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Novel Non-isolated LLC Resonant Converters

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Abstract— In this paper, a novel non-isolated LLC resonant converter is proposed. This converter can achieve most merits of isolated LLC resonant converter, like zero voltage switching and very low turn off loss for all MOSFETs. By non-isolated technique, the turns of transformer can be largely reduced. Meanwhile, the current through secondary windings is also reduced. Thus, the transformer loss is decreased. An 1MHz prototype is built to verify the proposed converter.

I. INTRODUCTION

High power density and high efficiency are the motivation for both point-of-load (POL) and the voltage regulator (VR) for processors. Thus, high switching frequency is required for small passive components. However, the conventional buck converters have several serious issues at high frequency: high switching loss, high driver loss and high body diode loss of the synchronous rectifier [1,2].

The typical benefits of LLC resonant converter [3-8], like no turn on loss, little turn off loss for primary side switches and nearly ZCS (Zero Current Switching) for output rectifier, are suitable for high frequency DC/DC application. However, the large turns ratio of transformer is an issue due to high ratio of input and output voltage.

The high conduction loss of buck converter due to the high voltage ratio can be relieved by non-isolated techniques [9-12]. The duty circle of converter can be extended by added transformer. Based on different non-isolated connection [10], the DC/DC converters can achieve synchronous rectifier (SR) self-driven, low current stress and low transformer turns ratio. the turns ratio and conduction loss can be reduced.

Based on non-isolated techniques and LLC resonant converters, the non-isolated LLC resonant converter is proposed as an alternative solution to future VR and POL converters. This converter combined the benefits of resonant converters and non-isolated structure. This concept also can be extended to other resonant converters.

II. BASIC CONCEPT OF NON-ISOLATED LLC RESONANT CONVERTERS

LLC resonant converter is widely used in many applications for its high power density and high efficiency. LLC resonant converter can achieve zero-voltage switching (ZVS), low turn off loss for primary side switches and ZCS for output rectifier. Mostly, LLC resonant converter is isolated

by transformer. In [9-12], the non-isolated structure of PWM converters shows their benefits for low conduction loss and driven loss. Due to the same concept, non-isolated structure also can bring some benefits to resonant converters

A. Non-isolated full-bridge LLC resonant converters

The full bridge LLC resonant converter is shown in Fig. 1. The three types of non-isolated LLC resonant converters are shown in Fig. 2.

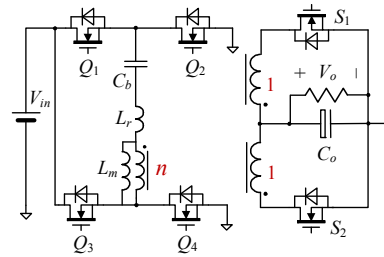
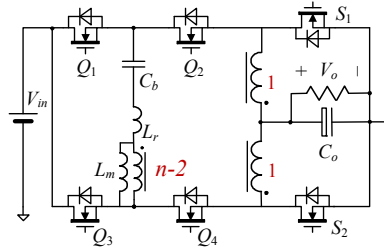
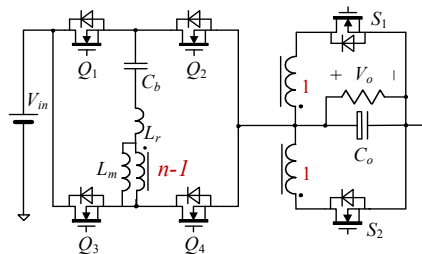


Fig 1. Full bridge LLC resonant converter.

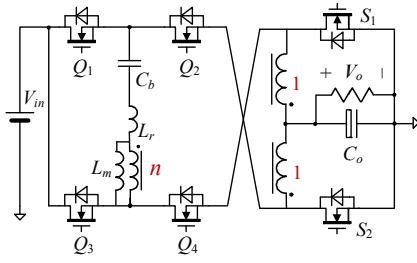


(a) Type 1



(b) Type 2

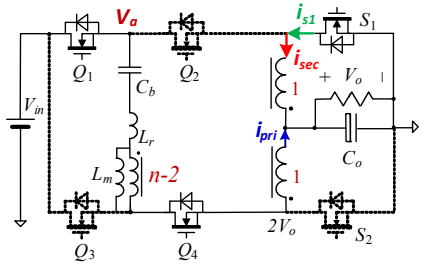
This work is supported by Chicony Power Technology Co., Ltd., Delta Electronics, Emerson Network Power, Huawei Technologies, International Rectifier, Intersil Corporation, Linear Technology, LiteOn Technology, NEC/TOKIN Corporation, NXP Semiconductors, Osram Sylvania, Power Integrations, Richtek Technology, Texas Instruments, ZTE Corporation.



