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Self-driven Gate Driver for LLC Synchronous Rectification

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Abstract- This letter proposes a self-driven gate driver solely composed of passive components for synchronous rectification (SR). It utilizes the energy of the converter itself, automatically considers component tolerances and temperature variations of critical design parameters, and tunes the SRs on-time. Furthermore, no microcontroller, auxiliary power supply or current-sensing/voltage-sensing components is required. A great amount of cost is therefore saved. The proposed gate driver is preferable to be used to any resonant converters operating as DC transformers. This letter presents its practical implementation in an LLC resonant converter. Experiment results illustrate that the body diodes conduction and reverse recovery are eliminated.

I. INTRODUCTION

Converters used for low voltage high current applications generally require synchronous rectification for the secondary side devices to improve the total system efficiency. For instance, the LLC resonant converter, as shown in Fig.1, benefits from zero-voltage-switching (ZVS) for primary switches and zero-current-switching (ZCS) for secondary synchronous rectifiers (SRs). It is often operating as a DC transformer whose switching frequency is the resonant frequency to achieve peak efficiency. A deal of research was conducted to improve SR driving schemes [1]-[14]. These driving schemes can be generally grouped into current sensing-based and voltage sensing-based methodologies. Large power loss is induced by the current sensing-base SR driving scheme due to additional current sensing components [1]-[3]. The accuracy of the voltage sensing solution is highly sensitive to the circuit parasitic inductance [4]-[9]. Publications [6]-[9] present an adaptive algorithm processed in a microcontroller. These driving schemes either add the system complexity or increase the cost. Commercial SR driving controllers [10]-[13] based on voltage-sensing schemes cannot achieve high-frequency operation causing by the propagation delay.

This paper proposes a new driving scheme: the driving signals V_{gs_SR} for the secondary SRs are generated from the drain-source voltage V_{ds_SR} . The auxiliary passive components create a resonant tank to extract the first harmonic of V_{ds_SR} with a 180-degree phase shift to create the gate signal V_{gs_SR} . This principle automatically considers component tolerances and temperature changes of critical design parameters [15]. It eliminates the body diodes conduction, and reverse recovery. Furthermore, no microcontroller or current-sensing/voltage-sensing components is required, thus significantly reducing the cost.

The remainder of this paper is organized as follows: The operating principle is given in Section II. Section III illustrates the design considerations to implement it practically in an LLC resonant converter. Section IV shows the experimental results of the LLC resonant converter using this passive gate driver. Section V concludes the paper.

Fig.1 Topology of the LLC resonant converter

Fig.2 (a) Circuit model of MOSFET and (b) proposed synchronous driving scheme

Fig.3 Equivalent circuit of the self-driven gate driver

II. OPERATING PRINCIPLE

The circuit diagram shown in Fig.2(a) illustrates a MOSFET with its parasitic capacitances, C_{ds} , C_{gs} and C_{gd} . The proposed synchronous driving scheme is only constituted by 3 passive components, L_{ad} , C_{ad} , and R_{as} , optional with additional MOSFET's capacitances C_{gd_ext} , C_{gs_ext} as shown in Fig.2 (b). No auxiliary power supply is needed. Generally, the gate signal V_{gs_SR} is generated from the square wave V_{ds_SR} . The added components compose a resonant tank. It attenuates the first harmonic of V_{ds_SR} with the 180-degree phase shift to adequate value to create the V_{gs_SR} . Other higher-order harmonics are

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highly attenuated and negligible. Detailed operating analyses are given as follows.

Fig.3 shows an equivalent circuit of the proposed driving scheme. The square wave V_{ds_SR} is seen as the input voltage source and the V_{gs_SR} is taken as the output. C_{ds} , C_{gs} and C_{gd} are inherent capacitances of the MOSFET. L_{ad} , C_{ad} , C_{gd_ext} , C_{gs_ext} and R_{as} are auxiliary passive components. The following equations (1) and (2) represent the transfer function G from the output V_{gs_SR} to the input V_{ds_SR} , and input impedance Z_{in} , respectively. Two resonant frequencies f_{r1} and f_{r2} can be solved by setting the input impedance Z_{in} to be zero: L_{ad} , C_{ad} , C_{gs_ext} and C_{gs} form the first resonant frequency f_{r1} ; C_{gd} , C_{gd_ext} and L_{ad} constitute the second resonant frequency f_{r2} . The bode plot of the transfer function G is shown in Fig.4. As mentioned before, 180-degree out of the phase with respect to the V_{ds_SR} at the switching frequency is expected for the V_{gs_SR} to achieve synchronous rectification. It can be seen that there is a 180 degree phase shift in the region between f_{r1} and f_{r2} , where the fundamental harmonic frequency f_r of the V_{ds_SR} is involved.

