximum gain (M_{max}) of the resonant network is chosen to be higher than 2, to ensure adequate gain even if the use of FHA is inaccurate.

To ensure ZVS, the input impedance of the resonant network needs to be inductive at the drive frequency. The boundary between the inductance region and the resistance region is when the impedance is pure resistance. When the imaginary part of the input impedance $(x-(1/x)+(xk/1+k^2x^2Q^2))$ is equal to zero, the value of Q is obtained:

$$Q=\sqrt{\frac{1}{(1-x^2)k}-\frac{1}{(k^2x^2)}} \tag{4}$$

Here, $x=f_{inv}/f_r$, where f_{inv} is the operating frequency of the resonant chamber of the inverter and f_r is the resonant frequency. The maximum gain (M_{max}) can be obtained by substituting the value Q in the expression into the gain M.

$$M=\sqrt{\frac{1}{1+\frac{1}{k}(1-\frac{1}{x^2})^2+Q^2(x-\frac{1}{x})^2}} \tag{5}$$

$$M_{max}=\frac{x}{\sqrt{x^2(1+\frac{1}{k})-\frac{1}{k}}} \tag{6}$$

At the maximum gain, we get the minimum normalized frequency. Replace the x_{min} value with an expression for Q to get the following maximum Q and keep ZVS.

$$Q_{max}=\frac{1}{k}\sqrt{\frac{1+k(1-\frac{1}{M_{max}^2})}{M_{max}^2-1}} \tag{7}$$

Use the values of n, k, and Q_{max} to calculate L_r, L_m, and C_r

$$R_n=\frac{8n^2V_{out}^2}{\pi^2P_{out}} \tag{8}$$

$$L_r=\frac{Q_{max}R_n}{w_r}=\frac{8Q_{max}n^2V_{out}^2}{w_r\pi^2P_{out}} \tag{9}$$

$$L_m=kL_r \tag{10}$$

$$C_r=\frac{1}{Q_{max}R_nw_r}=\frac{\pi^2P_{out}}{8Q_{max}n^2V_{out}^2w_r} \tag{11}$$

According to the above analysis, the steady-state voltage and current waveforms in the case of $f_s=f_r$ are shown in Figure 6 under the DSTS-FD modulation. The equivalent circuit diagram corresponding to each mode is shown in Figure 7. T is a complete switching cycle, and $V_{gS1a}, V_{gS1b}, V_{gS2}, V_{gS3}, V_{gS4a}$, and V_{gS4a} are the driving signals of the six switches, respectively. i_m and i_r are the excitation current and primary resonant current, respectively. The converter has a total of 16 operating modes in one switching period T. Due to the symmetry, only the first four operating modes are analyzed here.

Mode 1 [t_0–t_1]: S_{1a} is turned on at t_0, and the input of the resonant tank is equal to the input voltage V_{in}. The resonance between the resonant inductor L_m and the resonant capacitor C_r starts, the energy is transferred from the primary side to the secondary side through the transformer, and the secondary winding of the transformer is clamped

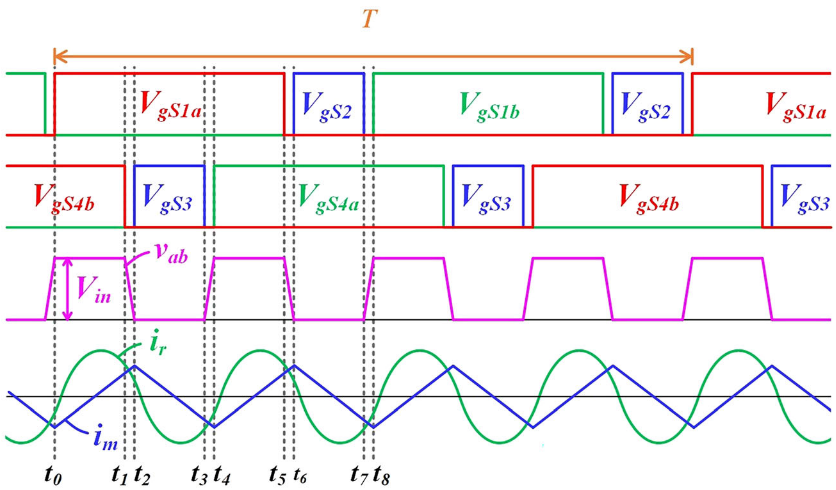

FIGURE 6 Steady-state circuit waveform [Colour figure can be viewed at wileyonlinelibrary.com]