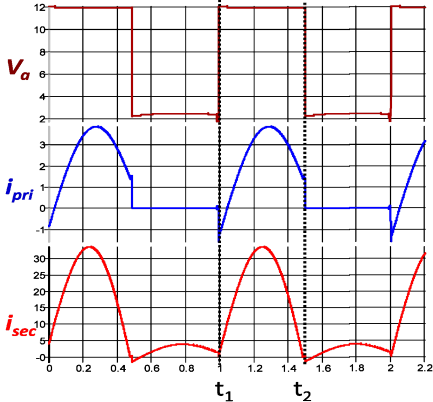
(c) Type 3

Fig 2. Non-isolated full bridge LLC resonant converter.

For the type 1 topology, the half circle equivalent circuit and waveforms are shown in Fig 3. At this interval, Q_1 and Q_4 are on, and Q_2 and Q_3 are off. The primary current helps to deliver the energy to the load. Thus, the currents through both secondary side winding and device S_1 are effectively reduced. Meanwhile, V_a in Fig 5 is in phase with the current through S_1 . It is easy to utilize V_a to drive S_1 , which can save much driving loss. The primary side turns can be reduced by two, because the voltage across the resonant tank is $V_{in}-2V_o$. The same phenomenon happens at the other half circle.



(a) Equivalent circuit

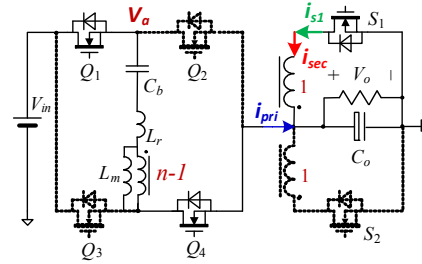


(b) Simulated waveforms

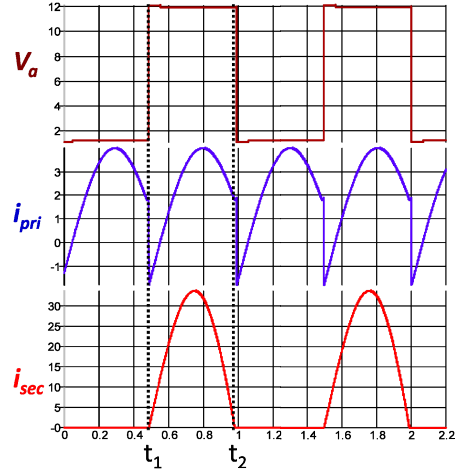
Fig 3. Type 1 non-isolated full bridge LLC resonant converter.

For the type 2 topology, the half circle equivalent circuit and waveforms are shown in Fig 4. At this interval, Q_1 and Q_4 are on, and Q_2 and Q_3 are off. The primary current helps to deliver the energy to the load. Thus, the currents through both secondary side winding and device S_1 are effectively reduced. Meanwhile, V_a in Fig 4 is in phase with the current through S_1 . It is easy to utilize V_a to drive S_1 , which can save much driving loss. The primary side turns can be reduced by one, because

the voltage across the resonant tank is $V_{in}-V_o$. The same phenomenon happens at the other half circle.



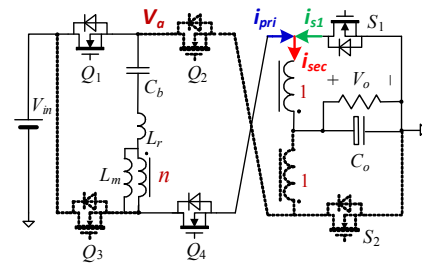
(a) Equivalent circuit



(b) Simulated waveforms

Fig 4. Type 2 non-isolated full bridge LLC resonant converter.

