A New LLC Converter Family with Synchronous Rectifier to Increase Voltage Gain for Hold-up Application

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***Abstract*—For low output voltage application, a half-bridge LLC resonant converter family with synchronous rectifier (SR) that has a boost pulse width modulation (PWM) converter characteristic for hold-up state operation is proposed in this paper. In proposed converters, an auxiliary switch (or an auxiliary switch and a diode) is added at the primary side to provide the charging branch for series resonant inductor. The converter has two different operational characteristics. In the nominal state, the proposed converters show the same operational performance with the conventional LLC converter, which is frequency modulation (FM) method. When ac line is lost and the converters operates at voltage boost operation mode, which needs high voltage gain, the Half-bridge switches keep the minimum switch frequency, and the additional switch operates at PWM mode to charge series inductor to obtain enough voltage gain. To verify the effectiveness of the proposed circuit, operational principle will be explained and simulation and experimental results will be presented with following specification. 250–400 V of input voltage range, 12 V of output voltage, and 300W output power.**

I. INTRODUCTION

Nowadays, two-stage ac/dc converter which includes a power factor correction (PFC) stage has been widely used for numerous industrial applications [1, 2]. Fig.1 shows the block diagram of two-stage ac/dc converter. PFC stage state can achieve high power factor and the output voltage V_{bus} can meet the requirement of DC/DC stage. LLC converter topology is used to achieve high efficiency and high power density because it can work in ZVS performance for primary side, and ZCS performance for secondary side [3]. The synchronous rectifier (SR) has been widely adopted in low output voltage applications to reduce the conduction loss of the output rectifier to improve the efficiency. As the LLC resonant converter is a current-fed topology and has no output inductor, the voltage stress of the output rectifier is much lower than in conventional voltage-fed topologies. Low-voltage rating MOSFET can be used as SR to achieve high efficiency [4]. Thus, a LLC converter with SR is an ideal topology to meet high efficiency in low output voltage application. Furthermore, the output voltage should be maintained for a certain period after loss of the ac voltage, called hold-up period as shown in Fig.2. During the hold-up period, the stored energy capacitor Cbus provides power for LLC converter. Thus, the dc/dc converter should meet the enough voltage gain to keep stable output voltage of LLC converter.

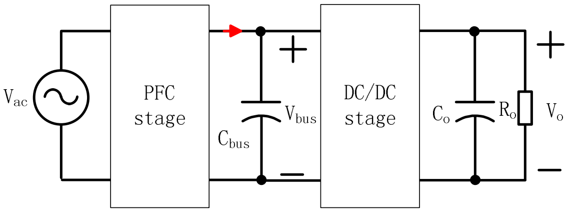

Fig.1 Block diagram of two-stage ac/dc converter

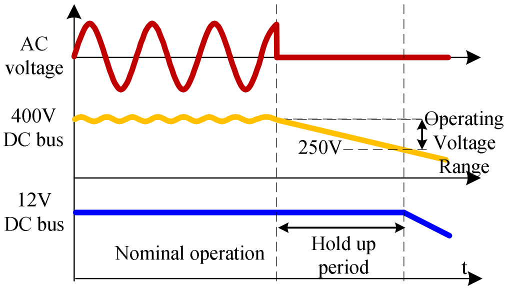

Fig.2 input voltage variation of dc/dc converter

In general, an LLC series resonant converter regulates the output voltage by decreasing the switching frequency, assuming that is operated in an inductive region. LLC converter for wide input voltage range