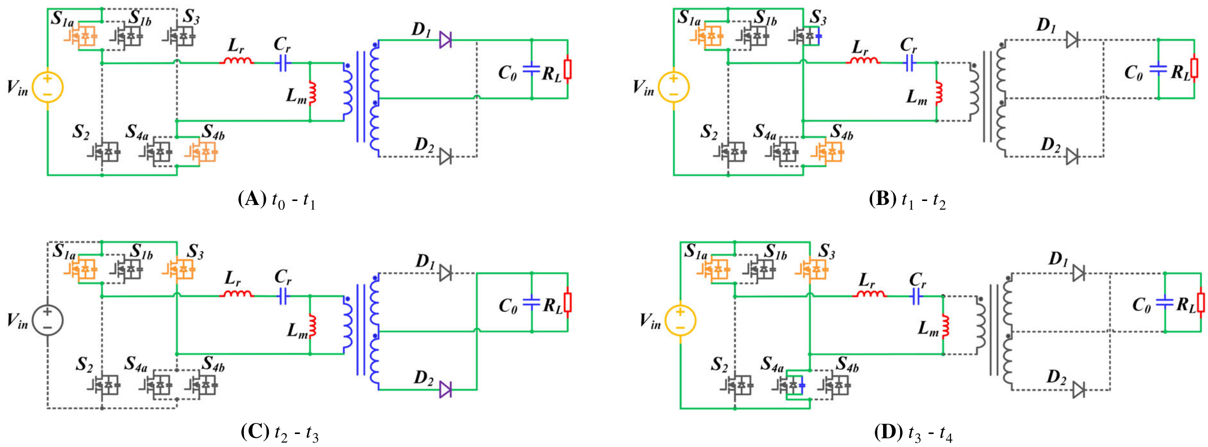

FIGURE 7 Equivalent circuit diagram of each operating mode [Colour figure can be viewed at wileyonlinelibrary.com]

to the output voltage V_{out}. The resonant current i_r rises sinusoidally at the resonant frequency f_r. The secondary diode D_1 is turned on, and D_2 is turned off in reverse. Due to the structural characteristics of full-wave rectification, D_2 withstands a cut-off voltage of $2V_{out}$. The voltage on the primary side of the transformer is $N \cdot V_{out}$, and i_m rises linearly.

Mode 2 [t_1–t_2]: S_{4b} is turned off at t_2. Due to the capacitance at both ends of S_{4b}, the drain-source voltage rises slowly when turned off, and the switch is an approximately zero-voltage soft turn-off. The converter then enters the dead-time phase of the right half-bridge module. Since the phase of the resonant current lags the input voltage of the resonant tank, i_r starts to charge the capacitor across S_{4b} and discharge the capacitor across S_3. When the charge of the capacitor at both ends of S_3 is drained, the voltage at both ends of S_3 is zero. i_r starts to flow through its anti-parallel diode until S_3 is turned on.

Mode 3 [t_2–t_3]: In the previous mode, the capacitor charges at both ends of S_3 are drained. At the beginning of this mode, S_3 is turned on softly at zero voltage. When S_{1a} and S_3 are turned on, the input voltage of the resonant tank is zero. However, there is a DC bias voltage of $0.5V_{in}$ on C_r, which will still excite the resonant tank L_r and C_r to start resonating. At the time, the resonant frequency is f_r. The secondary side of the transformer is clamped to the output voltage V_{out}. Similar to mode 1, i_r rises sinusoidally at the frequency of f_r, and i_m rises linearly, but in the opposite direction. The energy flows through the transformer and is transmitted to the output through D_2, and D_1 is turned off and withstands the reverse voltage of $2V_{out}$.

Mode 4 [t_3–t_4]: S_3 is turned off at t_3, during which the converter enters the dead time of the left half-bridge module. Similar to Mode 2, the resonant current charges the capacitor across S_3 and discharges the capacitor across S_{4a}.

The other stages work in a similar way to the previous modes 1–4, so they will not be repeated here.

2.3 | Soft switching conditions

For the DSTS-FD full-bridge LLC converter, the resonant current lags behind the input voltage to ensure zero-voltage soft switching of the switches. As shown in Figure 6, when one half-bridge module in the full-bridge is switched on, the other half-bridge arm does not commutate and keeps the state unchanged. Therefore, the switching action of each switch will not be affected by the other bridge arm and only depends on the working state of the resonant tank. Therefore, the soft-switching condition of the converter is similar to that of the SS-FD full-bridge LLC converter. It ensures a long enough dead time so that the resonant current can completely drain the charge in the parasitic output capacitance of the switch.

$$T_d = \frac{C_{zvs}}{i_{mp}} V_{in} \tag{12}$$

In the formula, i_{mp} is the peak value of the excitation current, which occurs during the switching action; C_{zvs} is the sum of the parasitic output capacitances of all the switches participating in the primary commutation. Under the same working frequency of the resonant tank, the dead time T_d of the two modulation modes should be equal.

