Digital Implementation of Adaptive Synchronous Rectifier (SR) Driving Scheme for LLC Resonant Converters

Chao Fei, Student Member, IEEE, Fred C. Lee, Fellow, IEEE, Qiang Li, Member, IEEE

Center for Power Electronics Systems
Virginia Tech, Blacksburg, VA 24061 USA
feichao@vt.edu

Abstract—In this paper, an adaptive synchronous rectifier (SR) driving scheme for the LLC resonant converters using the ripple counter concept is proposed, along with two methods of implementation. With the proposed scheme, the SR drain to source voltage is sensed to detect the body diode conduction, based on which the SR on-time can be well tuned to eliminate the body diode conduction. One proposed implementation tunes the SR on-time every switching cycle based on the ripple detection; another proposed implementation tunes the SR on-time every n^{th} switching cycle (n = 1, 2, 3 …) based on the ripple counter, which is suitable for the high frequency LLC converters. The proposed SR driving scheme has the simple implementation, requires only low-cost digital controllers and occupies very few controller resources. More importantly, since the digital controllers have already been widely adopted in the control of the LLC converters, the proposed adaptive SR driving method can be embedded into these digital controllers with little extra cost. Furthermore, how to integrate the proposed SR driving method with closed-loop control is explained in details. Experimental results are demonstrated on a 130kHz LLC converter with 100MHz microcontroller (MCU) and a 500kHz LLC converter with a 60MHz MCU and a ripple counter.

Keywords—LLC resonant converter, high frequency converters, synchronous rectification, digital control.

I. INTRODUCTION

The LLC resonant converter has been widely used as a DC-DC converter due to its high efficiency and hold-up capability [1][2]. With the fast development of the information technology, the demand for higher efficiency keeps growing. Since most of the IT applications require the DC-DC converters to provide a low-voltage high-current output, the diode rectifiers will induce very large conduction loss. The synchronous rectifiers (SR) are critical for the LLC converters to improve the efficiency by tremendously reducing the conduction loss of the diode rectifiers.

However, the SR driving scheme is quite challenging due to the discrepancy between the primary driving signal and the SR driving signal. The topology of the LLC converters is shown in Fig. 1, and the corresponding SR on-time under different switching frequency is shown in Fig. 2. If the switching frequency is below the resonant frequency, the SR on-time is smaller than the primary switch on-time; if the switching frequency is above the resonant frequency, the SR on-time is larger than the primary switch on-time; if the switching frequency is equal to the resonant frequency, the SR on-time is equal to the primary switch on-time. Besides, the SR on-time is also dependent on the load condition.

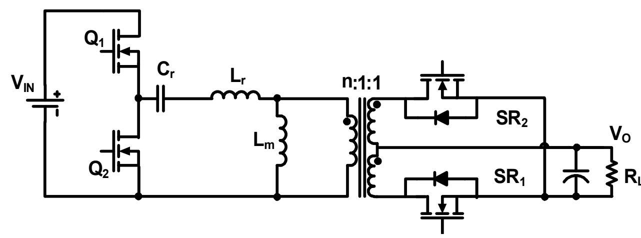


Fig. 1. Topology of the LLC converters

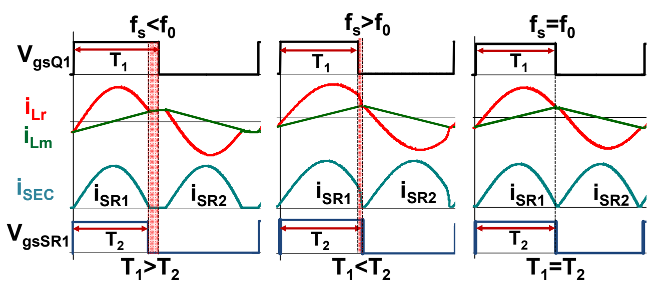


Fig. 2. SR on-time of the LLC converters under different switching frequency

Several SR driving methods have been proposed, most of which can be sorted into three categories. The first category of the SR driving methods is using the current sensing. One solution [3] is to use the current transformer to sense the SR current, and generate the corresponding driving signal, which is accurate but induces large loss due to the large current in the SRs. Another solution [4] using the CLL topology senses the primary current to generate the SR driving signal, but it requires an additional inductor with large inductance. Another SR driving method by sensing the primary resonant current was proposed in [5], but it requires the complex current-compensating winding in the current transformer to cancel out the magnetizing current and generate the suitable driving

This work is supported by the Power Management Consortium of Center for Power Electronics Systems (CPES) Industry Partnership.