For the type 3 topology, the half circle equivalent circuit and waveforms are shown in Fig 5. At this interval, Q_1 and Q_4 are on, and Q_2 and Q_3 are off. The primary current helps to deliver the energy to the load. Thus, the current through device S_1 is effectively reduced. Meanwhile, V_a in Fig 3 is in phase with the current through S_1 . It is easy to utilize V_a to drive S_1 , which can save much driving loss. The similar phenomenon happens at the other half circle.



(a) Equivalent circuit

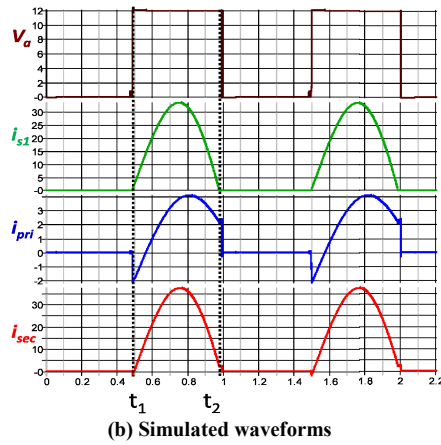


Fig 5. Type 3 non-isolated full bridge LLC resonant converter.

As mentioned full-bridge isolated LLC resonant converter can achieve low switching loss and low circulating energy. With non-isolated structure, less transformer windings and less SR current can be reached, that means simpler magnetic structure, less conduction loss and high efficiency.

B. Non-isolated full-bridge LLC resonant converters

The half bridge LLC resonant converter is another category to apply non-isolated structure to reduce turns ratio of transformer. The half bridge LLC resonant converter is shown in Fig. 6.

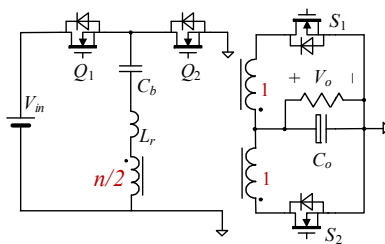


Fig 6. Half bridge LLC resonant converter.

The non-isolated half bridge LLC resonant converters are shown in Fig. 7. The similar conclusion can be made based on previous analysis for non-isolated full bridge LLC resonant converters, except the turns ratio of transformer halved for half-bridge structure. However, there is point that the input and output port are not share the ground. Thus, another modification should be made.

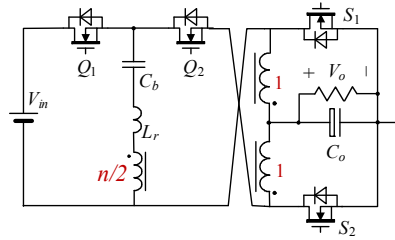
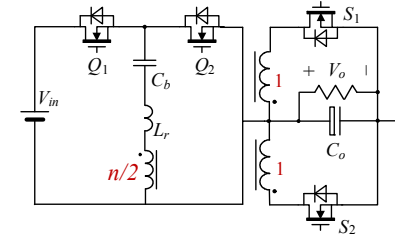
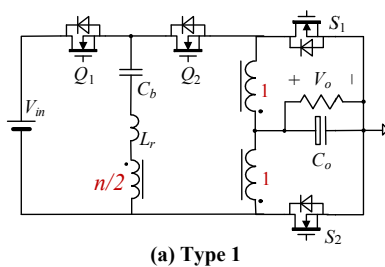


Fig 7. Non-isolated half bridge LLC resonant converter.

As shown in Fig. 8, the input side ground is the same with output port. This modification introduces some changes of topology performance.

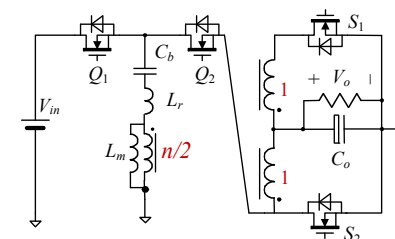
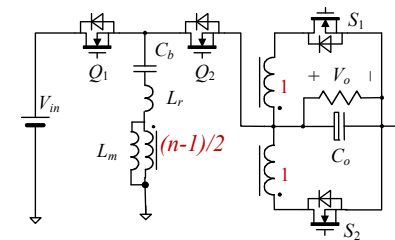
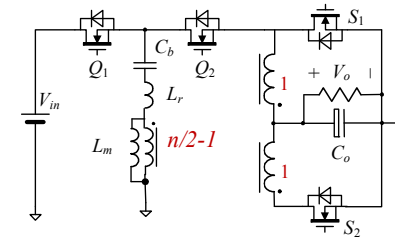


Fig 8. Non-isolated half-bridge LLC resonant converter (modification 1).