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should have a small magnetizing inductance to obtain a high peak gain. This will cause large conductions losses at the primary side. Thus, it is difficult to obtain an optimal design that cover wide input voltage and flat efficiency curve. In order to obtain good performance in nominal state and to satisfy the voltage gain requirement during hold-up period, many methods have been developed for hold up state based on an LLC converter [5-10]. Fig.3 shows an LLC converter using variable transformer ratios. Increasing the secondary turns during hold up state, the converter can achieve high voltage gain than traditional LLC converter. However, additional transformer windings means large transformer size, and a switch and a diode renders low power density and high cost. Fig.4 shows the LLC converter with secondary auxiliary circuit, which obtains ZVS performance to the transformer using the additional circuit. Although it can achieve higher voltage gain, the proposed converter has many bulky components and is not suit for low output voltage application when SR MOSFET is required. An asymmetric PWM control method is proposed in Fig.5, no additional circuit is added. The voltage gain can be increased only using the asymmetric, but it is still hard to achieve enough gain for hold up operation. The detailed explain is shown in [7]. Fig.6 and Fig.7 show two new LLC converters using boost PWM scheme. There are several advantages: First, it operates in a narrow switching frequency variation within wide input voltage range. Second, it is feasible to obtain optimal design in nominal state because of the decoupled designs between nominal state and hold-up state. However, they are not suitable for low output voltage application with SR because of short-circuit risk. It is observed from Fig.6 and Fig.7, two secondary diodes of rectifier are used instead of two switches [8] [9]. If these two diodes are replaced with SR, short-circuit condition will happen. Short circuit condition would also happen for boost PWM control at primary side, as shown in Fig.8, if SR MOSFET is used, [10].Once switches Q2, Q3 are turned on, the primary-side of transformer is short-circuit. Diode is required as rectifier at secondary-side.

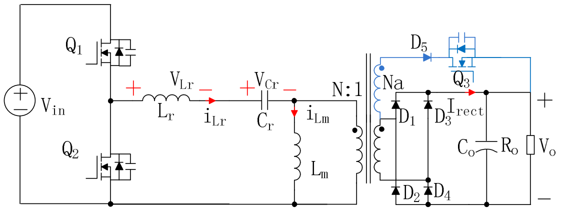


Fig. 3. An LLC converter using various transformer turn ratios [5].

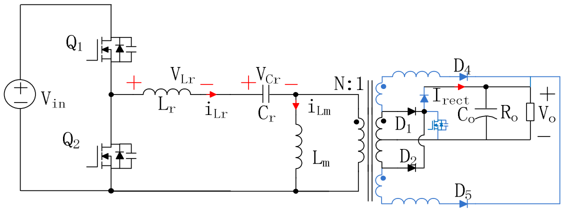


Fig. 4 An LLC converter using various a secondary auxiliary circuits [6].

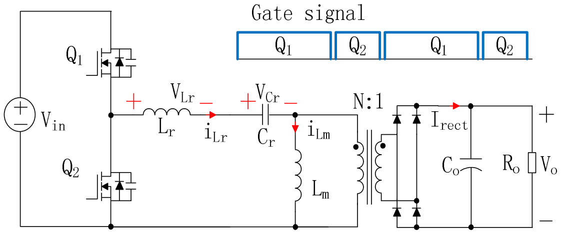


Fig. 5. An LLC using asymmetric PWM control scheme [7]

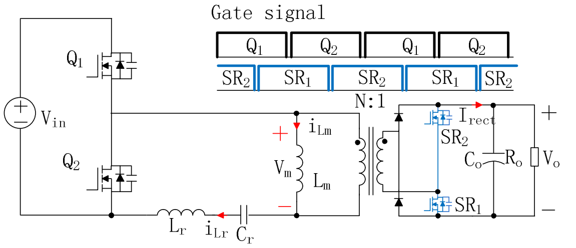


Fig. 6. An LLC using boost PWM control scheme at secondary-side [8]

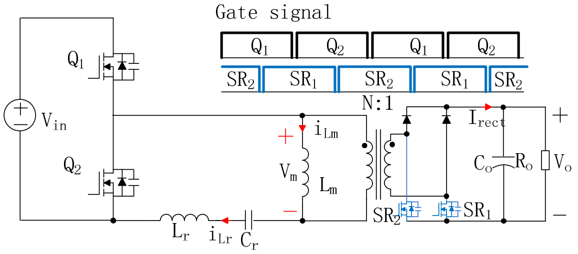


Fig. 7. An LLC using boost PWM control scheme at secondary-side [9]