$$G = \frac{V_{gs_SR}}{V_{ds_SR}} = \frac{R_{as} // \frac{1}{s(C_{gs} + C_{gs_ext})}}{R_{as} // \frac{1}{s(C_{gs} + C_{gs_ext})} + \frac{1}{s(C_{gd} + C_{gd_ext})} // \left(sL_{ad} + \frac{1}{sC_{ad}}\right)} \quad (1)$$

$$Z_{in} = R_{as} // \frac{1}{s(C_{gs} + C_{gs_ext})} + \frac{1}{s(C_{gd} + C_{gd_ext})} // \left(sL_{ad} + \frac{1}{sC_{ad}}\right) \quad (2)$$

$$f_{r1} = \frac{1}{2\pi\sqrt{L_{ad} \cdot (C_{gs} + C_{gs_ext}) // C_{ad}}}, f_{r2} = \frac{1}{2\pi\sqrt{L_{ad} (C_{gd} + C_{gd_ext})}} \quad (3)$$

Fig.4 Typical bode plot of the transfer function G

Additionally, considering the MOSFET safe operation, the peak-to-peak gate-source voltage must be designed in a safe range. It contains the DC offset and a sine voltage swing (the attenuated first harmonic of V_{ds_SR}). The DC offset can be used to change the duty cycle. Fig.5 shows two gate signals: one with DC offset and the other without DC offset. Higher DC offset yields a larger duty cycle. The resistor R_{as} can be used to control this DC offset. As the LLC resonant converter is operating at a fixed 50% duty cycle, the DC offset is not required for the SRs'

gate signal. It can be eliminated by choosing a smaller R_{as} . As mentioned earlier, the passive gate driver should be designed to attenuate the first harmonic of V_{ds_SR} with a 180-degree phase shift to adequate value. This means that the amplitude of the sine voltage swing must be lower than the MOSFET maximum allowed gate-to-source voltage, which can be calculated by (4).

$$V_{gs_SR}(f_r) = V_{ds_SR} \cdot 10^{\frac{G(j\omega f_r)}{20}} \quad (4)$$

Other higher-order harmonics located on f_r right side are not considered, because they suffer much larger attenuation than the fundamental harmonic, as shown in Fig. 4. Therefore, these higher-order harmonics have extremely low amplitude and negligible effect on the gate signal.

Based on the above discussions, the passive gate driver should be designed to satisfy three requirements: 1) the fundamental harmonic frequency of V_{ds_SR} is located in the region between the two resonant frequencies f_{r1} and f_{r2} where the phase shift is close to 180-degree; 2) the fundamental harmonic of V_{ds_SR} is attenuated to adequate value for the MOSFET safe operation, which can be calculated by (4); 3) The DC bias is well attenuated.

Fig.5 Two gate signals comparison

TABLE I
SPECIFICATION

Symbol	Quantity	Value
V_{in}	Input voltage	30V
V_o	Output voltage	5V
P_o	Output power	75W

TABLE II
CIRCUIT PARAMETERS

Circuit parameters	Value
$Q_1 \sim Q_2$	BSZ034N04LS
$SR_1 \sim SR_2$	BSC009NE2LS5I
Magnetizing inductance L_m	9uH
Resonant inductance L_r	40nH
Resonant capacitance C_r	2.35uF
Resonant frequency	500kHz
Transformer	n:1:1=3:1:1 ER18/3.2/10-ML91S

III. DESIGN CONSIDERATIONS

A design example of the LLC resonant converter as a DC transformer is given in this section. Table I gives the design specification and Table II illustrates detailed circuit parameters. The maximum drain-to-source voltage V_{ds_SR} for SRs is 10V.

