Coupled Dual Interleaved Flyback Converter for High Input Voltage Application

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Abstract - **This paper proposes an integrated magnetic DC-DC converter suitable for high input voltage application. The converter is based on a coupled input-series and output-parallel dual interleaved Flyback converter concept. All the center and outer legs are gapped, and the transformers are integrated into one magnetic core with not so tight coupling. The gap is beneficial for suppressing current spike caused by the voltage mismatch between the windings. The two transformers are inversely coupled, and current ripple reduction can be achieved with suitable coupling design. A prototype with 350-450V input and 24V/4A output is built. Experimental results verify the performance of the new topology.**

I. INTRODUCTION

There is an increasing demand in modern power electronics for high density power converters. In most cases, the size of the magnetic components, including transformers and inductors, significantly influences the overall profiles of the converters. Integrated magnetic techniques [1-10] seem to be suitable solutions for high density application. The attraction is that transformers and inductors are combined in a single core, and therefore, cost and size of the converters may be reduced. Generally, there are two dominant types of isolated topologies using integrated magnetics: buck mode topologies, such as Forward [1,2], Push-Pull [3,4], Half-Bridge [5,6] and Full-Bridge [5,6], and buck-boost mode topologies, such as dual Flyback [9,10]. More recently, there are newly proposed integrated boost converters [7] that are beginning to see applications in automotive power electronics.

For large step-down power conversions, such as 48V to 1V, buck mode isolated topologies have become popular solutions. As a result, integrated magnetic techniques [1-6] have been widely developed for buck mode topologies. Historically, magnetic integration is utilized for Forward converters [1,2]. However, recent research pays more attention to full wave integrated magnetic DC/DC converters [3-6], which includes Push-Pull, Half-Bridge and Full-Bridge, etc. For example, magnetic integration is utilized for Push-Pull Forward circuit with coupled-inductor current doubler circuit [3,4]. A single EI or EE core is used for all the magnetic components, including the input inductor, the step-down transformer and the output filtering inductor. As well as reducing the overall size of the converter, coupled output inductor greatly reduces the current ripple, and thus improves the power efficiency. Incorporating an independent inductor winding into the transformer is another example for full wave integrated magnetic topologies [5,6]. The original full wave buck mode circuit operation is retained for this approach. A flexible output inductor winding is added in the center leg to optimize the design of output inductor.

This research mainly focuses on the discussion of integrated magnetic techniques related with buck-boost mode isolated topologies. In this definition, an integrated magnetic buck-boost mode topology means double or multiple Flyback circuits using a single magnetic core, since a single Flyback utilizes only one gapped magnetic core to store the energy in the power transformer. A Flyback converter is a popular choice for low power applications, due to its simplicity and low cost [11]. For example, it is suitable for use in a two-stage AC/DC converter at a power level of 150Watts or less.

Fig.1 shows a traditional full wave buck-boost (Flyback) power converter [9,10] that utilizes one magnetic core to integrate two Flyback transformers. In this case, the two transformers are coupled with a low reluctance in the outer legs of the magnetic core. The relatively higher reluctance magnetic property of the inductor L is integrated into the magnetic structure center leg. The transformers store the energy when S_1 or S_2 is turned on, and release the energy to the load when both S_1 and S_2 are turned off. Ideally, D_1 and D_2 conduct simultaneously to deliver the energy to the load so that the two inductors are coupled to reduce the current ripple.

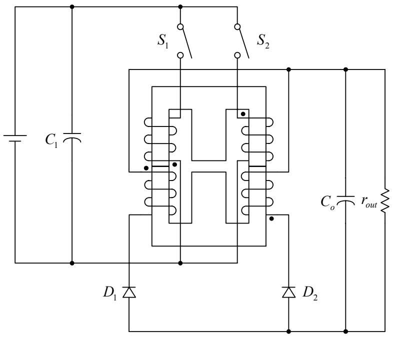

Fig.1 Traditional full wave buck-boost power converter [9,10]

This paper proposes a new integrated magnetic dual Flyback converter that is more suitable for high input voltage

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applications. Specifically, two interleaved Flyback converters are connected in series on the primary side and in parallel on the secondary side. Due to interleaved operation of the Flyback circuits, the current ripple is, thus, reduced as in typical interleaved Flyback circuits [12]. All the center and outer legs are gapped in the new converter, and the transformers are integrated into one magnetic core with not so tight coupling. This is beneficial for suppressing current spike caused by the voltage mismatch between the windings. The two transformers are inversely coupled so that significant current ripple reduction can still be fulfilled without tight coupling. The details of current ripple reduction are explained in Section III. The following features are presented.