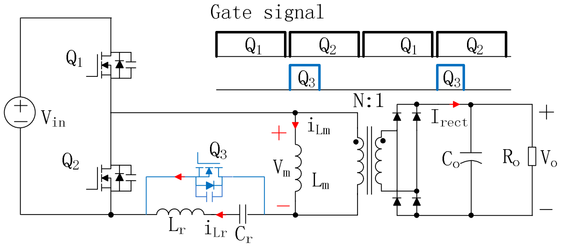


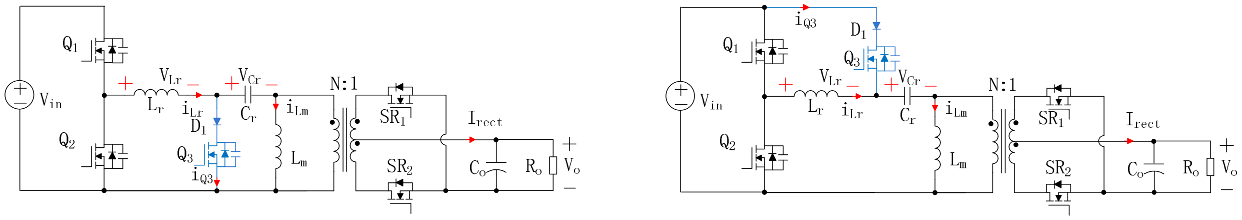
Fig. 8. An LLC using boost PWM control scheme at primary-side[10]

In this paper, a new half-bridge (HB) LLC converter family is proposed to increase the voltage gain. The proposed converters can operate at maximum efficiency point of the HB LLC converter during nominal input voltage range. When input voltage is low, the added switch starts to operate at PWM mode to increase the energy transferred from the input source to resonant tank, which is then transferred to output, and therefore, voltage gain is increased. This is particular suitable for hold-up operation. As it is decoupled design between nominal operation and hold-up operation, the switching frequency variation range is not wide, which means high efficiency. Section II provides the topologies of the proposed converter. Section III shows the detailed operation of the proposed LLC converter. Section IV provides simulation and experimental results of a 300W prototype; and Section V is conclusion.

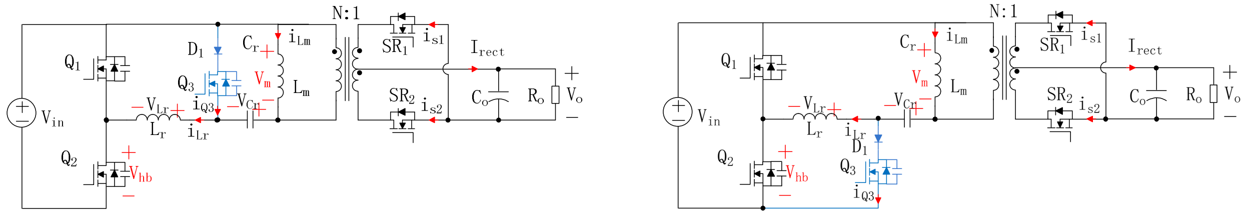
II. TOPOLOGIES OF THE PROPOSED CONVERTER

The new topology family of the proposed converters based on HB LLC is presented in Fig.9. There are six new converters. A switch and a diode are added in Fig.9 (a), (b), (c), (d), (e), (f). The series diode and switch is added. The diode makes a function to interrupt the branch to charge the parasitic capacitor of additional switch. Only one switch is added in Fig.9 (g), (h). The source of the additional switch, Q3, is same as the source of Q2, which simplifies the gate drive circuit for Q3. The detailed analysis will be done based on Fig.9 (h) in this paper. The operation of other circuits is similar.