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The passive components should be designed with a given MOSFET and specification. From (3), the inductor L_{ad} should be designed with the consideration of f_{r1} and f_{r2} , as they are both controlled by this auxiliary inductor. Additionally, the capacitor $C_{gs\ ext}$ in parallel with C_{gs} can be used to adjust the resonant frequency f_{r1} . Likewise, the resonant frequency f_{r2} can be changed by $C_{gd\ ext}$ connected in parallel with C_{gd} . Nevertheless, it is not mandatory to add the two capacitors $C_{gs\ ext}$ and $C_{gd\ ext}$ to the circuit unless the fundamental harmonic frequency is not covered in the region between the two resonant frequencies f_{r1} and f_{r2} . The DC bias of $V_{gs\ SR}$ can be controlled by the resistor R_{as} and thus change the duty cycle. As mentioned before, the LLC resonant converter is operating at a fixed 50% duty cycle. The DC bias is not required and can be eliminated by choosing a smaller R_{as} .

Ltspice simulation is a faster and more practical approach to design the circuit parameters compared to analytical calculation, considering the non-linear behavior of MOSFET parasitic capacitances. The auxiliary passive components are designed after a series of simulations, as documented in Table IV. Fig.6 gives the bode plot of G from the small-signal analysis performed in Ltspice. Table V represents detailed characteristics. It is evident to see that the designed parameters satisfy all the requirements as mentioned above: The phase shift is close to 180-degree at the resonant frequency f_r ; The fundamental harmonic is involved in the region formed by f_{r1} and f_{r2} ; The DC bias is well attenuated; $G(j2\pi f_r)$ is in a safe region.

Fig.6 Bode plot of V_{gs} with designed circuit parameters

TABLE IV
PARAMETERS OF THE GATE DRIVER

Circuit parameters	Value
L_{ad}	12uH
C_{ad}	47nF
$C_{gd\ ext}$	0
R_{as}	200Ω
$C_{gs\ ext}$	33nF

TABLE V
CHARACTERISTICS OF THE BODE PLOT

Characteristics	Value
f_{r1}	350kHz
f_r	500kHz
f_{r2}	2MHz
$G(j2\pi f_r)$	-8dB

IV. EXPERIMENT VERIFICATION

The LLC resonant converter is built to verify the proposed gate driver for synchronous rectification. Fig.7 shows the gate signal and drain-to-source voltage of Q_2 along with resonant current waveform i_r and gate signal for SR_2 . Q_2 realizes ZVS soft-switching. Due to the feature of half-bridge configuration, Q_1 also realizes ZVS soft-switching. Fig.8 presents driving signals for SR_1 and SR_2 . It can be seen that the self-driven gate driver works very well. The two gate signals automatically oscillate 180-degree out of phase with the drain-source voltage and toggle complementarily with respect to each other. The efficiency curve of the LLC resonant converter is shown in Fig.9. It achieves the 96.2% peak efficiency.

Fig.7 ZVS soft-switching waveform of Q_2 at full load

Fig.8 Driving signals for SR_1 and SR_2

Fig.9 Efficiency curve of the LLC resonant converter

To prove the proposed gate driver eliminates the body diode conduction, this paper makes a comparison with the converter employing the traditional low side gate drivers Si8271 whose gate signals are in phase with primary switches. The forward voltage drop of the body diode is 0.5V, as shown in Fig.10. 100ns body diode conduction due to the propagation delay is detected for the converter with the gate driver Si8273. By contrast, no body diode conduction appears for the converter

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employing the proposed gate driver at either light load (10% of the full load) or full load condition.

Fig.10 Measurement of body diode conduction at (a) 10% load with Si8271, (b) 10% load with the passive gate driver, (c) full load with Si8271, and (d) full load with the passive gate driver

V. CONCLUSION

This letter proposes a synchronous driving scheme primarily for resonant converters working as DC transformers, and presents its design considerations and practical implementation on an LLC resonant converter. Unlike conventional current sensing-based and voltage sensing-based SR driving solutions, it benefits from low cost and reliable solution only constituted by passive components. Furthermore, the proposed SR scheme is not affected by the circuit parasitic components and automatically tunes the SR on-time in different load conditions.

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