- *Connecting the primary side in series reduces the voltage stresses of the primary components.* The primary switches are rated at half of the corresponding voltage values in a single Flyback or a traditional full wave buck-boost power converter [9,10]. The on-resistance and cost of the primary switches are, thus, significantly reduced.
- *Interleaved operation with paralleled connection on the secondary side keeps the benefits of ripple reduction as a traditional full wave buck-boost power converter [9,10] does.*
- *To satisfy a certain current ripple requirement, magnetizing inductance can be reduced by means of suitable inductor coupling design.* Due to the mutual influence of the two coupled inductors that is combined with the transformers, further current ripple reduction can be achieved when compared with interleaved Flyback converters without coupling.
- *Current spike caused by the voltage mismatch between the windings can be suppressed by gapping all the center and outer legs.* Compared with tight coupling, such as the condition in a traditional full wave buck-boost power converter shown in Fig.1, gapping all the legs weakens the coupling between the two Flybacks' windings, and thus, reduces the effect of the voltage mismatch.

II. OPERATION PRINCIPLE

Figure 2 shows the proposed coupled input-series and output-parallel dual interleaved Flyback converter, and Fig.3 represents the related waveforms. The primary switches are rated at half of the corresponding voltage values in a single Flyback or a traditional full wave buck-boost power converter [9,10] due to series connection of the two Flybacks. Also, gap filling is used for all the three legs. As shown in Fig.2, the upper Flyback (Flyback 1) consists of C_1, S_1, D_1, C_o and two windings in one outer leg. The lower Flyback (Flyback 2) consists of C_2, S_2, D_2, C_o and two windings in the other outer leg. Since gapping all the three legs weakens the coupling, the two Flybacks can actually operate independently (if desired). The current ringing caused by the voltage mismatch between the two Flybacks' windings can be significantly suppressed due to the weakened coupling. Therefore, the duty ratio can exceed 50%. It should be emphasized that weakened coupling does not necessarily sacrifice ripple cancellation in this case. Detailed ripple calculation is available in Section III. However, synchronized operation with suitable coupling design is beneficial for ripple reduction. This paper mainly analyzes the interleaved condition when duty ratio is less than 50% as shown in Fig.3. S_1 and S_2 are the main primary switches. V_{T1} and V_{T2} are the voltages across the primary windings as shown in Fig.2. i_{p1} and i_{p2} are the current through the primary windings. i_{s1} and i_{s2} are the current through the secondary windings. An E magnetic core is used in this paper. Each transformer utilizes one outer leg for windings. The following description explains the detailed principle of the proposed topology. t_0-t_4 is defined as one duty cycle T. The length of t_0-t_1 and t_2-t_3 are defined as DT, which represents the duty ratio. Assume N_p and N_s are the turns of the primary and secondary windings. The input to output transfer ratio is