The operation waveforms of Fig 8 (a) are shown in Fig. 9. During t_1-t_2 , the load current is i_{sec1} , as shown in Fig 9 (a). During t_2-t_3 , the load current is split into two parts, one is i_{sec1} and the other is i_{sec2} , as shown in Fig 9. (b). The primary current goes through one secondary winding to help reduce the current stress on secondary side windings.

During the switching circle, the voltage across resonant tank is $V_{in}/2-V_o$, thus, the turns ratio of transformer equals $(V_{in}/2-V_o)/V_o$. The winding numbers is decreased. The size and loss of transformer are reduced.

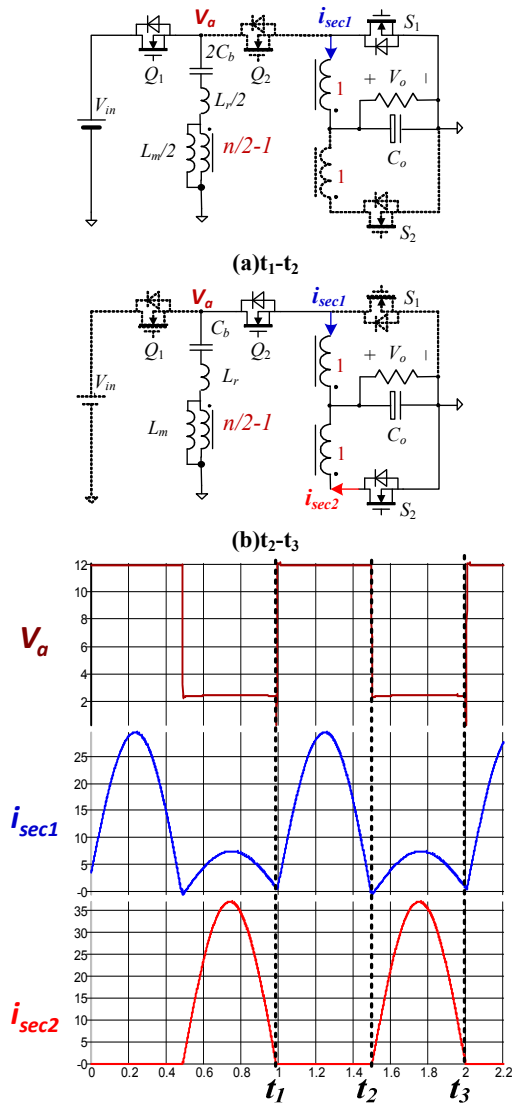


Fig 9. Half-bridge non-isolated LLC resonant converter type 1 (modification 1).

The operation waveforms of Fig 8 (b) are shown in Fig 10. During t_1-t_2 , the load current is i_{s2} , as shown in Fig 10 (a). Q2 is off, thus the primary side current does not contribute the output power. During t_2-t_3 , the load current is split into two parts, one is i_{s1} and the other is i_{pri} , as shown in Fig10. (b). The primary current directly go to the secondary side winding to help reduce the current stress on secondary side windings.

During the switching circle, the average voltage across resonant tank is $V_{in}/2-V_o$, thus, the turns ratio of transformer equals $(V_{in}/2-V_o)/V_o$. The winding numbers is decreased. The size and loss of transformer can be reduced.