2.4 | Resonant current

For LLC resonant converter, the peak excitation current: i_{mp} can be expressed as

$$i_{mp} = \frac{NV_{out}}{4L_m f_s} \tag{13}$$

where N is the transformer ratio, V_{out} is the output voltage, L_m is the excitation inductance, and f_s is the operating frequency of the resonant tank. The values are N_1, V_{out1}, L_{m1}, f_{s1} in SS-FD LLC converter. In DSTS-FD LLC converter, the values are N_2, V_{out2}, L_{m2}, and f_{s2}. The only difference between the two converters is the inverter, and the other hardware are identical, so $N_1 = N_2, L_{m1} = L_{m2}$. In addition, both converters operate at the same input voltage and resonant frequency, so $V_{out1} = V_{out2}$, $f_{s1} = f_{s2}$. In summary, the LLC resonant converter has the same resonant current under the two control methods.

3 | LOSS ANALYSIS OF SWITCH

3.1 | Loss calculation method of switch

In order to verify that each switch losses of the LLC converter under the DSTS-FD modulation are more balanced than SS-FD modulation, it is first necessary to calculate the losses of the switches under the two modulations. Losses can be calculated according to the methods given in previous studies.[17–20] Since both modulation methods can make the primary side realize soft switching, the turn-on loss is almost zero and can be ignored. The loss formula is as follows:

$$P_{mos} = P_{swoff} + P_{cond} = \frac{1}{2} V_{ds} I_d (t_{vr} + t_{if}) f_s + R_{on} I_{drms}^2 \tag{14}$$

where P_{swoff} is the turn-off loss and P_{cond} is the turn-on loss. V_{ds} is the drain-source voltage of the switch; I_d is the steady-state current flowing through the switch; f_s is the switching frequency; I_{drms} is the RMS current when the switch is on, and R_{on} is the on-resistance under actual conditions; t_{vr} is the voltage rising phase duration; t_{if} is the current falling phase duration.

$$t_{vr} = \frac{2L_s Q_{dio}}{\left(-R_g + \sqrt{R_g^2 + \frac{4L_s Q_{dio} V_{pl}}{Q_{gd}^2}} Q_{gd}\right.} \tag{15}$$

$$t_{if} = \frac{2R_g(Q_{gs} + \frac{L_s I_d}{R_g})}{V_{pl} - V_{th}} \tag{16}$$

L_s is the sum of L_{s1} (the parasitic inductance of the source lead) and L_{s2} (the parasitic inductance generated by the printed circuit board traces connected to the source stage); Q_{dio} is the freewheeling diode junction capacitance stored charge; R_g is the driving resistance, and V_{pl} is the Maitreya electric flat; Q_{gd} is the drain charge; Q_{gs} is the gate charge; V_{th} is the turn-on voltage.

3.2 | Comparison of theoretical losses of switches under two controls

The circuit is designed and operated according to the parameters given in Table 1, and then the losses of each switch of the LLC converter under the two control modes are calculated. Among them, the switch selects IRFP350, which meets the experimental requirements. The parameters of this switch are shown in Table 2.

V_{ds} and I_d under different output power (100 W, 500 W, 1000 W) can be obtained through MATLAB simulation when the resonant tank's working frequency f_s is equal to f_r. Then, the loss of each switch can be obtained according to Equations (14)–(16). Figure 8 shows the comparison of losses with different output powers at an input voltage of 288 V and a resonant tank frequency of 500 kHz. It can be seen from Figure 7 that when the output power of the converter is 100 W, the loss of the switch with a duty ratio of 0.75 is 2.11 times that of the switch with a duty ratio of 0.25, while loss of the switch with a duty cycle of 0.375 is only 1.09 times that of a switch with a duty cycle of 0.25. When the

TABLE 1 Test prototype configuration

Parameter	SS-FD LLC converter	DSTS-FD LLC converter
Input voltage V_{in}	288 V	288 V
Output voltage V_{out}	48 V	48 V
Maximum output power P_{omax}	1 KW	1KW
Primary switching frequency f_{sp}	250 kHz	250 kHz/125 kHz
Resonant frequency f_r	500 kHz	500 kHz
Transformer ratio N	14:5	14:5
Excitation inductance L_m	252 μ H	252 μ H
Resonant Inductance L_r	36 μ H	36 μ H
Resonant capacitor C_r	2.85 nF	2.85 nF
output filter capacitor C_o	470 μ F	470 μ F

TABLE 2 IRFP350 parameters

Parameter	Values
Q_{gs}/Q_{gd}	10/33 nC
V_{th}/V_{pl}	2/5 V
V_{Dr}	15 V
Q_{rr}	1.7 nC
L_s	12.5 nH
C_{dio}	62 pF
Q_{dio}	18.6 nC
T_{rr}	270 nS
R_{on}	0.3 Ω