$$V_o = V_{in} \cdot N_s \cdot D / [2 \cdot (1-D) \cdot N_p] \tag{1}$$

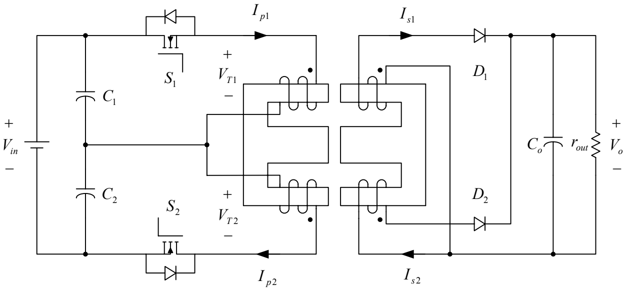


Fig.2 Proposed dual coupled Flyback converter

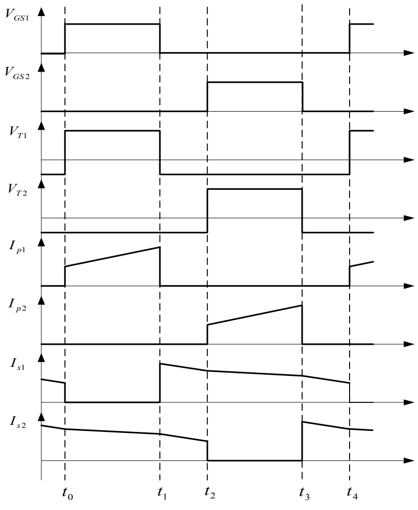
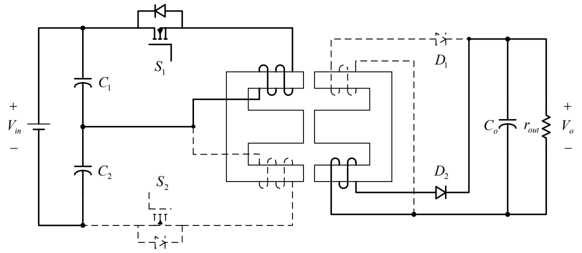


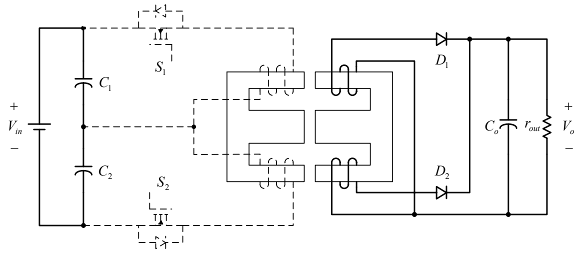
Fig.3 Timing and waveforms of the proposed circuit in steady state

Interval 1 (t_0-t_1): The condition of this period is shown in Fig.4 (a). During this interval, S_1 is turned on. The voltage across the primary winding of the upper Flyback is equal to $V_{c1} = V_{in}/2$. The upper Flyback circuit delivers energy from

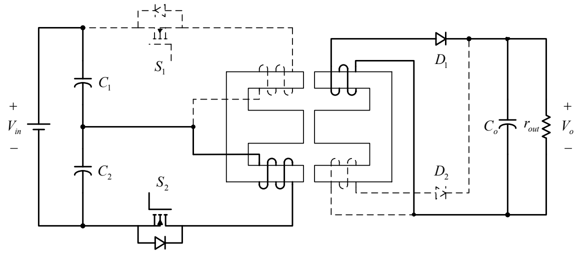
C_1 to the transformer on the primary side. The primary current i_{p1}, which is shown in Fig.2, increases linearly. The secondary diode D_1 is reverse-biased. At the same time, S_2 is off. The secondary side current of the lower Flyback, which is i_{s2}, flows through D_2 and charges C_o. The current value begins to decrease. In this case, the output voltage V_o is applied to the secondary winding of the lower Flyback.



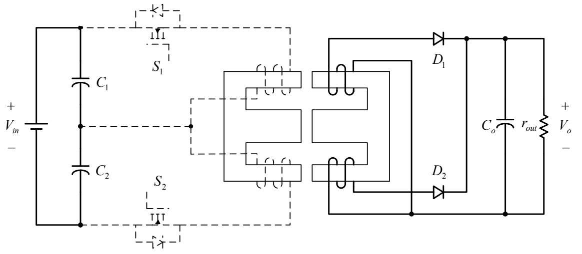
(a) Interval 1 ($t_0 - t_1$)



(b) Interval 2 ($t_1 - t_2$)



(c) Interval 3 ($t_2 - t_3$)



(d) Interval 4 ($t_3 - t_4$)

Fig.4 Detailed description of the operation principle of the proposed circuit

Interval 2 ($t_1 - t_2$)*:* As shown in Fig.4 (b), S_1 is turned off during this interval. Both Flyback circuits start to release the stored energy from the transformer to the output capacitor and load. Therefore, current i_{s1} goes through diode D_1 and i_{s2} goes through diode D_2. The voltage across each secondary winding is equal to V_o.

Interval 3 ($t_2 - t_3$)*:* The condition of this interval, which is shown in Fig.4 (c), is similar as interval 1. The two Flyback circuits switch the condition. S_2 is turned on. The voltage across the primary winding of the upper Flyback is equal to $V_{c2} = V_{in}/2$. The lower Flyback circuit delivers energy from C_2 to the transformer on the primary side. The primary current i_{p2}, which is shown in Fig.2, increases linearly. At the same time, S_1 remains off. The secondary side current of the upper Flyback, which is i_{s1}, flows through D_1 and charges C_o. The current value begins to decrease. The output voltage V_o is applied to the secondary winding of the upper Flyback.

