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Design of Transformer Less Converter with Coupled Inductors for Hybrid Vehicles

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Abstract:

The far reaching reverberation examination and soft switching outline of the separated help converter with coupled inductors are explored in this paper. Because of the reverberation took an interest by the voltage doubler capacitor, bracing capacitor and spillage inductance of coupled inductors, the converse recuperation issue of the optional diodes is controlled inside the entire operation range. By picking fitting attractive inductance of the coupled inductors, zero voltage exchanging (ZVS) one of the primary MOSFETs is acquired on the whole at the same working conditions with no extra gadgets.

In addition, the scope of obligation proportion is developed to accomplish delicate exchanging and an ideal operation point is gotten with insignificant info current swell, when obligation proportion approaches 0.5. Also, two sorts of resonances are broke down and an improved reverberation is used to accomplish better power thickness. The model is actualized for the vehicle inverter requiring a 150 W yield power, information voltage range fluctuating from 10.8 to 16 V, and 360 V yield voltages. Test comes about check the configuration and demonstrates that the base proficiency is around 93.55% and 90.53% at low load and full load, separately.

Index Terms:

Interleaved boost converter, resonance analysis, soft switching, and vehicle inverter application.

I. INTRODUCTION:

Vehicle inverter is currently spreading over the world. Top-end Audi and Bavarian Motor Works (BMW) autos are getting a charge out of solace and comfort of vehicle inverters. Most customary vehicle inverters are created by two phases: DC/DC converter and DC/AC inverter. To accomplish 220V Root-Mean-Square (RMS) sine wave, the info voltage of DC/AC inverter ought to be no less than 360Vdc in an exceedingly effective way [1]. It merits seeing that the vehicle battery displays low voltage trademark (10.8V to 16V, run of the mill 12V), the DC/AC inverter must have a high voltage change proportion DC/DC converter toward the front. Considering life range of vehicle battery, mounting space and normal cooling, DC/DC converter with low-enter current swell, high operation recurrence and high effectiveness are required in this application [2] - [9].

Also, galvanic confinement is important to meet the well being models. Push-pull topology is generally utilized as a part of DC/DC stage [8]-[13]. Voltage-bolstered push-pull converter proposed in [9] highlights high information current swell on the grounds that the current in the essential side is intermittent. A low-pass LC info channel is connected to minimize the swell. At that point it builds the volume of the framework for high information current. Additionally, the converter's voltage transformation proportion is just controlled by turn proportion of transformer.

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To accomplish a high stride up highlight, a substantial turn proportion brings expansive transformer volume and spillage inductance which corrupts power thickness and circuit execution. Current-nourished push-force is appropriate for low info voltage, high information current application because of the information inductor. Moreover, critical topologies are utilized as a part of energy component framework and battery sourcing application[10] ,[11] and dynamic clasping with reverberation innovation has picked up fascination which can understand zero voltage exchanging (ZVS) on of MOSFETs [14]-[16] or resolve reverse - recuperation issue of auxiliary correcting diodes [12],[17]. With delicate exchanging characters, the operation recurrence can be sufficiently high to acquire high power thickness as well as high proficiency. A dynamic clasping current-nourished push-pull converter in [8] has fulfilled execution for vehicle inverter application. Examination of two said converters is recorded in TABLE I. Be that as it may, more nitty gritty reverberation examination still should be displayed. Enhanced reverberation will be intended to minimize capacitors volume, and enhance power thickness. From the past inquires about [11]-[17], converters with reverberation can be isolated into two classes regarding delicate exchanging trademark. One is to get ZVS on of the primary MOSFETs [11], [14]-[16] while the other is to kill auxiliary diodes delicately [12], [13], [17]. A novel disconnected ZVT support converter with coupled inductors has been proposed which has a place with the top of the line [14]. The information parallel setup is received to share the substantial information current and to diminish the conduction misfortunes. Additionally, the dynamic clasp circuits are utilized to accomplish zero-voltage-move (ZVT) for all the dynamic switches. Nonetheless, switch recuperation issue of optional diodes is still remained and obligation proportion must be bigger than 0.5 to accomplish ZVS on of the fundamental MOSFETs. Moreover, these two sorts of delicate exchanging attributes are still not acquired all things considered at the same working conditions among the said converters yet.

In this paper, reverberation investigation and delicate exchanging outline of the separated help converter with coupled inductors are introduced. The schematic of converter is actualized as Fig.1. Contrasted and the previous proposed converter, both ZVS on of the main MOSFETs and zero Current switching (ZCS) off of the secondary diodes are obtained. This paper is sorting out as taking after. Rule of operations is appeared in Section II. The examination and outline of reverberation and circuit are shown in Section III and IV, individually. At long last, trial brings about Section IV approve the examination and configuration. The synopsis is given in the last area.

II. PRINCIPLE OF OPERATIONS

Due to interleaved control of S_1 and S_2, the frequency of i_L is twice as high as the switching frequency so input current ripple is reduced. When D is 0.5, input current ripple is approximately zero. Principle of operation is presented as follows.

TABLE I
COMPARISON OF TWO MENTIONED CONVERTERS

Converter	Input current ripple	Soft switching of MOSFETs	Soft switching of Diodes	Efficiency (12V input voltage)	Core of Transformer
Voltage-fed push-pull in [9]	Large	Part ZVS on	ZCS off	95.4% @150W 94.3% @60W	PQ32/30 PC44
Current-fed push-pull in [8]	Small	ZVS on when D>0.5	ZCS off	92.4% @150W 91.1% @60W	PQ26/25 PC40

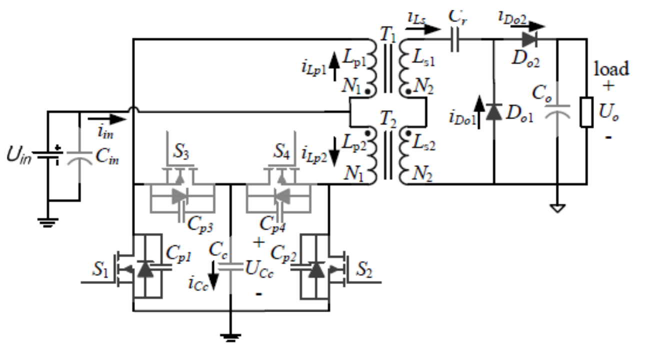

Fig.1. Schematic of the converter.