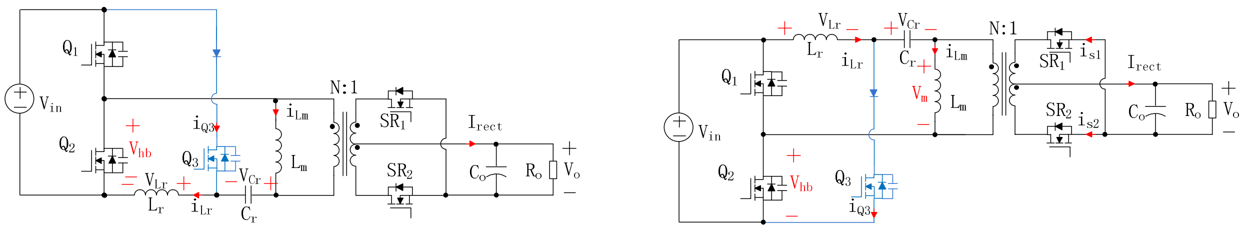
Under normal input voltage range, the additional MOSFET, Q3, in the proposed converters does not turn on and the converters operate like the traditional HB LLC converter. The output voltage is controlled by switching frequency control. The switching frequency can be designed nearby the resonant frequency, thus, it can be designed as an optimal HB LLC converter. When the input voltage is low, the proposed converter will operate at voltage boost mode when half bridge switches (Q1 and Q2) operate at minimum switching frequency and the added switch Q3 operates at PWM mode to increase the energy transferred from input source to resonant tank, and to increase the voltage gain. Several variable parameters are defined as follows. i_{Lr}, i_{Lm}, i_{Q3}, I_{rect} are the current of series inductor Lr, magnetic inductor Lm, and switch Q3, rectifier current, respectively. V_{HB}, Vm and Vo are the voltage of half-bridge, primary-side voltage of transformer, output voltage, respectively. The transformer turns ratio is N.



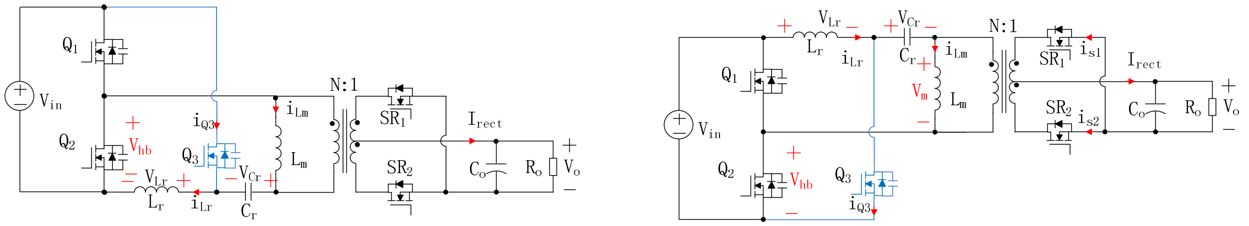
(a) SLLC#1 (b) SLLC#2



(c) SLLC#3 (d) SLLC#4



(e) SLLC#5 (f) SLLC#6



(g) SLLC#7 (h) SLLC#8

Fig.9 A New LLC Converter Family with Increased Voltage Gain

III. BASIC OPERATION OF THE PROPOSED LLC CONVERTER

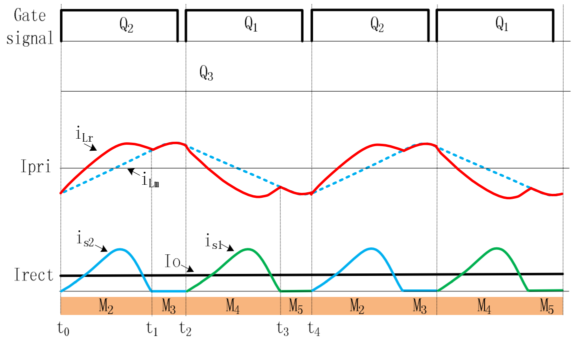
Fig. 10 shows the principle of normal operation mode and voltage boost operation mode. In the normal operation mode, the operation of the proposed converter is the same of the LLC resonant converter. The key waveform of the normal operation mode is illustrated in Fig. 10 (a). In the voltage boost operation mode. The key waveform is shown in Fig.10 (b). Fig.11 shows the all model operation under voltage boost operation mode.

Mode 1(M1): Q2, Q3 turn on at t_0 as shown in Fig.11 (a). The resonant current iLr increases linearly due to the positive input voltage Vin applied on the Lr. The magnetic inductor Lm is charged by the resonant capacitor Cr. The current is through Q3 and body diode of Q2.