Interval 4 ($t_3 - t_4$)*:* Fig.4 (d) shows the condition of the last interval. This case is the same as interval 2. Both Flyback circuits release energy on the secondary sides. The output voltage V_o is applied to the two secondary windings.

III. RIPPLE CALCULATION FOR COUPLED CONDITION

For two coupled inductors, the following typical relations can be obtained [3,8],

$$v_1 = L_1 \cdot \frac{di_1}{dt} - M \cdot \frac{di_2}{dt} \tag{2}$$

$$v_2 = L_2 \cdot \frac{di_2}{dt} - M \frac{di_1}{dt} \tag{3}$$

In the above case, let $\alpha = \frac{M}{L_1} = \frac{M}{L_2}$, and v_1 and v_2 are the voltages applied on the two corresponding windings. M is the coupling inductance.

For this proposed coupled Flyback, the following equations about the current ripple can be achieved based on typical equations and specific conditions. Using the derived equations, optimized design can be achieved for converters according to their specific requirement. When all the legs have gaps with approximately same distances, α is approximately equal to $1/3$. Assume M is the coupling inductance between the two primary windings. L_p and L_s are the magnetizing inductance of the primary and secondary winding. V_{in} and V_0 are the input and output voltages. For each Flyback, $V_{in}/2$ is applied.

Interval 1 ($t_0 - t_1$)*:* During this interval, currents circulate through the primary winding of Flyback 1 and the secondary winding of Flyback 2. These two windings are considered as two coupled inductors. Since $V_{in}/2$ is applied to the primary winding of Flyback 1, and V_o is applied to the secondary winding of Flyback 2, the following formulas related with current ripple are obtained according to equation (2) and (3).

$$L_p \frac{di_{p1}}{dt} = \frac{V_{in}/2 - \alpha V_0 \cdot (N_p / N_s)}{1-\alpha^2},$$

$$L_s \frac{di_{s2}}{dt} = \frac{\alpha V_{in} \cdot (N_s / N_p)/2 - V_0}{1-\alpha^2} \tag{4}$$

Since $i_{s1} = 0$, we also have $C_o \frac{dV_o}{dt} = i_{s2} - \frac{V_o}{r_{out}}$. The capacitor is in a discharge state. i_{p1} is increasing approximately linearly because $V_{in}/2 - \alpha V_o \cdot (N_p / N_s)$ is positive.

Interval 2 ($t_1 - t_2$): During this interval, currents circulate through the secondary winding of both Flyback circuits. These two windings are considered as two coupled inductors. Since V_o is applied to the secondary winding of each Flyback, the following formulas related with current ripple can be achieved according to equation (2) and (3).

$$L_s \frac{di_{s1}}{dt} = L_s \frac{di_{s2}}{dt} = \frac{-V_0}{1-\alpha} \tag{5}$$

Also, $C_o \frac{dV_o}{dt} = i_{s1} + i_{s2} - \frac{V_o}{r_{out}}$. The capacitor is in a charge state since $i_{s1} + i_{s2} > \frac{V_o}{r_{out}}$. The two coupled secondary inductors are both releasing their energy into the load.

Interval 3 ($t_2 - t_3$): During this interval, currents circulate through the second winding of Flyback 1 and the primary winding of Flyback 2. These two windings are considered as two coupled inductors. Since V_o is applied to the secondary winding of Flyback 1, and $V_{in}/2$ is applied to the primary winding of Flyback 2, the following formulas related with current ripple are obtained.

$$L_s \frac{di_{s1}}{dt} = \frac{\alpha V_{in} \cdot (N_s / N_p)/2 - V_0}{1-\alpha^2},$$

$$L_p \frac{di_{p2}}{dt} = \frac{V_{in}/2 - \alpha V_0 \cdot (N_p / N_s)}{1-\alpha^2} \tag{6}$$

Since $i_{s2} = 0$, we also have $C_o \frac{dV_o}{dt} = i_{s1} - \frac{V_o}{r_{out}}$. Similar to Interval 1, the capacitor is in a discharge state and i_{p2} is increasing approximately linearly.