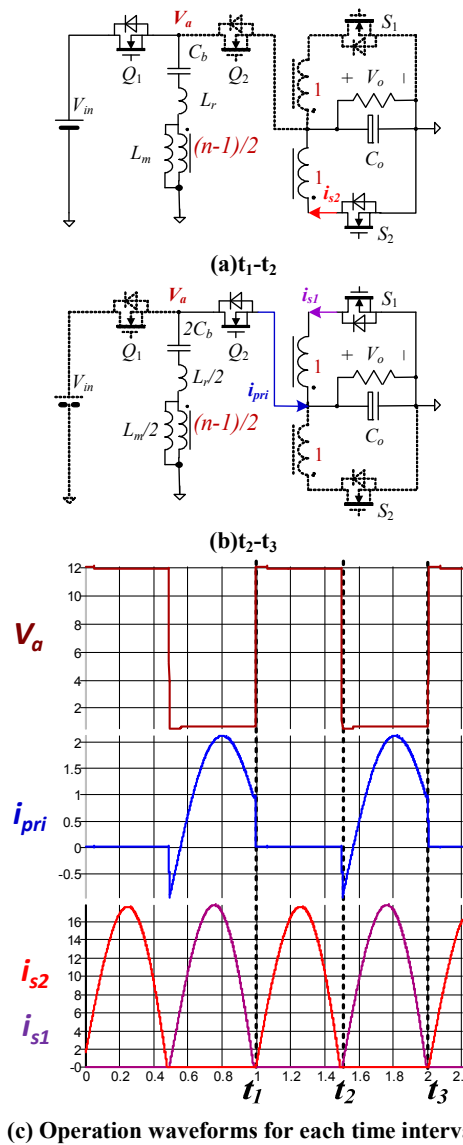
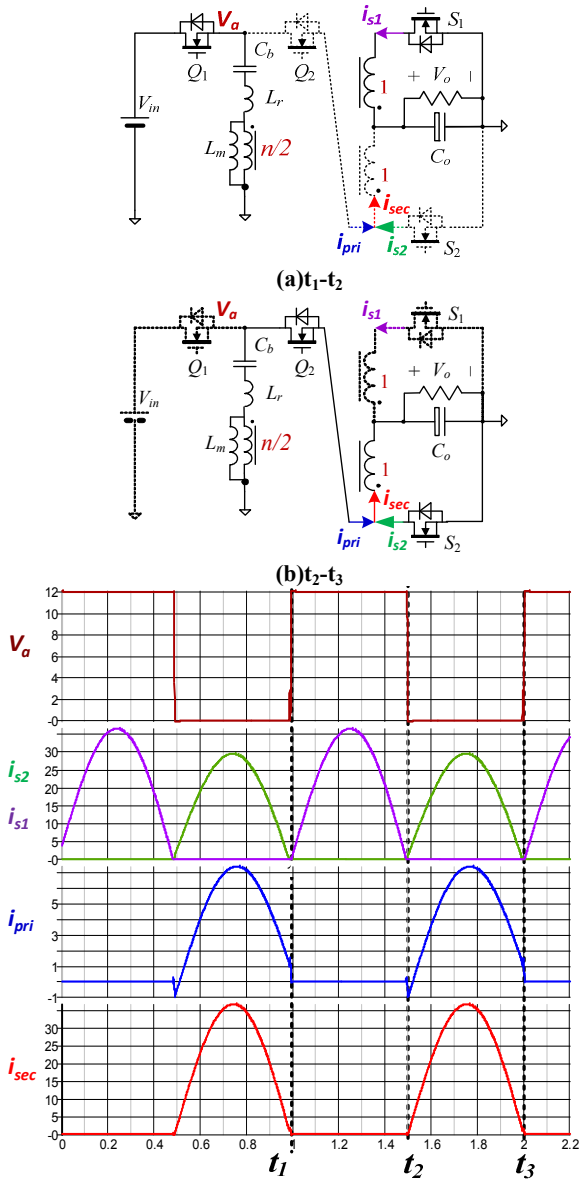


Fig 10. Half-bridge non-isolated LLC resonant converter type 2 (modification 1).

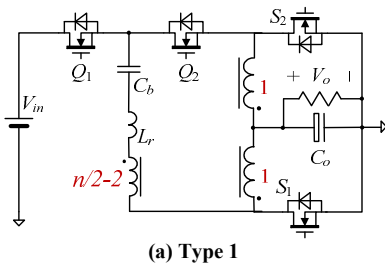
The operation waveforms of Fig 8 (c) are shown in Fig 11. During t_1-t_2 , the load current is i_{s2} , as shown in Fig 11 (a). Q2 is off, thus the primary side current does not contribute the output power. During t_2-t_3 , the load current is split into two parts, one is i_{s1} and the other is i_{pri} , as shown in Fig11 (b). The primary current directly goes to the secondary side winding to help reduce the current stress on S2.

During the switching circle, the average voltage across resonant tank is $V_{in}/2$, thus, the turns ratio of transformer equals $(V_{in}/2)/V_o$. The winding numbers is decreased. The size and loss of transformer can be reduced.