signals for the SRs. The second category of the SR driving methods is to use the independent driving circuit based on the SR drain to source voltage V_{ds_SR}, which works in the following principle: at the beginning, the SR is in the off-state; when there is the body diode conduction, it would result in a large forward voltage drop; then the controller would compare the V_{ds_SR} with the turn-on threshold voltage; if the V_{ds_SR} is larger than the threshold, the controller would turn on the SR; in the LLC converters, during the SR on-time, the current in SR will first increase and then decrease to zero; as the current approaches zero, the V_{ds_SR} also becomes very small, which is compared with the turn-off threshold voltage to determine when to turn off the SR. Most of the solutions in the second category of the SR driving methods are the smart ICs [6][7][8]. However, the accuracy of the SR driving methods in the second category is highly affected by the SR package. The actual SR on-time is shorter than the expected value due to the inevitable package inductance of the SRs. This problem is extremely severe in the high frequency application. A compensation network can be connected to the sensed terminals to solve this problem [9]. The third category of the SR driving methods is the adaptive SR driving scheme. The drain to source voltage of SR V_{ds_SR} is detected to tune the gate driving signal. If there is the body diode conduction, the large forward voltage drop in V_{ds_SR} will be sensed and the SR on-time will be increased accordingly. One solution [10] proposes to use a compensator to generate the SR on-time. Another solution [11] proposes to detect the body diode conduction just at the SR turn-off moment, and tune the SR on-time step-by-step until it reaches around the optimal point.

The digital controllers are gradually taking the place of the analog controllers in the control of the LLC converters. Among the digital controllers, the cost-effective microcontrollers (MCU) are preferred in the industrial applications. The high frequency LLC converters can reduce the total cost due to its high power density and integrated magnetics [12][13]. And with the fast development of the wideband gap devices and the novel magnetic materials [14][15][16][17], the trend of pushing switching frequency higher continues.

Recently, a lot of efforts have been made to achieve the low-cost digital implementation of Simplified Optimal Trajectory Control (SOTC) for the LLC converters. Compared with the conventional control methods for the LLC converters, the SOTC has the benefits of the fast transient response and relatively simple implementation [18]. For the first time, the SOTC has been implemented by a low-cost MCU and demonstrated on a 130kHz LLC converter with 100MHz MCU [19]. The whole control system integrates the fast load transient response, the soft start-up with minimum stresses and the burst mode for the light load efficiency improvement, whose control scheme is shown in Fig. 3.

Furthermore, a lot of research have been conducted to analysis how to control the high frequency LLC converters with the low-cost MCUs based on the SOTC concept, including: detailed analysis of the optimal trajectory control for the soft start-up of the high frequency LLC converters [20], the digital implementation of the SOTC for the fast load transient response of the high frequency LLC converters [21], and the light load efficiency improvement for the high frequency LLC converters based on the SOTC [22]. The results in these papers are demonstrated on a 500kHz LLC converter with a 60MHz MCU.

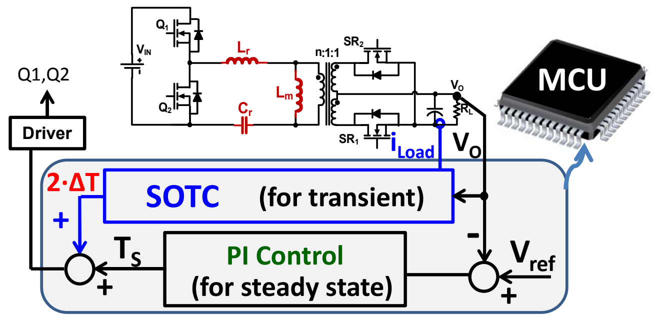


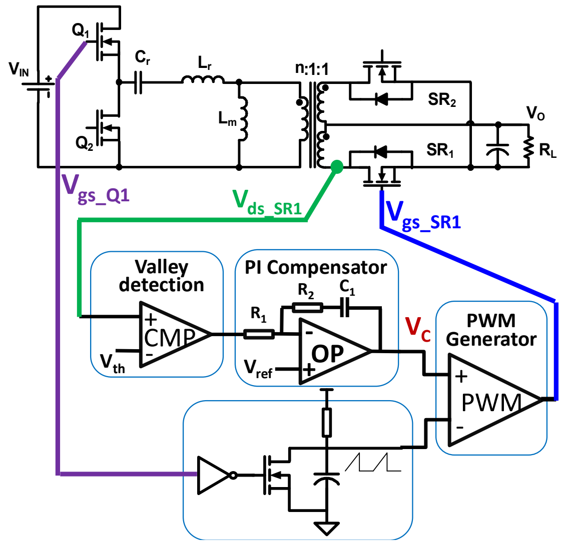
Fig. 3. Control scheme of SOTC with MCU implementation

To sum up, it is of great meaning to integrate the SR driving within the cost-effective digital controllers and combine with closed-loop control while at the same time utilizing very few controller resources. Furthermore, it is even more challenging to integrate the SR driving within the digital controller for the high frequency LLC converters with the minimum additional cost. Compared with the first and the second categories of the SR driving methods, which are independent solutions, the third category, which is adaptive SR driving, is more suitable to be integrated within the digital controllers.