Interval 4 ($t_3 - t_4$): During this interval, currents circulate through the secondary winding of both Flyback circuits. These two windings are considered as two coupled inductors. Since V_o is applied to the secondary winding of each Flyback, the following formulas related with current ripple are obtained.

$$L_s \frac{di_{s1}}{dt} = L_s \frac{di_{s2}}{dt} = \frac{-V_0}{1-\alpha} \tag{7}$$

Similar to Interval II, $C_o \frac{dV_o}{dt} = i_{s1} + i_{s2} - \frac{V_o}{r_{out}}$. The capacitor is in a charge state. The two coupled secondary inductors are both releasing their energy into the load.

Further Discussions on the Proposed Circuit

As shown in Fig.3, the current ripple is determined by

$$\Delta i_{p1} = \Delta i_{p2} = \frac{V_{in}/2 - \alpha V_0 \cdot (N_p / N_s)}{(1-\alpha^2) \cdot L_p \cdot f_s} \cdot D \tag{8}$$

When compared with no coupling condition (Suppose using same inductance value L_p, and the current ripple is determined by $\Delta i_p = \frac{V_{in} D}{2 L_p \cdot f_s}$.), $\frac{V_{in}/2 - \alpha V_0 \cdot (N_p / N_s)}{1-\alpha^2} \le V_{in}/2$ should be satisfied in order to achieve a reduced current ripple. In other words, smaller inductor can be used to satisfy identical current ripple requirement when $\alpha \le \frac{2 \cdot V_o \cdot N_p}{V_{in} \cdot N_s}$.

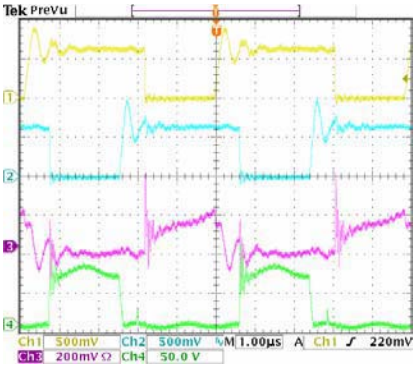
Specifically, the following differences are remarked when compared with a traditional converter [15,16] in Fig.1.

1. The new approach connects the input of the two Flybacks in series, while the traditional method connects the input in parallel.
2. The proposed converter has 3 gaps in all legs. The traditional converter only has 1 gap in the center leg.
3. The secondary windings are inversely coupled in the new converter, and directly coupled in the traditional converter.

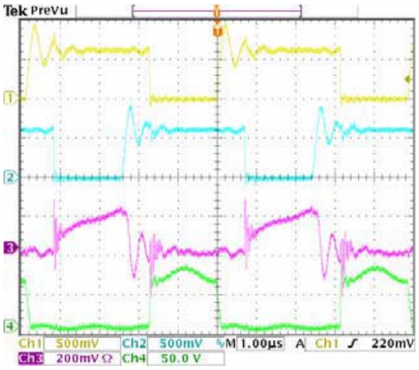
From the first difference, it can be concluded that the proposed method has half of the voltage stress when compared with the traditional method. Due to input-series and output-parallel connection, DUal Magnetic parts with Balanced Operation can be fulfilled in the proposed circuit. According to the second and third differences, the secondary windings of the traditional converter are directly coupled with tight coupling. However, for practical circuits, especially for this high voltage application, switches cannot operate exactly simultaneously. Minor mismatch can lead to high current spikes and resonance when the two windings have good coupling and small leakage inductance. On the other hand, the secondary windings of the new converter are inversely coupled with not so tight coupling since all three legs are gapped. Current spikes and resonance due to voltage mismatch can be suppressed since the leakage inductance has a big value. Also, current ripple reduction can still be achieved with suitable coupling designs, and the weakened coupling between the two transformers allows the duty ratio to be greater than 50% in the propose circuit.

IV. EXPERIMENTAL RESULTS

To verify the principle of the proposed scheme, a prototype with 350V-450V input and 24V/4A output is built by using the proposed topology switched at 200kHz hard switched. FDD6N50TF (500V, 6A, DPAK) is used for the primary switches. (It should be remarked that MOSFETs rated at 800-1000V are needed in this specification for a single Flyback or a full wave Flyback [15,16] shown in Fig.1.) Secondary diodes (D_1 and D_2) use 12CWQ10FN (100V, 12A, DPAK). The two coupled transformers are integrated into one E22 magnetic core. The cross sectional area of the magnetic core is 78.5mm^2. The gaps are the same in each leg. Therefore, α is approximately equal to $1/3$. Each transformer has 60 turns for the primary winding and 13 turns for the secondary winding.