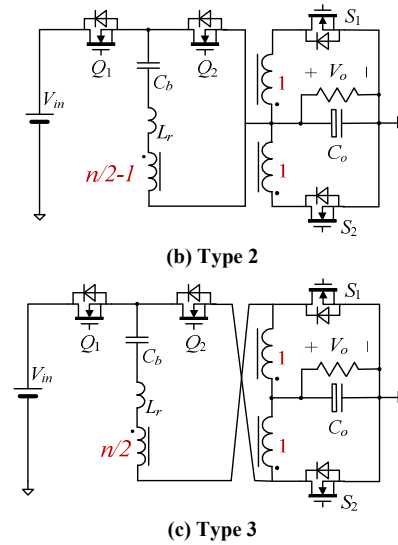


(c) Operation waveforms for each time interval
Fig 11. Half-bridge non-isolated LLC resonant converter type 3 (modification 1).

For better current distribution in transformer windings and less transformer turns ratio, more advanced modification is made in Fig 12.



(a) Type 1



(c) Type 3

Fig 12. Non-isolated half-bridge LLC resonant converter (modification 2).

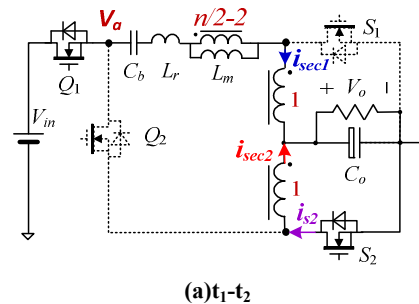
The operation waveforms for Fig 12 (a) are shown in Fig. 13 (c).

During t_1-t_2 , the load current is split into two parts, one is i_{sec1} and the other is i_{sec2} , as shown in Fig 13. (a). By this non-isolated structure, the primary current goes through one secondary winding to help deliver power. The SR and transformer winding current are effectively reduced, which means lower loss and high efficiency.

During t_2-t_3 , the load current is split into two parts, one is i_{sec1} and the other is i_{sec2} , as shown in Fig 13. (b). The primary current goes through one secondary winding to help reduce the current stress on secondary side windings.

During the switching circle, the voltage across resonant tank is always $V_{in}/2-2V_o$, thus, the turns ratio of transformer equals $(V_{in}/2-2V_o)/V_o$. The winding numbers is decreased. The size and loss of transformer are effectively reduced.

The node voltage V_a is in phase with i_{s1} and i_{s2} when switching frequency is at and above resonant frequency. Thus, V_a can be utilized to achieve self-driven for synchronous rectifier.



(a) t_1-t_2

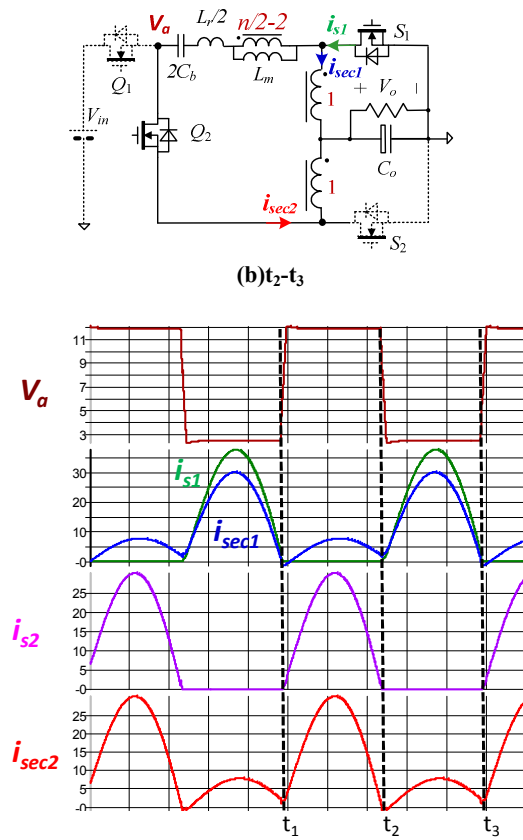


Fig 13. Half-bridge non-isolated LLC resonant converter type 1 (modification 2).

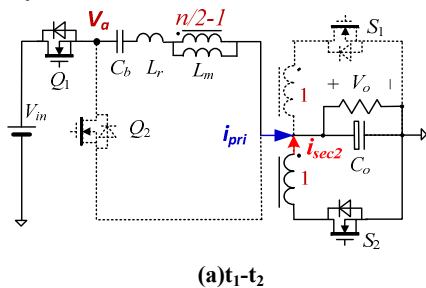
The operation for Fig 12 (b) are shown in Fig. 14.