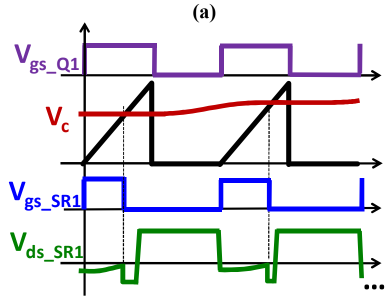
In this paper, Section II investigates the limitation of the previous adaptive SR driving methods. Section III proposes the adaptive SR driving scheme based on the ripple detection, and analysis how to combine the proposed SR driving method with the closed-loop control. Section IV extends the proposed adaptive SR driving scheme to the high frequency LLC converters by adding a ripple counter. Section V presents the experimental results on a 130kHz LLC converter with a 100MHz MCU and a 500kHz LLC converter with a 60MHz MCU. The conclusions are given in Section VI.

II. THE LIMITATIONS OF THE PREVIOUS ADAPTIVE SR DRIVING METHODS

The control scheme and waveforms of the adaptive SR driving method using linear compensator [10] are shown in Fig. 4. The SR body diode forward voltage drop is detected and compared with a threshold voltage. The output of the comparator is connected to the input of a linear compensator. The control signal of the linear compensator is connected to the positive input of the PWM generator, and a triangular waveform generated from the primary driving signal is connected to the negative input of the PWM generator. If the body diode conduction is detected, the compensator will increase the SR on-time gradually until the steady state. If no body diode conduction is detected, the compensator will decrease the SR on-time gradually to the new steady state.



(a)

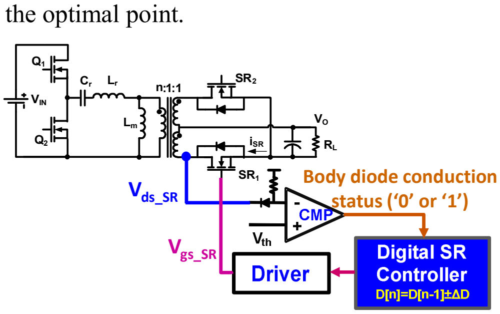


(b)

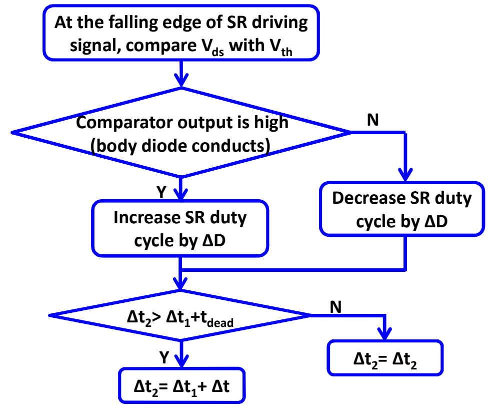
Fig. 4. Adaptive SR driving method using the linear compensator: (a) control scheme; (b) waveform

There would be two main limitations if this SR driving method is integrated within the cost-effective digital controllers. The first limitation is that it requires a linear compensator, which would either require the additional circuit or occupy a lot of CPU resources. The second limitation is that since the negative input of the PWM generator is from the primary driving signal, the maximum SR on-time cannot be large than the on-time of the primary switches, which is not suitable when the switching frequency is above the resonant frequency.

The control scheme and the control flowchart of the adaptive SR driving method based on the digital tuning [11] are shown in Fig. 5. The SR body diode forward voltage drop is detected and compared with a threshold voltage. The turn-on of the SRs in the LLC converters is synchronized with the primary switches. The on-time of the SRs is tuned step by step to be around the optimal point.



(a)



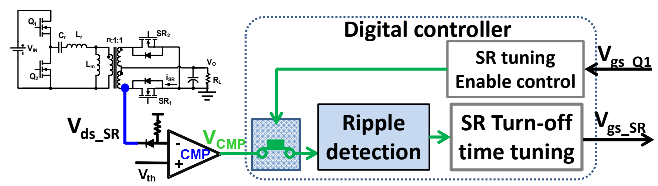
(b)

Fig. 5. Adaptive SR driving method based on the digital tuning: (a) control scheme; (b) control flowchart

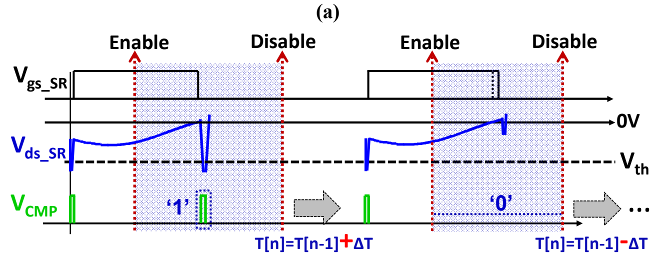
The limitation with this SR driving method is that it requires comparing the V_{ds_SR} with the threshold voltage (which means sensing the output of the comparator) just at the falling edge of the SR driving signal. The implementation of this function requires the additional logic circuit or an FPGA controller as demonstrated in [11], which cannot be integrated within the cost-effective digital controllers.

III. The Proposed Adaptive SR Driving Scheme Based on the Ripple Detection

To integrate the adaptive SR driving within the cost-efficiency digital controllers, an adaptive SR driving method based on the ripple detection is proposed, whose control scheme is shown in Fig. 6(a). The V_{ds_SR} is sensed and compared with the threshold voltage and the output of the comparator is connected to the ripple detection function of the digital controller, i.e. the external interrupt of the microcontrollers. Since the proposed adaptive SR driving method is integrated within the digital controller, the primary driving signal can be used to control the enable/disable of the ripple detection.