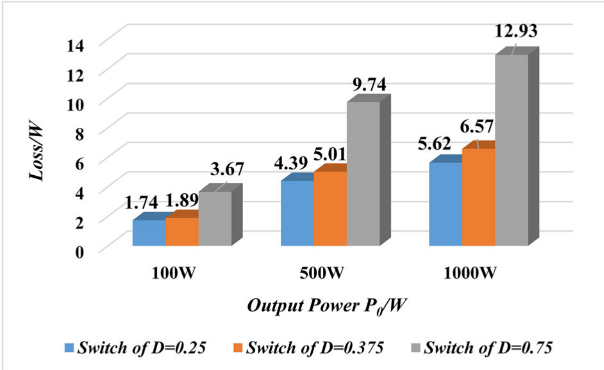

FIGURE 8 Loss comparison of switches under different output powers [Colour figure can be viewed at wileyonlinelibrary.com]

output power of the converter is 500 W, the loss of the switch with a duty ratio of 0.75 is 2.22 times that of the switch with a duty ratio of 0.25, while the loss of switch with a duty cycle of 0.375 is only 1.14 times that of a switch with a duty cycle of 0.25. Similarly, when the output power of the converter is 1000 W, the loss of the switch with a duty ratio of 0.75 is 2.3 times that of the switch with a duty ratio of 0.25, while the loss of switch with a duty cycle of 0.375 is only 1.17 times that of a switch with a duty cycle of 0.25. Through the above comparative analysis, it can be seen that although there is a difference between the loss of switch with a duty ratio of 0.375 and the loss of switch with a duty ratio of 0.25, the difference between them is very small compared with the loss of switch with a duty ratio of 0.75. The losses of each switch under the DSTS-FD modulation are closer, on the premise of ensuring the realization of the resonant tank voltage division and frequency multiplication, which can increase the overall life of the equipment. So, the DSTS-FD modulation is an optional solution.

4 | ANALYSIS OF TEST RESULTS

In order to verify that the heat of each switch is more balanced when the converter operates under the proposed DSTS-FD modulation, lab established a 1 KW, 288V-48 V SS-FD LLC converter prototype and a DSTS-FD LLC converter prototype. The two converters are the same except for the different operating frequencies of the transistors. The specific parameters are shown in Table 1. The test prototype is shown in Figure 9, including the drive circuit, inverter circuit, resonant circuit, and rectifier circuit. The device parameters used by the two experimental prototypes are exactly the same, and the comparison and analysis are carried out under the same experimental conditions. In addition, the switches all use DSP28335 for digital control.

Figure 10A,B is the V_{gs} waveforms of each switch at no-load under SS-FD control and DSTS-FD control, respectively. In Figure 10A, the gate-source voltages of switches S_1, S_2, S_3, and S_4 are defined as $V_{gs1}, V_{gs2}, V_{gs3}$, and V_{gs4}, respectively, and the amplitude voltage is +15V; the duty cycle of S_1 and S_4 is 0.25, and the phase difference is 180°, the duty cycle of S_2 and S_3 is 0.75, the phase difference is also 180°, and the modulation waveforms of S_1 and S_2 are complementary; the switching frequencies of these four switches are all 250 kHz. $V_{gS1a}, V_{gS1b}, V_{gS2}, V_{gS3}, V_{gS4a}$, and V_{gS4b} represent the gate-source voltages of switches $S_{1a}, S_{1b}, S_2, S_3, S_{4a}$, and S_{4b} in Figure 10B, respectively, and the amplitude voltage is also +15V. The switching frequency of S_{1a} and S_{1b} is 125 kHz, whose duty cycle is 0.375, and the phase difference between the two is 180°; the switching frequency of S_2 is 250 kHz, and the duty cycle is 0.25. In addition, the modulation waveforms of S_{1a}, S_{1b}, and S_2 are complementary in one cycle. The switching frequency of S_3 is 250 kHz, and the duty cycle is 0.25. The switching frequency of S_{4a} and S_{4b} is 125 kHz, whose duty cycle is 0.375, and the phase difference between the two is 180°. In addition, the modulation waveforms of S_3, S_{4a}, and S_{4b} are complementary in one cycle. The experimentally measured gate-source waveforms are the same as the theoretical waveforms in Section 2.