During t_1-t_2 , the load current is split into two parts, one is i_{pri} and the other is i_{sec2} , as shown in Fig 14. (a). By this non-isolated structure, the primary current goes to the load to help deliver power. The SR current are effectively reduced, which means lower loss and high efficiency.

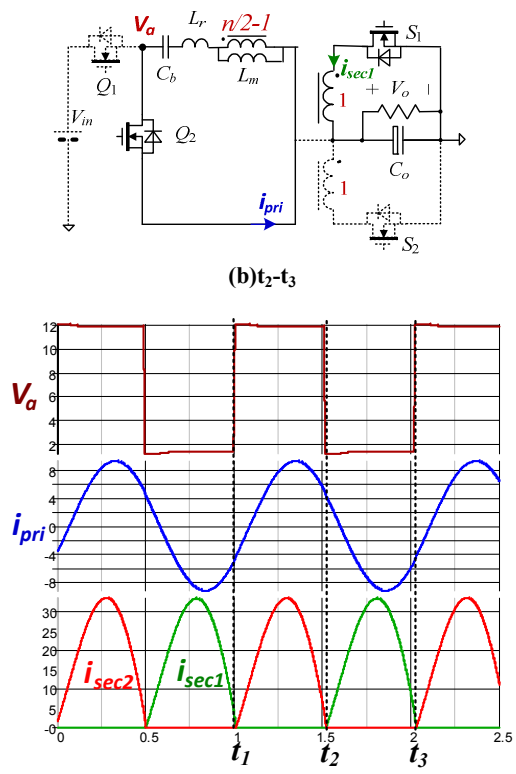
During t_2-t_3 , the load current only comes from i_{sec1} , as shown in Fig 14. (b).

During the switching circle, the average voltage across resonant tank is $V_{in}/2-V_o$, thus, the turns ratio of transformer equals $(V_{in}/2-V_o)/V_o$. The winding numbers is decreased. The size and loss of transformer is reduced.

It is the same as type 1, the node voltage V_a is in phase with i_{s1} and i_{s2} when switching frequency is at or above resonant frequency. Thus, V_a can be utilized to achieve self-driven for synchronous rectifier.



(a) t_1-t_2



(c) Operation waveforms for each time interval

Fig 14. Half-bridge non-isolated LLC resonant converter type 2 (modification 2).

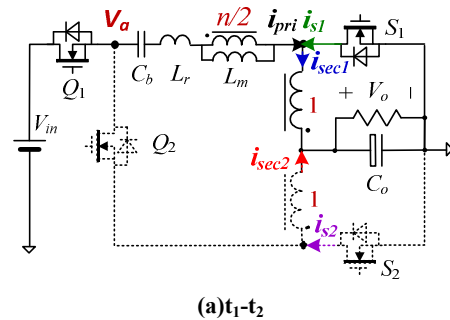
The operation for Fig 12 (c) are shown in Fig. 15.

During t_1-t_2 , the load current is split into two parts, one is i_{pri} and the other is i_{s1} , as shown in Fig 15. (a). By this non-isolated structure, the primary current goes to secondary side winding to help deliver power. The SR current are effectively reduced.

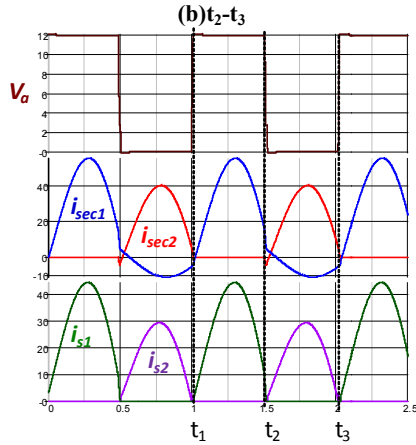
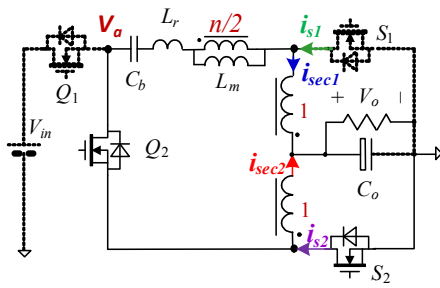
During t_2-t_3 , the load current is split into two parts, one is i_{sec2} and the other is i_{sec1} , as shown in Fig 15. (b).