(a)



(b)

Fig. 6. The proposed adaptive SR driving based on the ripple detection: (a) control scheme; (b) waveform around the steady state

The control principle is explained in the followings. The turn-on time of the SR is synchronized with the turn-on of the primary switch, and there is a very small duration of the body diode conduction. After that, the ripple detection is enabled. And before the next SR turn-on moment, the ripple detection is disabled. If there is the body diode conduction, the controller would detect the ripple at the output of the comparator, and will increase the SR on-time by ΔT (ΔT is a very small period of time) for the next switching cycle. If there is no body diode conduction, the controller cannot detect the ripple, and will decrease the SR on-time by ΔT for the next switching cycle. The tuning process is the same as the previous adaptive SR driving method. And Fig. 6(b) shows the waveforms around the steady state.

To integrate the proposed adaptive SR driving method based on the ripple detection and the closed-loop control within the digital controller, execution of the closed-loop control and the adaptive SR driving must be properly allocated to the CPU of the digital controller. As shown in Fig. 7, within one switching cycle, the execution of the adaptive SR driving (red shade area) is divided into 3 parts and inserted into the closed-loop control (yellow shaded area). The Part 1 is to enable the ripple detection; the Part 2 is to store the result of the ripple detection; and the Part 3 is to disable the ripple detection and update the SR on-time for the next switching cycle.

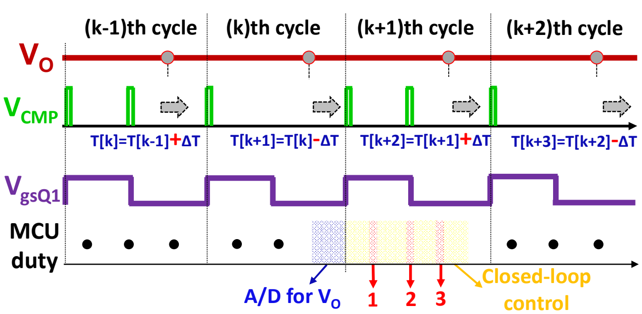


Fig. 7. Allocation of MCU duty for the closed-loop control and the adaptive SR driving within one switching cycle

Furthermore, the SR on-time must be changed accordingly during the transient to guarantee the proper operation when the proposed adaptive SR driving works together with the closed-loop control, especially for the fast load transient response proposed in [18][19].

When the switching frequency suddenly decreases as shown in Fig. 8(a), which means the pulse width of the primary switches suddenly increases from T_S to $T_S + \Delta T_{UP}$, in such case, the current in the SR may reach zero earlier than the corresponding primary switch since magnetizing inductor will take part in the resonance when the switching frequency is below the resonant frequency. So the SR on-time is kept the same as the previous switching cycle when the switching frequency suddenly increases.

When the switching frequency suddenly increases as shown in Fig. 8(b), which means the pulse width of the primary switches suddenly decreases from T_S to T_S - ΔT_{DOWN}, in such case, the current in the SR may reach zero later than the corresponding primary switch. To guarantee there is no shoot-through in the SRs, the SR on-time is also reduced by ΔT_{DOWN}. Since both the closed-loop control and the adaptive SR driving are integrated in the digital controller, the SR on-time can always be updated accordingly as mentioned above to guarantee the optimal transient and no shoot-through.

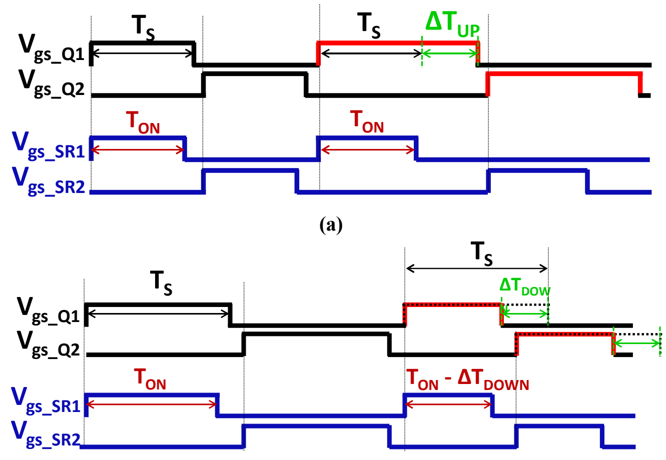


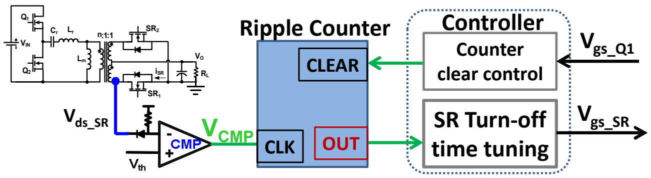
Fig. 8. Change the SR on-time accordingly during transient: (a) switching period suddenly increases; (b) switching period suddenly decreases

Compared with the other adaptive SR driving methods, the proposed adaptive SR driving method can be easily integrated within the digital controller. It only requires a comparator in addition to the digital controller. And it takes very few controller resources, so that the execution of the closed-loop control functions is not impacted. For a 130kHz LLC converter with a 100MHz digital controller (TMS320F2808), the execution of the proposed adaptive SR driving method requires a maximum of 50 CPU cycles at each switching cycle, which corresponds to only 6.5% CPU utilization.