Make both converters work under the input voltage of 288 V and the resonant tank in the resonant state. Take the output power of 500 W as an example. Switch voltage waveform V_{ds}, gate-source voltage waveform V_{gs}, resonant tank current waveform I_r, and inverter output voltage waveform V_{ab} were measured experimentally, as shown in Figures 11 and 12. It can be seen from Figure 11A that the voltage across the switch S_1 has dropped to 0 before it is turned

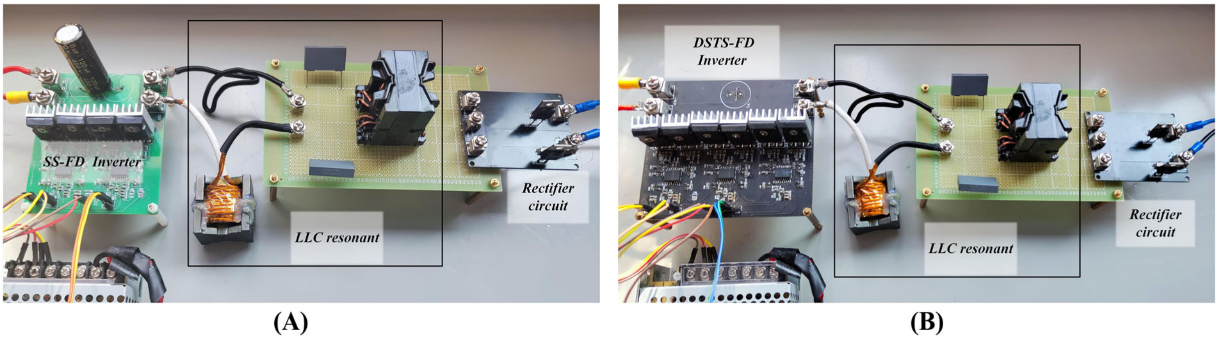

FIGURE 9 Experimental prototype. (A) SS-FD LLC converter. (B) DSTS-FD LLC converter [Colour figure can be viewed at wileyonlinelibrary.com]

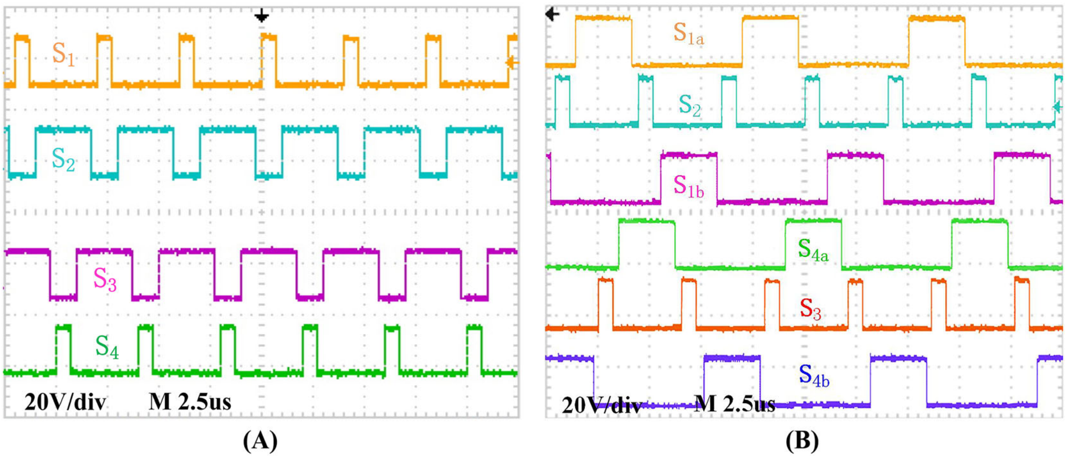

FIGURE 10 Modulation waveform (no load). (A) SS-FD modulation. (B) DSTS-FD modulation—gate-source voltage of left half-bridge switches $S_{1a}, S_2, S_{1b}, S_{4a}, S_3, S_{4b}$ [Colour figure can be viewed at wileyonlinelibrary.com]

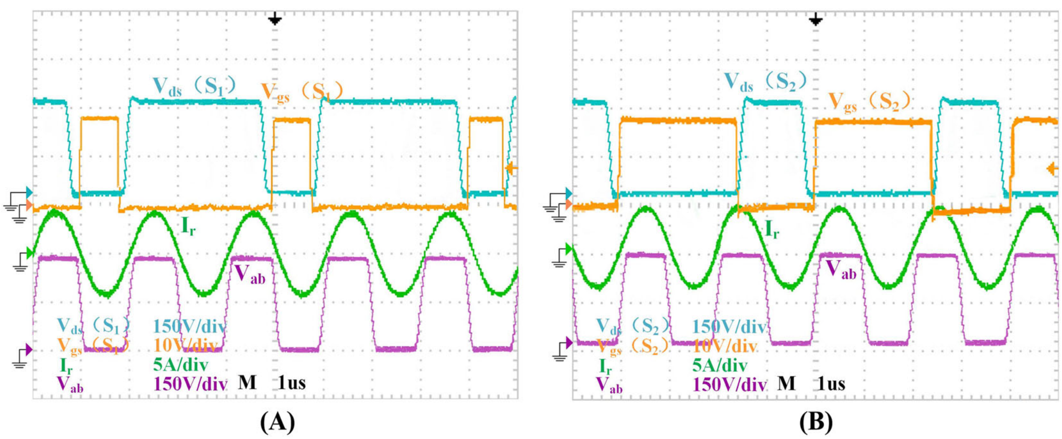

FIGURE 11 Switching waveform under SS-FD modulation. (A) Switch S_1 ($D = 0.25$). (B) Switch S_2 ($D = 0.75$) [Colour figure can be viewed at wileyonlinelibrary.com]