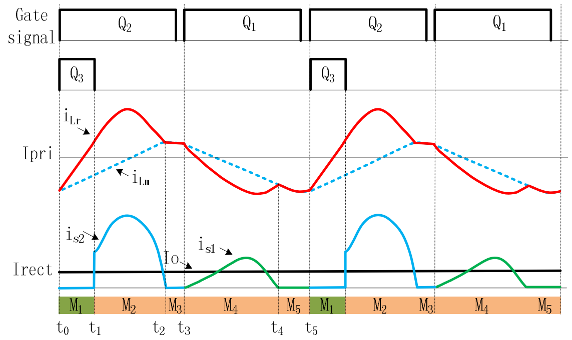
Mode 2(M2):.Q3 turns off at t_1 as shown in Fig.11 (b). The large resonant current is through the resonant capacitor Cr, magnetic inductor Lm, transformer and Q2. The large rectifier current charges output capacitor by SR2.

Mode 3(M3):.At $t=t_2$, the current flowing through the secondary-side of transformer reaches zero, which is shown in Fig.11 (c). The converter enters an idle mode where no power is being transferred from the source to the load. Three components Lr, Cr and Lm are resonant each other.

Mode 4(M4):.At $t=t_3$, Q2 turns off and Q1 turn on as shown in Fig.11 (d). The primary-side voltage Vm is clamped NVo; the input energy is transmitted to secondary-side. This mode is similar with the conventional LLC converter.



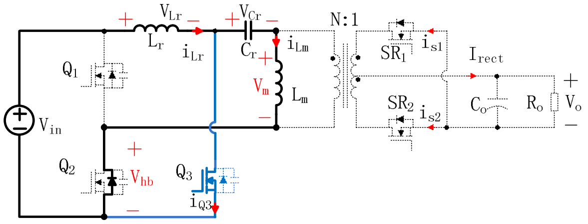
(a) Nominal operation mode



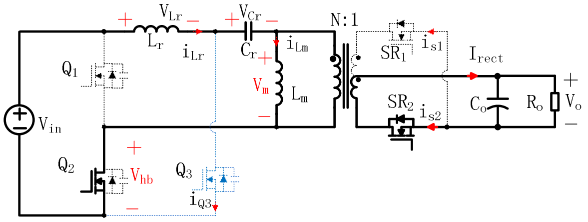
(b) Voltage boost operation mode

Fig.10 Key operation of the proposed converter

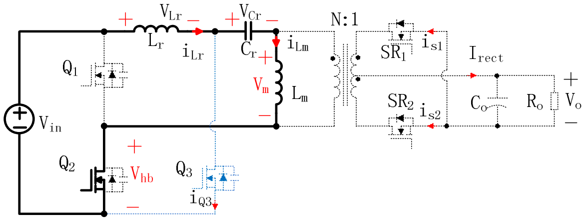
Mode5 (M5):.At $t=t_4$, the current flowing through the secondary-side of transformer reaches zero, which is shown in Fig.11 (e). The converter enters an idle mode where no power is being transferred from the source to the load. Three components Lr, Cr and Lm are resonant each other.