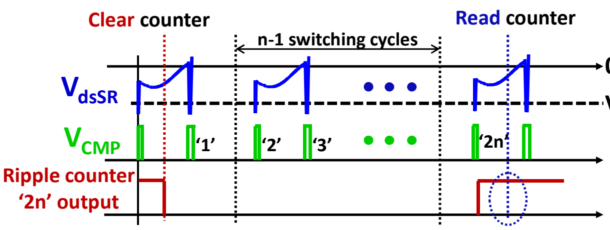
IV. The Extension of the Proposed Adaptive SR Driving Method for the High Frequency LLC Converters Using the Ripple Counter

The proposed adaptive SR driving method based on the ripple detection is suitable for the conventional LLC converter (resonant frequency is below 150kHz) with the cost-effective digital controllers. However, when this method is applied to the high frequency LLC converters, there would be a problem caused by the dramatically increased CPU utilization. For a given 60MHz digital controller (TMS320F28027), the execution of the proposed adaptive SR driving method requires a maximum of 50 CPU cycles; if this is applied to a 500kHz LLC converter, it would take 42% CPU utilization, which means the controller has little spare CPU time for the closed-loop control function.

To solve the challenge of the SR driving for the high frequency LLC converters, the proposed adaptive SR driving method is extended to the high frequency LLC converters by adding a ripple counter. The control scheme and the waveforms of the extended proposed method are shown in Fig. 9. Compared with the previous adaptive SR driving method based on the ripple detection, the digital controller does not need to provide the ripple detection function, instead, a ripple counter is required to be added to the control scheme.



(a)



(b)

Fig. 9. The extension of the proposed adaptive SR driving scheme by adding a ripple counter: (a) control scheme; (b) waveforms

By using the ripple counter, the extended proposed method can tune the SR on-time every $(n+1)^{th}$ switching cycle ($n = 1, 2, 3\ldots$), as shown in Fig. 9(b). The turn-on time of the SRs is still synchronized with the primary switches, so there is always a very small time of the body diode conduction at the turn-on moment. The extended proposed method counts the ripples at the output of comparator to determine if there is extra body diode conduction after the SR turn-off. The controller clears the ripple counter after the SR turn-on of the first switching cycle; then after the SR turn-on of the $(n+1)^{th}$ switching cycle ($n = 1, 2, 3 \ldots$), the controller reads the ripple counter. If the output is '2n', it means that there is the body diode conduction after the SR turn-off. Otherwise, there is no body diode conduction.

The tuning process is shown in Fig. 10. The SR tuning cycle is $n+1$ switching cycles ($n = 1, 2, 3\ldots$). At the beginning, there is a large body diode conduction after the SR turn-off, and the ripple counter indicates $2n$ ripples. So the controller keeps increasing the SR on-time. Every $n+1$ switching cycles, the SR on-time is increased by ΔT, which continues until when the ripple counter indicates that there is only n ripples. Then the controller decreases SR on-time by ΔT. In the next $n+1$ switching cycles, there are $2n$ ripples again. Thus, the SR on-time is tuned step-by-step to eliminate the body diode conduction, and finally it's around the optimal point.

For the extension of the proposed adaptive SR driving scheme by adding a ripple counter, the ripple counter could be cleared at the k^{th} switching cycle in the SR tuning cycle and read at the m^{th} switching cycle in one SR tuning cycle ($n+1$ switching cycles), as long as $k < m < n+1$, and in such case, '$2\cdot(m-k)$' ripples mean the extra body diode conduction after the SR turn-off.

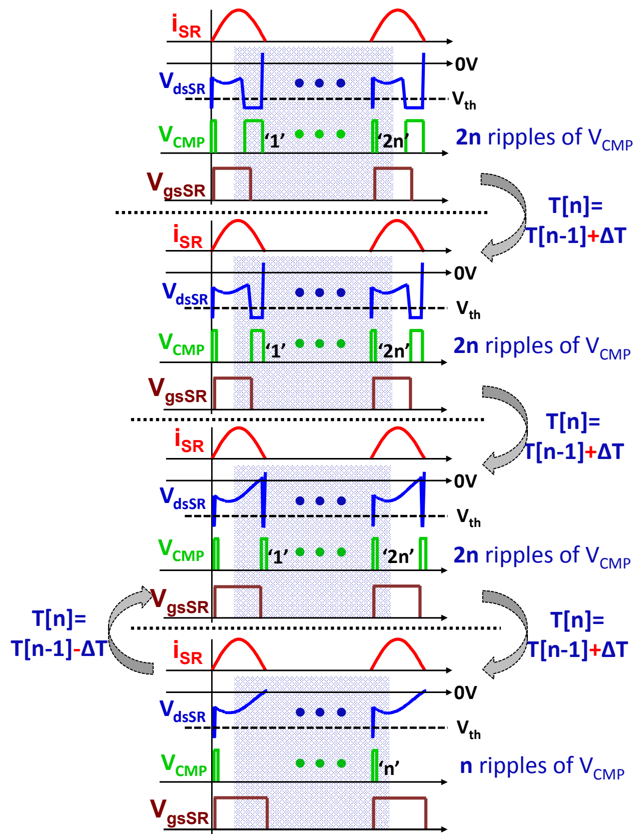


Fig. 10.Tuning process of the extended proposed adaptive SR driving scheme using the ripple counter