on. Similarly, as shown in Figure 11B, the voltage across the switch S_2 drops to 0 before it is turned on. Therefore, all switches of the SS-FD LLC converter realize soft switching, which reduces the switching loss. It can be seen from the I_r waveform in Figure 10 that the converter works in a resonant state, and the efficiency is the highest at this time. The frequency of output voltage V_{ab} and the frequency of the resonant tank current I_r are both 500 kHz, which is twice the

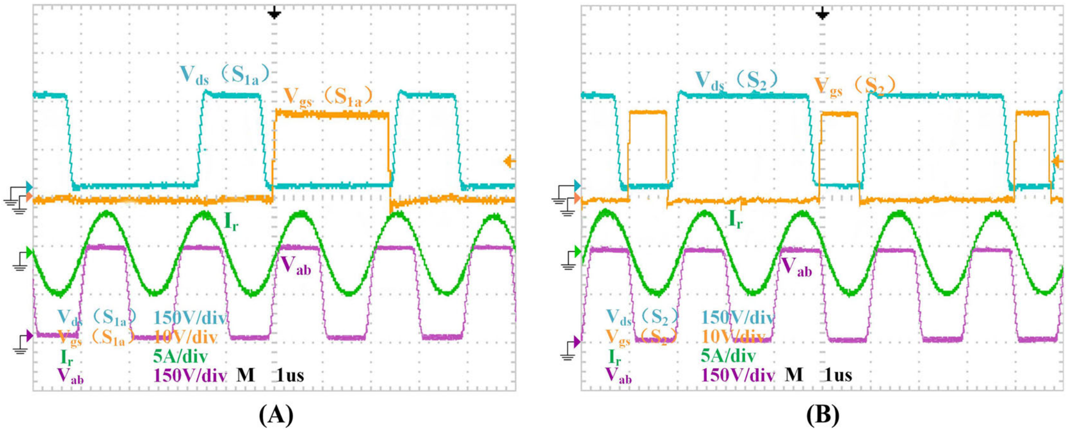

FIGURE 12 Switching waveform under DSTS-FD modulation. (A) Switch S_{1a} ($D = 0.375$). (B) Switch S_2 ($D = 0.25$) [Colour figure can be viewed at wileyonlinelibrary.com]

switching frequency, achieving the effect of frequency doubling. As shown in Figure 12A, the switch S_{1a} is turned on after the voltage at both ends drops to 0; as shown in Figure 12B, the voltage at both ends of the switch S_2 drops to 0 before it is turned on. At this time, the DSTS-FD LLC converter also realizes the soft switching of the switches, reducing the switching loss. It can be seen in Figure 11A,B that the converter works in the resonant state, that is, in the state with the highest efficiency. The frequency of output voltage V_{ab} and the frequency of the resonant tank current I_r are also 500 kHz, which is four times the switching frequency of the switch S_{1a} and is two times the switching frequency of the switch S_2, which also achieves the effect of frequency multiplication.

In this paper, the loss of the switch is judged by measuring the calorific value of each switch. In order to make the experiment more convincing, the heating conditions of the switch during stable operation were measured under different output powers (100 W, 500 W, 1000 W). Figure 13 is the thermal image of the switch under different output power, in which Figure 13A,C,E is the thermal image of the SS-FD LLC converter at different output power; Figure 13B,D,F is the thermal images of the DSTS-FD LLC converter at different output powers.

When the output power of the converter is 100 W (light load), as shown in Figure 13A, the average temperature of switches with a duty ratio of 0.25 is 30.4°C, and the average temperature of switches with a duty ratio of 0.75 is 34.5°C. As shown in Figure 13B, the average temperature of switches with a duty ratio of 0.375 is 31.5°C, and the average temperature of switches with a duty ratio of 0.25 is also 30.4°C. As can be seen from the above data, the average temperature difference between the switches with a duty ratio of 0.25 and those with a duty ratio of 0.75 is 4.1°C. However, the average temperature difference between the switches with a duty cycle of 0.25 and those with a duty ratio of 0.375 is only 1.1°C.