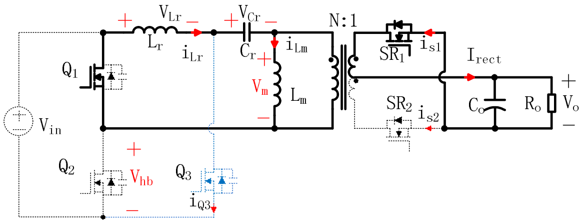
(a) Mode 1



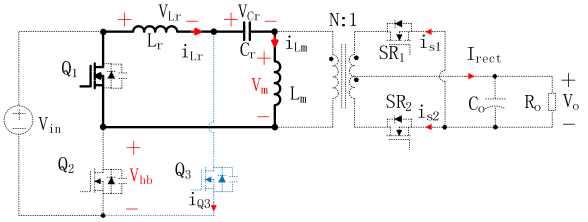
(b) Mode 2



(c) Mode 3



(d) Mode 4



(e) Mode 5

Fig.11 Equivalent circuit of at voltage boost operation mode

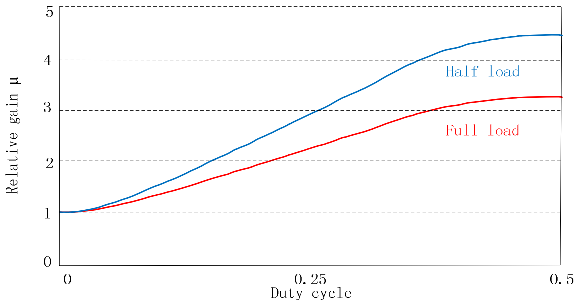


Fig.12 relative gain with different duty cycle of Q3

The proposed converter has two different input-output voltage conversion ratios depending on its operational state. For nominal state, it has the same operational characteristic with the traditional HB LLC converter. Fig.12 shows the simulated relationship of the voltage gain and duty cycles, in which the switching frequency keeps the minimum frequency f_{min}. The duty cycle of additional switch Q3 is defined as the ratio of the on time of Q3 over the switching period of the minimum frequency $(1/Fs_{min})$.

For voltage boost operation state, the switch frequency is fixed in minimum frequency. Increasing the duty cycle of the Q3, the relative gain is significant boost, there are 3.2 time, 4.5 time gain compared with conventional LLC at minimum frequency.

As the normal input voltage is 400V, the optimal LLC converter can meet the gain requirement between 330V and 400V at full load. The minimum input voltage is 250V to satisfy the holdup operation. Thus, 1.5 times gain-increasing is enough for hold up operation. The duty cycle is limited to 15% in the experiment. The detailed experiment results are shown in next.

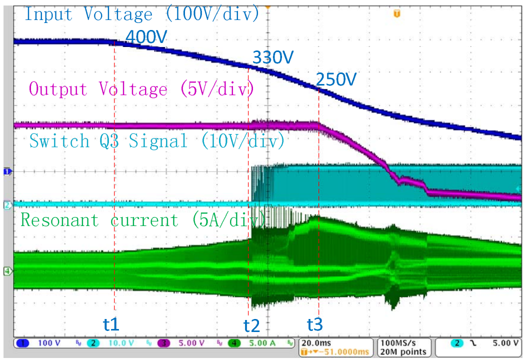
IV. EXPERIMENT RESULTS

To verify the performance of the proposed converter family, a prototype is designed with following 300W, 12V output. Tab.1 shows the experimental prototype parameters.

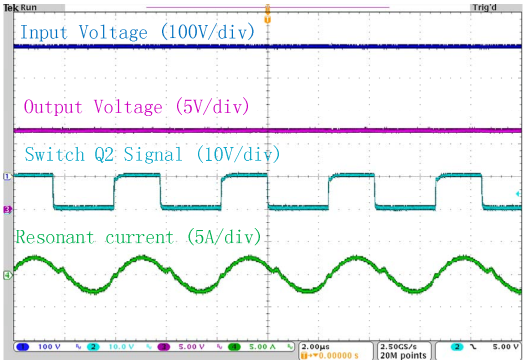
Tab.1 Experimental Prototype Parameters

Switching frequency	150KHZ-270KHZ
Input voltage	330V-400V LLC 250V minimum voltage
Rated power	300W
Transformer turn ratio N	17:1:1
Magnetic Inductance (Lm)	250uH
Series Inductance (Lr)	16.5uH
Series Capacitance(Cr)	23.5nF
Output capacitance	800uF