For most digital control system in the high frequency applications, the control loop are executed every several switching cycles since the digital delay is longer than the switching period, as mentioned in [21]. For these applications, the extended proposed adaptive SR driving method can be easily combined with the closed-loop control within the digital controller. Fig. 11 is an example of the control loop executed every third switching cycle. Within one control cycle (3 switching cycles), the execution of the adaptive SR driving (red shade area) is divided into 2 parts and inserted into the closed-loop control (yellow shaded area). The Part 1 is to clear the ripple counter; the Part 2 is to read the ripple counter and change T_{ON} accordingly. All the PWM signals are updated together at the end of the third switching cycle.

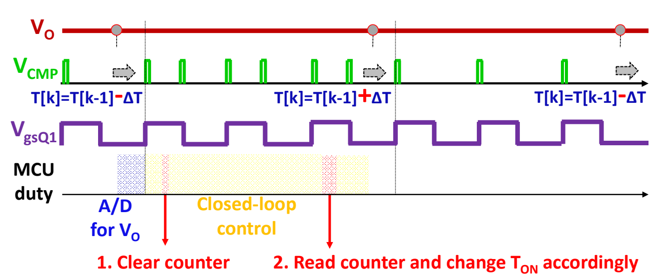


Fig. 11. Allocation of MCU duty for the closed-loop control and the adaptive SR driving within 3 switching cycles

There are three major benefits of the extended proposed method. The first benefit is that it does not require the digital controller to provide the ripple detection function, which means less resources occupation and less CPU utilization of the digital controllers. It takes less than 20 CPU cycles with TI's 60MHz MCU TMS320F28027 to execute the proposed method once. The second benefit is that the SR tuning can be selected to be executed every *(n+1)*th switching cycle to further reduce the CPU utilization. For a 500kHz LLC converter with a 60MHz MCU, if the SR tuning is selected to be executed every third switching cycle, the CPU utilization is significantly reduced to 5%. The third benefit is that it can easily cooperate with the closed-loop control if the control cycle is the same as the closed-loop control.

V. Experimental Results

The proposed adaptive SR driving method based on the ripple detection is verified on a 130kHz 300W 380V/12V LLC converter as shown in Fig. 12, which is TI's demo board TMDSHVRESLLCKIT with the following circuit parameters: L_r = 55uH, C_r = 24nF, L_m = 280uH, C_O = 1.32mF. The controller is the 100MHz MCU TMS320F2808.

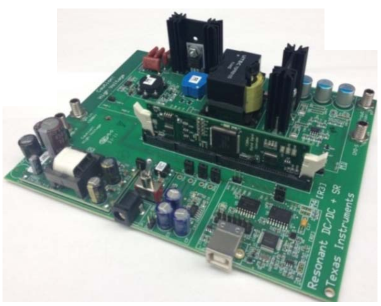


Fig. 12. The 130kHz LLC converter hardware

The experimental waveform of the proposed adaptive SR driving method based on the ripple detection is shown in Fig. 13. It is shown clearly that the body diode conduction is minimized in the steady state.

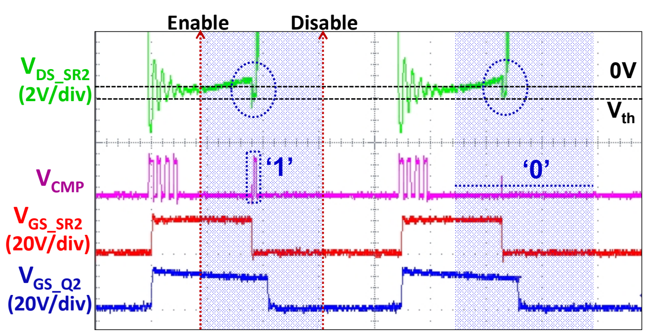


Fig. 13. Steady state waveform of the proposed adaptive SR driving method based on ripple detection on the 130kHz LLC converter

The extended proposed adaptive SR driving method by adding a ripple counter is verified on a 500kHz LLC converter as shown in Fig. 14. The 500kHz LLC converter is designed based on the matrix transformers for the LLC converters [17], which was originally a 1MHz 1kW 390V/12V unregulated DCX with GaN devices. Here the LLC converter is redesigned as a 500kHz 1kW 390V/12V regulated DC/DC converter with Si devices. The parameters of the 500kHz LLC converter is: *Lr* = 4.5uH, *Cr* = 22nF, *Lm* = 22uH. The controller is the 60MHz MCU TMS320F28027.