Due to the unsymmetrical non-isolated structure, i_{sec1} and i_{sec2} , i_{s2} and i_{s1} are very different.

During the switching circle, the average voltage across resonant tank is $V_{in}/2$, thus, the turns ratio of transformer equals $(V_{in}/2)/V_o$.



(a) t_1-t_2



(c) Operation waveforms for each time interval

Fig 15. Half-bridge non-isolated LLC resonant converter type 2 (modification 2).

Based on the analysis above, different non-isolated structure gives different characteristics. All other resonant topologies can have similar behaviors if specific non-isolated structure applied accordingly.

III. EXPERIMENTAL RESULTS

The type 1 (modification 2) non-isolated half bridge LLC resonant converters (Fig. 12 (a)) is picked for its low turns ratio low SR current stress and low winding current stress. A 1MHz 12V/1.2V 25A DC/DC prototype is built to verify proposed non-isolated LLC resonant converters. The transformer turns ratio is 3:1:1. The primary device is CSD17312Q5, and the synchronous rectifier device is BSC011N03LS. The experimental results show i_{Lr} , V_{dsQ1} and V_{dsQ2} . ZVS for Q_1 and Q_2 is achieved.

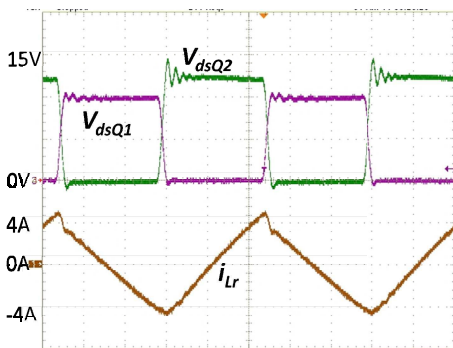
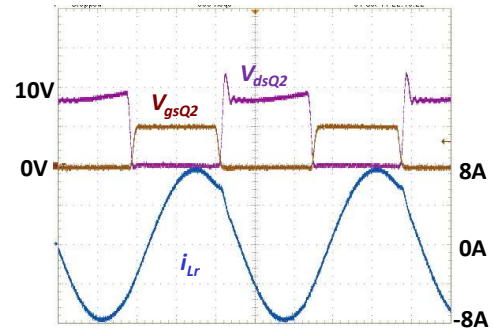


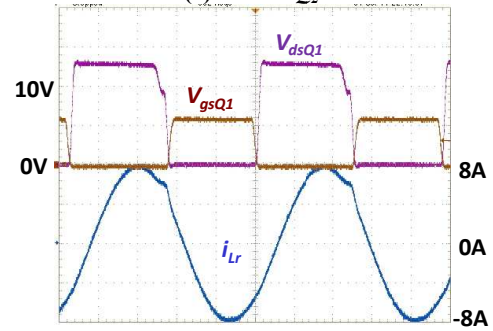
Fig 16. Experimental waveforms for no load

The no load situation is shown in Fig 16. Fig 17 shows ZVS achieved for both Q_1 and Q_2 .

The efficiency is shown in Fig 18. If self-driven technique applied, the efficiency can reach as high as 89%~90%.



(a) ZVS of Q_2



(b) ZVS of Q_1

Fig 17. Experimental waveforms for 10A load

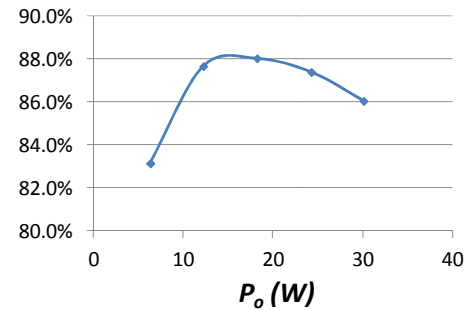


Fig 18. Efficiency of proposed non-isolated LLC resonant converter

IV. CONCLUSION

A group of non-isolated LLC resonant converters are proposed. Each of them has its own merits and demerits. One topology is picked as an example to illustrate the benefits.

ACKNOWLEDGMENT

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