Open Loop Synchronous Rectifier Driver for LLC Resonant Converter

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Abstract — Synchronous rectifier (SR) is widely used in LLC resonant converter to reduce the conduction loss. Due to different operation modes, the SR control is complicated and increases system cost. In this paper, based on the observation on LLC diode conduction time, an open-loop fixed-on-time SR driving method is proposed. The optimal on-time is used to control the SR to simplify the implementation in different operation mode and reduce the system cost while maintaining large efficiency improvement. The total efficiency of LLC resonant converter with SR driven by the proposed scheme is proved to increase by 2% under different load conditions with minimum system cost.

Index Terms — Synchronous rectifier driver, LLC resonant converter application, efficiency, fixed time, primary side gate drive, low cost, different load conditions.

I. INTRODUCTION

The pursuit of higher efficiency and power density in DC/DC converters has pushed power electronic devices to their maximum capable switching frequency. Under such circumstances, LLC resonant converter becomes very popular due to its potential in low power loss with high switching frequency [2]. The topology (shown in Figure 1.) has been widely adopted in applications such as digital TV, PC power and server powers. The zero-voltage-switching (ZVS) for primary side switching devices and zero-current-switching (ZCS) for secondary side rectifiers provide the benefits of less switching loss thus improve the converter efficiency and power density in the meantime [1, 2, 3].

Control of the secondary synchronous rectifier (SR) is one of the design challenges for LLC resonant converter. A lot of research efforts have been focused on this area. For example, Figure 2(a) shows the idea of sensing the SR current with current transformer, then initiating the SR gate drive with emergence of diode current signal, is limited by the volume of large current transformer for high power applications [3, 7]. While in Figure 2 (b), transformer secondary side voltage is used to drive the SR directly. However, the driving method is not optimal due to sinusoidal voltage waveform induced [3-6]. Currently, the most adopted solution is to measure the SR drain to source voltage and determine the timing for turning ON and OFF the devices.

II. PROPOSED FIXED-ON-TIME SR DRIVE

The idea of using primary side gate drive as secondary trigger signal might draw some attention. As could be observed in Figure 3, which shows three cases of different switching frequencies vs. resonant frequencies, primary side gate drive may not always be utilized to drive secondary side SR.

In Figure 3 (a) and (b), when the switching frequency is equal or higher than the resonant frequency, the primary side gate drive could be used since the current on diode is not reaching negative on the primary side gate drive signal edge.
and full percentage of diode conduction loss could be saved under such condition.

However, in the case of switching frequency below resonant frequency, the diode current reaches zero before gate drive reverses. If primary side gate drive is applied in this circuit, current on secondary side SR will backflow causing energy transferring backward to primary side. Since the converter is designed to be power unidirectional, this situation might cause overheat in the transformer or even other disastrous situations.

Figure 4 shows diode on-time measurements under different line and load situations with Texas Instruments UCC25600EVM (power rating 300 W, input 390 V, output 12 V) [8]. The diode conduction time varies with different load conditions. In order to develop a feasible, easy, efficient and inexpensive way to drive the SR, the idea of choosing a fixed on-time gate drive for secondary SR under normal to heavy load conditions while directly applying primary side gate drive under light load condition was proposed.

The principle could be illustrated in Figure 5. By fixing the SR ON time, certain amount of diode conduction loss would be saved while the rest of conduction loss sacrificed as marked in grey shadow in the figure. Under statistics shown in Figure 4., most of the conduction loss could be saved by choosing the fixed on-time of 2.7 us.

Further conduction loss calculation estimation under different SR on-time with input voltage of 375 V and load of 144 W shown in Figure 6. reveals that the converter's total conduction loss is 5.17 W by using diode. The conduction loss drops to 0.32 W if SR ideally replaces the diodes through conduction period. However, with SR on-time of 2.7 us, the loss reduces to 1.2 W, which is about 80% conduction loss reduction.

Although the SR controller might further reduce the conduction loss by keep SR conduction time longer, there are a few difficulties and actual results might be worse: the SR control adds the system cost; due to the LLC operation mode, before SR turns off, the di/dt generates offset voltage on SR parasitic inductor and cause SR to pre-maturely turn off; the lowest conduction loss SR might not be used because
of early turn off at the fixed threshold. For most of the time, the SR controller might not get as much conduction loss reduction as wished.

Based on the proposed control method, the on-time of the SR is fixed for all the line and load conditions when the switching frequency is equal or below the resonant frequency. When the switching frequency is higher than the resonant frequency, the SR on-time is limited by primary side switch on-time. This way, the SR control is completely open loop and operating normally amount different line and load conditions, even during transient.

Figure 7 shows the detailed SR gate drive single generation implementation scheme based on primary side gate signals. By OR logic operation of primary side gate drive, the gate driver turn-on edges are extracted and used to excite the 555 timer.

After the fixed 2.7 us on-time generated, it is processed through AND logic gate to ensure proper operation under different load conditions. The output signals are converted to gate drive signals to control SR. The primary side gate signal automatically limits the maximum on–time of SR, allows proper operation among different line and load conditions.

III. EXPERIMENTAL RESULT AND EFFICIENCY COMPARISON

The experiment verification setup is implemented on Texas Instruments UCC25600EVM [8]. Hardware picture is shown in Figure 8. Right side on the breadboard is the gate drive circuit, and the left green PCB is the evaluation board with two MOSFETs with small passive heatsinks paralleled to the diode rectifier on the secondary side of LLC resonant converter.

Figure 9 (a) and (b) show the converter waveforms with SR under heavy and light load conditions.

As can be observed in (a), during heavy load condition, SR gate drive covers most of the SR conduction time and raises the efficiency. Though part of the diode conduction time is not covered, that part of conduction loss is ignored.

In (b) light load condition, the diode conduction time is approaching the fixed time of 2.7 us. The transient of SR switching to diode conduction induces large voltage spikes due to parasitic inductance effect.

As revealed in Figure 10, the efficiency is increased by 2% using SR. Further conduction loss improvement can be achieved by using lower conduction loss SRs, because the conduction time won’t affected by the MOSFET on resistance.
The statistics result shown in Figure 11 tells that the efficiency of light load with SR could be lower than converter without SR. That is because under light load condition, the switching related loss increases and causes the efficiency to drop dramatically. The SR can be disabled during light load condition and this negative effect can be eliminated.

IV. CONCLUSION

This paper proposed a fixed on-time SR driver used for LLC resonant converter applications. The design procedure is introduced as: collecting diode conduction time; choose the best SR on time for normal and heavy load; implement the fixed time control scheme and save efficiency.

Instead of "actively" acquiring the diode conduction time used in most adopted applications, the proposed method "passively" sets the SR on time and saves most of the diode conduction loss with extremely low cost and simple control. It works well with different load conditions and especially provides a cost effective solution for cost sensitive applications.

ACKNOWLEDGMENT

This work was supported by Customer Isolated Power department in Texas Instruments located at Manchester, NH 03104.

REFERENCES