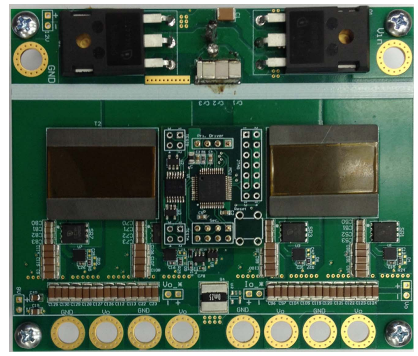


Fig. 14. The 500kHz LLC converter hardware

The tuning process of the extended proposed adaptive SR driving method on the 500kHz LLC converter is shown in Fig. 15. The initial SR on-time is relatively small, which means the body diode conduction time is very large. The proposed adaptive SR driving would tune the SR on-time step-by-step until finally the body diode conduction is around the minimum point.

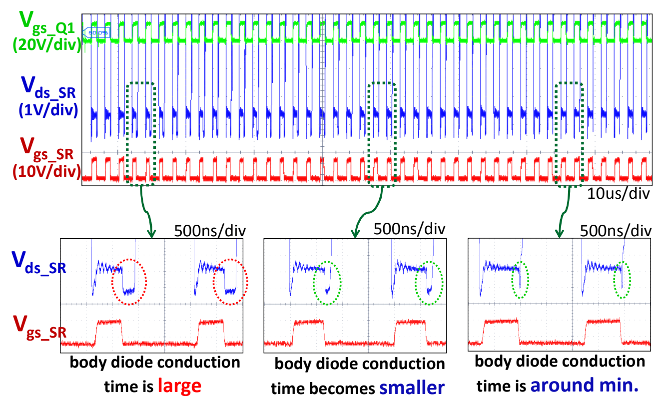


Fig. 15. Tuning process of the proposed adaptive SR driving method based on ripple counter on the 500kHz LLC converter

The efficiency curve of the 500kHz LLC converter with the extended proposed adaptive SR driving method is shown in Fig. 16 with a peak efficiency of above 95% and a full load efficiency of above 94%.

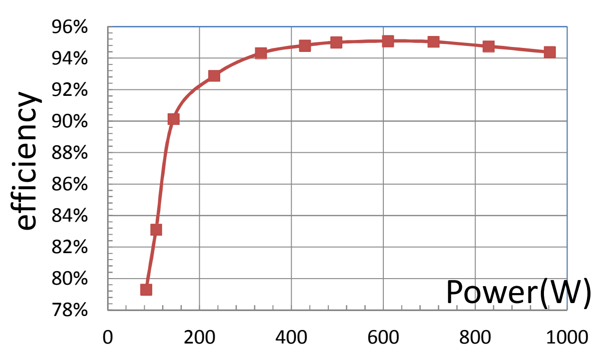


Fig. 16. Efficiency of the 500kHz LLC converter with the proposed adaptive SR driving method based on the ripple counter

VI. CONCLUSIONS

In this paper, the adaptive SR driving for the LLC converters is investigated and its limitation with the digital implementation is explained in details. The previous adaptive SR driving methods require either the additional circuit or the high-performance digital controllers.

To solve this challenge, the adaptive SR driving method based on the ripple detection and its extension for the high frequency LLC converters are proposed. The original proposed method is suitable for the conventional LLC converters (resonant frequency is below 150kHz). It requires very little CPU utilization, thus, can be implemented by the low-cost digital controllers. The extension of the proposed method is suitable for the high frequency LLC converters. With the help of a ripple counter and by tuning the SR on-time every $(n+1)^{th}$ switching cycle ($n = 1, 2, 3…$), it can also be implemented by the low-cost digital controllers with the minimum CPU utilization.

The original proposed method is verified on a 130kHz LLC converter with a 100MHz microcontroller. It's very simple, requiring only a comparator. However, the CPU utilization for the SR driving will increase as the switching frequency increases, which means it is not quite suitable for the high frequency applications.

The extension of the proposed method is verified on a 500kHz LLC converter with a 60MHz microcontroller and a ripple counter. Compared with the original proposed method, an additional ripple counter is needed, however, the CPU utilization for the SR driving is reduced significantly.

Both methods require very little CPU utilization and can approach around the optimal point at the steady state.

REFERENCES

[1] B. Yang, F. C. Lee, A. J. Zhang, and G. Huang. "LLC resonant converter for front end DC/DC conversion." In *Applied Power Electronics Conference and Exposition, 2002. APEC 2002. Seventeenth Annual IEEE*, vol. 2, pp. 1108-1112. IEEE, 2002.

[2] B. Lu, W. Liu, Y. Liang, F. C. Lee, and J. D. Van Wyk. "Optimal design methodology for LLC resonant converter." In *Applied Power Electronics Conference and Exposition, 2006. APEC'06. Twenty-First Annual IEEE*, pp. 533-538. IEEE, 2006.

[3] X. Xie, J. Liu, F. N. K. Poon, and M. Pong, "A novel high frequency current-driven SR applicable to most switching topologies," *IEEE Trans. Power Electron.*, vol. 16, no. 5, pp. 635–648, Sep. 2001.