When the output power of the converter is 500 W (medium load), it can be seen from Figure 13C that the average temperature of switches with a duty ratio of 0.75 is 51.5°C, and the average temperature of switches with a duty ratio of 0.25 is 41.3°C. As shown in Figure 13D, the average temperature of switches with a duty ratio of 0.375 is 42.9°C, and the average temperature of switches with a duty ratio of 0.25 is also 41.3°C. It can be seen that the average temperature difference between the switches with a duty ratio of 0.25 and that with a duty ratio of 0.75 is 10.2°C. While the average temperature difference between the switches with a duty cycle of 0.25 and those with a duty ratio of 0.375 is only 1.6°C.

When the output power of the converter is 1000 W (heavy load), as shown in Figure 13E, the average temperature of switches with a duty ratio of 0.75 is 59.5°C, and the average temperature of switches with a duty ratio of 0.25 is 46.3°C. As shown in Figure 13F, the average temperature of switches with a duty ratio of 0.375 is 48.4°C, and the average temperature of switches with a duty ratio of 0.25 is 46.4°C. As can be seen from the above data, the average temperature difference between the switches with a duty ratio of 0.25 and those with a duty ratio of 0.75 is 13.2°C. However, the average temperature difference between the switches with a duty cycle of 0.25 and those with a duty ratio of 0.375 is only 2.1°C.

As can be seen from the above analysis and Figure 14, there are some differences in the heat of each switch under DSTS-FD modulation. But compared with SS-FD modulation, the heat difference of each switch is very small. The experimental results are consistent with the analysis results in Section 3, which verifies the superiority of the DSTS-FD modulation.