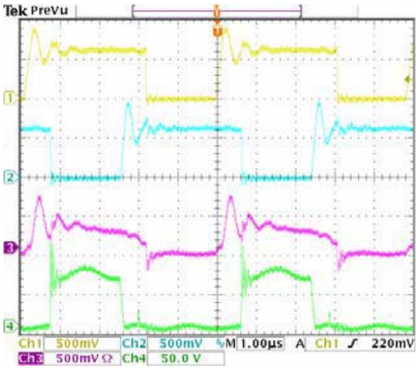
(a) Primary current of the upper Flyback is shown



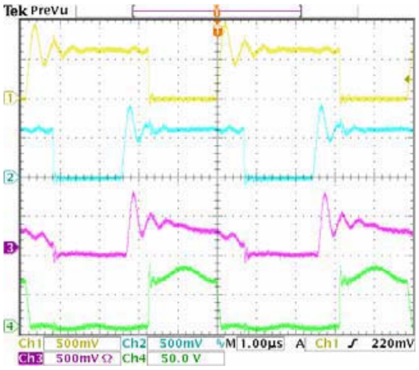
(b) Primary current of the lower Flyback is shown

Fig.5 V_{ds1} (Channel 1, 250V/div), V_{ds2} (Channel 2, 250V/div), primary current (Channel 3, 1A/div) and voltage across the secondary diode (Channel 4, 50V/div)

Fig.5 shows the waveforms of V_{ds1} (Channel 1, 250V/div), V_{ds2} (Channel 2, 250V/div), primary current (Channel 3, 5A/div) and voltage across the secondary diode (Channel 4, 50V/div) when the input voltage is 400V. Fig.6 shows the waveforms of V_{ds1} (Channel 1, 250V/div), V_{ds2} (Channel 2, 250V/div), secondary current (Channel 3, 5A/div) and voltage across the secondary diode (Channel 4, 50V/div) when the input voltage is 400V. The two Flyback circuits are interleaved. The waveforms of the secondary side are in phase with the primary side. The change rate of the secondary current of one Flyback differs as expected when the other Flyback operates at different modes. This phenomenon occurs due to the mutual effect between the coupled windings. By comparing the waveforms from the upper and lower Flyback circuits, it can be clearly seen that the two parts are self-balanced. Each part shares half of the input voltage.



a) Secondary current of the upper Flyback is shown



((b) Secondary current of the lower Flyback is shown

Fig.6 V_{ds1} (Channel 1, 250V/div), V_{ds2} (Channel 2, 250V/div), secondary current (Channel 3, 5A/div) and voltage across the secondary diode (Channel 4, 50V/div)

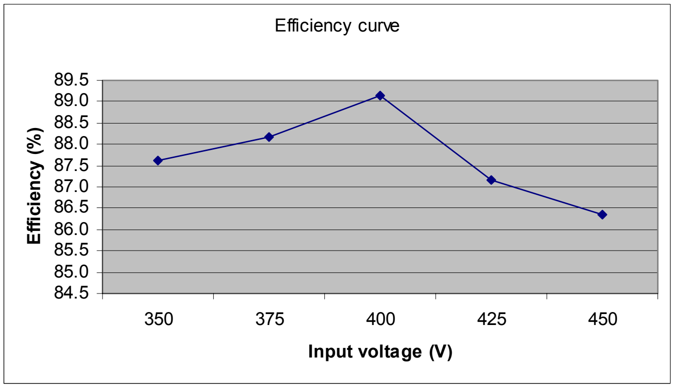


Fig.7 Efficiency of the built prototype

By applying the proposed coupled input-series and output-parallel dual interleaved Flyback converter, an efficiency of 89.1% at 400V input and 24V/4A output is obtained. Fig.7 shows the efficiency curve during the whole input voltage variation range. The experimental results verify the principle and performance of the scheme.

V. CONCLUSION

A coupled input-series and output-parallel dual interleaved Flyback converter for high input voltage application is proposed. Connecting the primary side in series reduces the voltage stresses of the primary components. All the center and outer legs are gapped, and the transformers are integrated into one magnetic core with not so tight coupling. The current ringing caused by the voltage mismatch between the two Flybacks' windings can be suppressed due to the weakened coupling. The two transformers are inversely coupled so that significant current ripple reduction can still be fulfilled with not so tight coupling. Experimental results verify the performance of the new topology.

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