[4] D. Huang, D. Fu, and F. C. Lee, "High switching frequency, high efficiency CLL resonant converter with synchronous rectifier," In *Proc. IEEE Energy Convers. Congr. Expo.*, 2009, pp. 804–809.

[5] X. Wu, G. Hua, J. Zhang, and Z. Qian, "A new current-driven synchronous rectifier for series–parallel resonant (LLC) DC-DC converter," *Industrial Electronics, IEEE Transactions on*, vol. 58, no. 1, pp. 289–297, Jan. 2011.

[6] NXP Semiconductors, "TEA1795T: GreenChip synchronous rectifier controller" (Nov. 2010). [Online]. Available: http://www.nxp.com/documents/data_sheet/TEA1795T.pdf

[7] International Rectifier, "IR11682S: DUAL SmartRectifier DRIVER IC" (Jul. 2011). [Online]. Available: http://www.irf.com/product-info/datasheets/data/ir11682spbf.pdf

[8] STMicroelectronics, "Synchronous rectifier smart driver for LLC resonant converters" (Aug. 2013). [Online]. Available: http://www.st.com/st-web-ui/static/active/en/resource/technical/document/datasheet/CD00282226.pdf

[9] D. Fu, Y. Liu, F. C. Lee, and M. Xu, "A novel driving scheme for synchronous rectifiers in LLC resonant converters," *Power Electronics, IEEE Transactions on*, vol. 24, no. 5, pp. 1321–1329, May 2009.

[10] L. Cheng, T. Liu, H. Gan, and J. Ying, "Adaptive synchronous rectification control circuit and method thereof," U.S. Patent 7.495.934, Feb. 24, 2009

[11] W. Feng, F. C. Lee, P. Mattavelli, and D. Huang, "A universal adaptive driving scheme for synchronous rectification in LLC resonant converters," *Power Electronics, IEEE Transactions on*, vol. 27, no. 8, pp.3775-3781, Aug. 2012

[12] B. Yang, R. Chen, and F. C. Lee. "Integrated magnetic for LLC resonant converter." In *Applied Power Electronics Conference and Exposition*, 2002. APEC 2002. Seventeenth Annual IEEE, vol. 1, pp. 346-351. IEEE, 2002.

[13] D. Fu, B. Lu, and F. C. Lee. "1MHz high efficiency LLC resonant converters with synchronous rectifier." *In Power Electronics Specialists Conference*, 2007. PESC 2007. IEEE, pp. 2404-2410. IEEE, 2007.

[14] D. Reusch, F. C. Lee, D. Gilham, and Y. Su. "Optimization of a high density gallium nitride based non-isolated point of load module." In *Energy Conversion Congress and Exposition (ECCE)*, 2012 IEEE, pp. 2914-2920. IEEE, 2012.

[15] X. Huang, Z. Liu, Q. Li, and F. C. Lee. "Evaluation and application of 600V GaN HEMT in cascode structure." In *Applied Power Electronics Conference and Exposition (APEC)*, 2013 Twenty-Eighth Annual IEEE, pp. 1279-1286. IEEE, 2013.

[16] S. Ji, D. Reusch, and F. C. Lee. "High-frequency high power density 3-D integrated gallium-nitride-based point of load module design." *Power Electronics, IEEE Transactions* on 28, no. 9 (2013): 4216-4226.

[17] D. Huang, S. Ji, and F. C. Lee. "LLC resonant converter with matrix transformer." In *Applied Power Electronics Conference and Exposition (APEC)*, 2014 Twenty-Ninth Annual IEEE, pp. 1118-1125. IEEE, 2014.

[18] W. Feng, F. C. Lee, and P. Mattavelli. "Simplified optimal trajectory control (SOTC) for LLC resonant converters." *Power Electronics, IEEE Transactions on* 28, no. 5 (2013): 2415-2426.

[19] C. Fei, W. Feng, F. C. Lee, and Q. Li. "State-trajectory control of LLC converter implemented by microcontroller." In *Applied Power Electronics Conference and Exposition (APEC), 2014 Twenty-Ninth Annual IEEE*, pp. 1045-1052. IEEE, 2014.

[20] C. Fei, F. C. Lee, and Q. Li. "Soft start-up for high frequency LLC resonant converter with optimal trajectory control." In *Applied Power Electronics Conference and Exposition (APEC), 2015 IEEE*, pp. 609-615. IEEE, 2015.

[21] C. Fei, F. C. Lee, and Q. Li. "Multi-step Simplified Optimal Trajectory Control (SOTC) for fast transient response of high frequency LLC converters." In *Energy Conversion Congress and Exposition (ECCE), 2015 IEEE*, pp. 2064-2071. IEEE, 2015.

[22] C. Fei, F. C. Lee, and Q. Li. "Light load efficiency improvement for high frequency LLC converters with Simplified Optimal Trajectory Control (SOTC)." In *Energy Conversion Congress and Exposition (ECCE), 2015 IEEE*, pp. 1653-1659. IEEE, 2015.