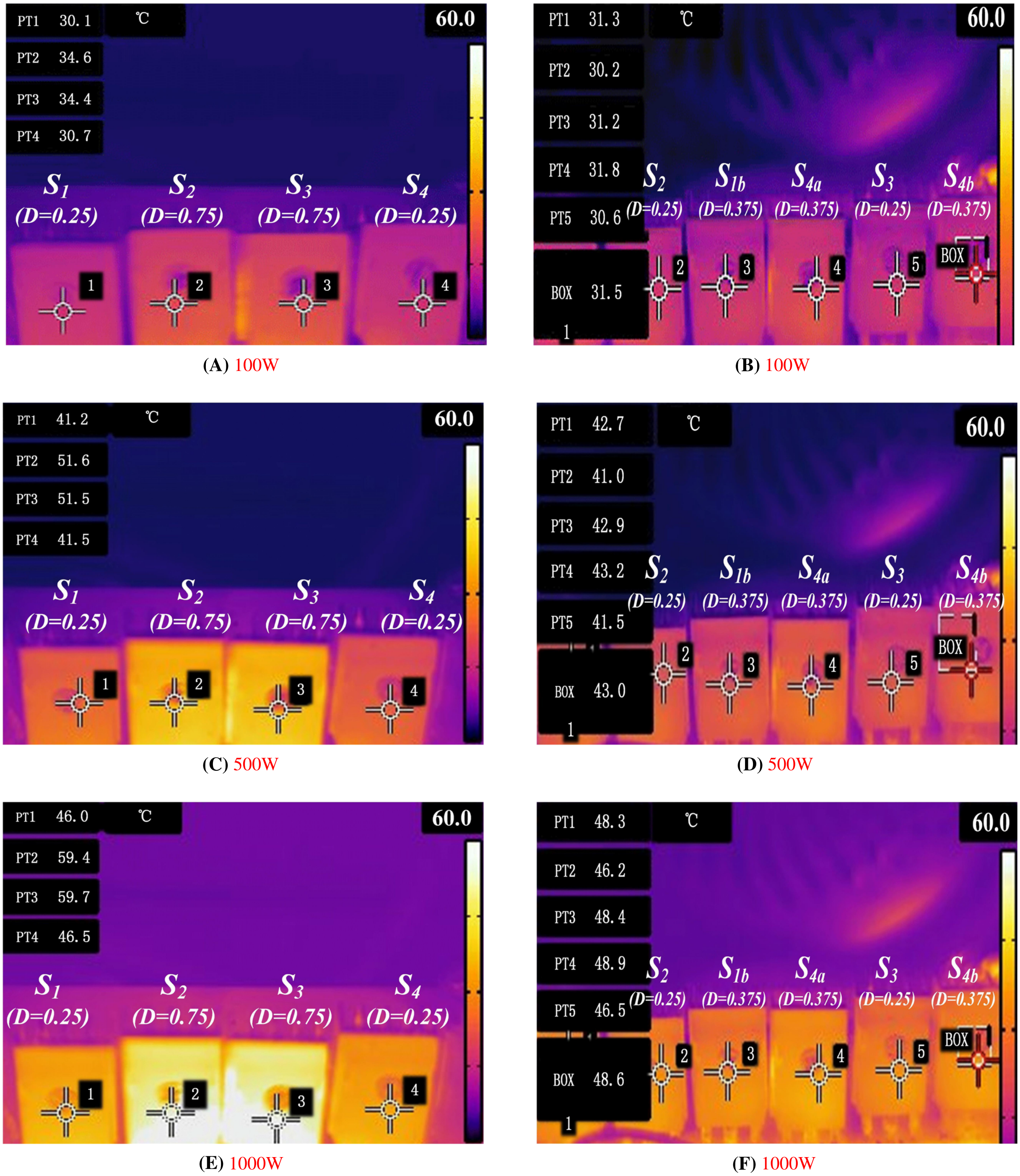

FIGURE 13 Thermal images at different output powers. (A, C, E) Thermal image of SS-FD LLC converter. (B, D, F) Thermal image of DSTS-FD LLC converters [Colour figure can be viewed at wileyonlinelibrary.com]

The efficiency of the two experimental prototypes under different loads is shown in Figure 15. At different power points, the efficiency of SS-FD modulation is slightly higher than that of DSTS-FD modulation, but the difference is not significant. The loss of the whole machine mainly includes MOSFET loss, drive loss, diode loss, transformer loss, resonant inductor loss, and resonant capacitor loss. According to the analysis in Section 2.4, the resonant current of the two modulation methods is the same when working under the same load. So, diode loss, transformer loss, resonant inductor loss, and resonant capacitor loss are respectively the same under the two modulation methods. Because DSTS-FD modulation has two more driving circuits than SS-FD modulation, the drive loss of the converter in DSTS-FD modulation is slightly larger, which reduces the efficiency of the converter. This makes the converter slightly less efficient in DSTS-

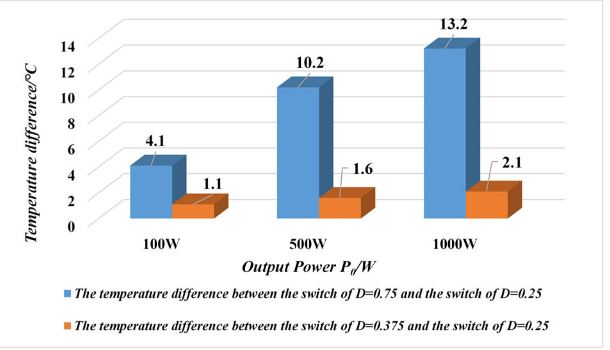

FIGURE 14 Temperature difference of switches under different output power [Colour figure can be viewed at wileyonlinelibrary.com]

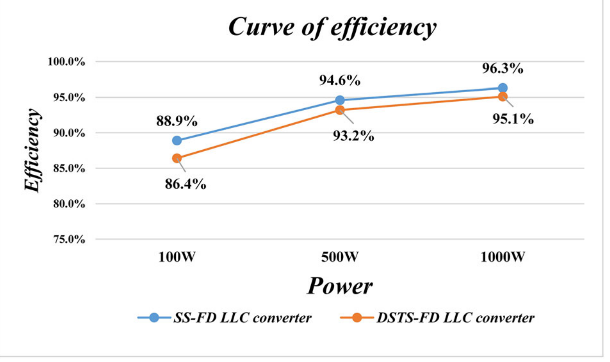

FIGURE 15 Prototype efficiency curve [Colour figure can be viewed at wileyonlinelibrary.com]

FD modulation than in SS-FD modulation. However, under the condition of sacrificing a certain loss, DSTS-FD modulation makes the loss difference between each switching tube become small, which significantly increases the service life of the converter.

5 | CONCLUSION

In this paper, a DSTS-FD modulation is proposed to optimize the problem of uneven loss of each switch when the full-bridge LLC circuit operates under the SS-FD modulation. The proposed modulation method is applied to the DSTS-FD LLC converter. The duty ratio of the two switches connected in parallel in each bridge arm is 0.375, and they have the same switching frequency and are 180° out of phase. And the duty cycle of the other switch is 0.25, and the switching frequency is twice that of the former. In addition, the two half-bridge modules are 180° out of phase. This paper expounds the working principle of the DSTS-FD modulation and introduces the analysis process of the switch loss. Through theoretical calculation, the losses of each switch under SS-FD modulation and DSTS-FD modulation are compared. The results show that the losses of each switch are basically same when the LLC converter operates under the proposed modulation mode in this paper. Finally, experiments are carried out on a prototype of a full-bridge LLC converter based on 288 V–1 kW. The converter is operated under the proposed modulation method and the existing modulation method, respectively. By comparing the losses of each switch during stable operation, the experimental results verify the superiority of the proposed modulation method.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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