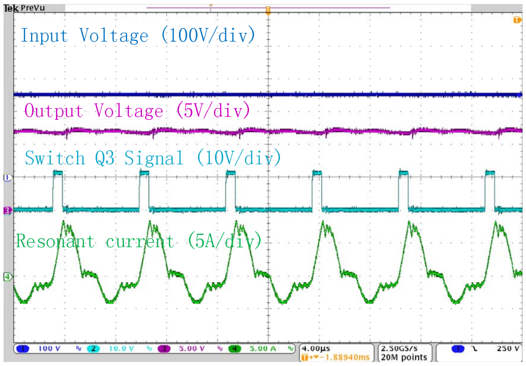
Fig.13 shows the experiment results of 25A load current from nominal state to voltage boost operation state. The input voltage is reduced from 400V at t_1 to 250V at t_3. During t_1-t_2; the optimal LLC converter can meet the gain requirement. When the input voltage is decreased below 330V, the additional switch starts operating, such as t_2-t_3. The output voltage remains at 12V during all the operation. Fig.13 (b), (c) show the waveform at 400V, and 250V input voltage. The series current peak value is 3A at t_1, 7.5A at t_3. Fig.14 shows the experiment results at 15A load current from nominal state to voltage boost operation state. The input voltage is reduced from 400V at t_1 to 220V at t_3. During t_1-t_2; the optimal LLC converter can meet the gain requirement. When the input voltage is decreased into 310V, the additional switch is working smoothly once the input voltage goes on down, such as t_2-t_3. The output voltage keeps at 12V during all the operation. Fig.14 (b), (c) show the waveform at 400V, and 220V input voltage. The series current peak value is 1.8A at t_1, 5A at t_3.



(a) Dynamic operation

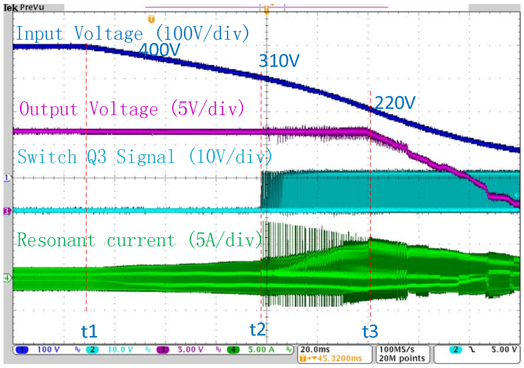


(b) Waveform working at 400V input voltage

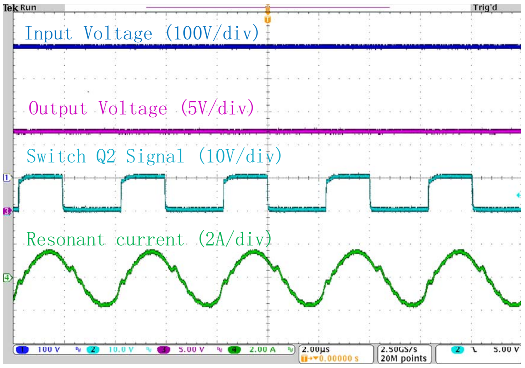


(c) Waveform working at 250V input voltage

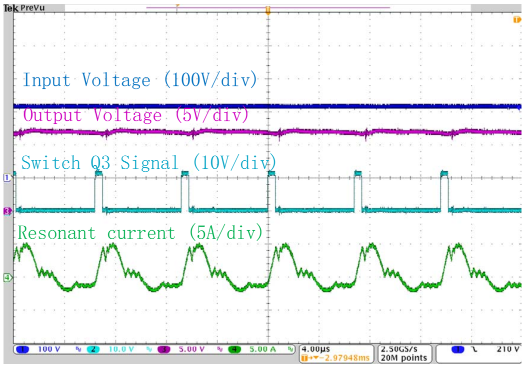
Fig.12 Hold-up test under 25A load current



(a) Dynamic operation



(b) Waveform working at 400V input voltage



(c) Waveform working at 250V input voltage

Fig.13 Hold-up test under 15A load current

V. CONCLUSION

A new HB LLC converter family with SR for low output voltage application has been proposed. The proposed converter has a narrow switch frequency range which maintains the advantages of the traditional LLC converter. During hold-up operation, a boost PWM method is used for an additional switch. The transition between normal operation and voltage-boost mode operation can be achieved smoothly. The simulation result has proven the validity of proposed converter family. A 300W prototype is built to verify the effectiveness and feasibility of these topologies.

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