A. Operational principle for D < 0.5:

When D is small than 0.5, resonance operates at non-overlapping interval.

Mode 1 [t_0, t_1]: S_1 is turned off at t_0 while S_2 is off. Inductor $L_{p1}$and $L_{p2}$are discharging and di/dtequals (U_{in}-U_{Cc})/L_p. Dueto small inductance of L_{p1} and L_{p2}, i_{Lp2} is under zero at t_1. The reverse current is flowing from clamping capacitor C_c, auxiliary MOSFET S_4 to

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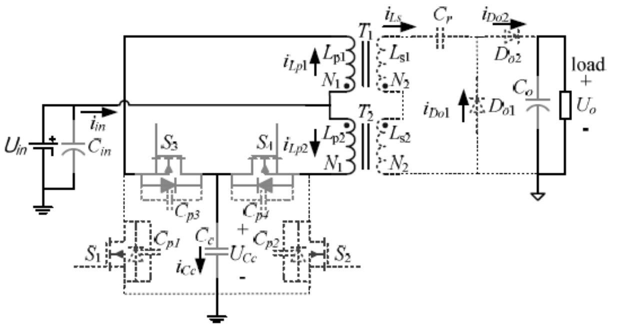
inductor L_{p2}. No energy is transferred to secondary side. Equivalent circuit is presented as Fig.2a.

Mode 2 [t_1, t_2]: S4 is killed at t1 when iLp2 is converse. Inductor Lp2 releases parasitic capacitor Cp2 of S2 for Freewheeling. In the event that the converse current of Lp2 is sufficiently huge, there will be adequate vitality to release uDS2 to zero at t_2.



(a)

Equivalent circuit is presented as Fig.2b.

Mode 3 [t_2, t_3]: S_2 is turned on at t_2 when u_{DS2} reaches to zero. ZVS on of S_2 is achieved. S_1 is still off. Hence, inductor$L_{p1}$is discharging and di/d t equals $(U_{in}-U_{Cc})/L_p$. Inductor L_{p2}ischarging and di/dt equals U_{in}/L_p. Secondary circuit begins toconduct. Transformer T_1 works as a flyback converter and transformer T_2 works as a forward converter. Leakage inductor of transformer, clamping capacitor C_c and voltage doubler capacitor C_r start to resonate. Therefore, both i_{Lp1} and i_{Lp2}contain magnetizing current and resonant current.Equivalent circuit is presented as Fig.2c.

Mode 4 [t_3, t_4]: Secondary current i_{Ls} decreases to zero at t_3 and resonant circuit is cut off by diode D_{o2}. Therefore, secondary diode is turned off softly and reverses. Inductor L_{p2} is still charging with rate determined by U_{in}/L_p. Equivalent circuit is presented as Fig.2d.

During the remaining half period of T_S, Modes 5 to 8 are analogous to the operation of Modes 1 to 4. Voltage-second balance law of inductor L_{p1} and L_{p2} is written as

$$U_{in}D + (U_{in} ? U_C)(1 ? D) = 0 \quad (1)$$

Thus,

$$U_C = \frac{U_{in}}{1 ? D} \quad (2)$$

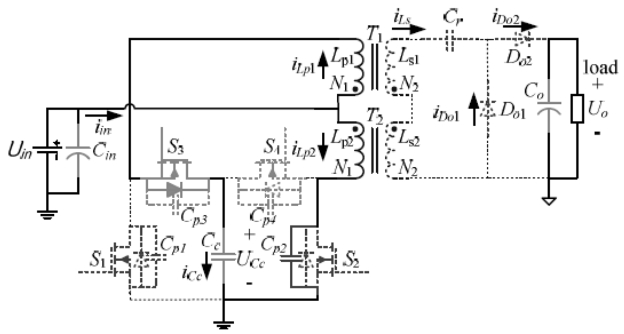
Since secondary topology is secondary windings in series

$$U_o = 2\cdot[\frac{N_2}{N_1}U_{in} + \frac{N_2}{N_1}(U_C ? U_{in})] = \frac{2N_2U_{in}}{N_1(1 ? D)} \quad (3)$$

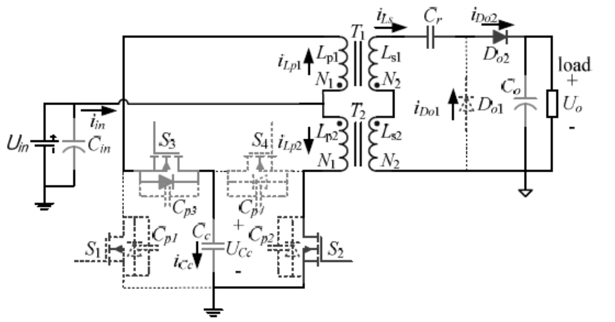
From (3), though magnetizing currents of inductor L_{p1} and $L_{p2}$are reverse at some intervals, the voltage gain does notchange. Fig.3 shows key waveforms for D< 0.5.

B. Operational principle for D > 0.5:

When D is > 0.5, resonance operates at overlapping interval. Analogous analysis is omitted due to space restriction. Fig.4 shows key waveforms for D> 0.5.



(b)



(c)

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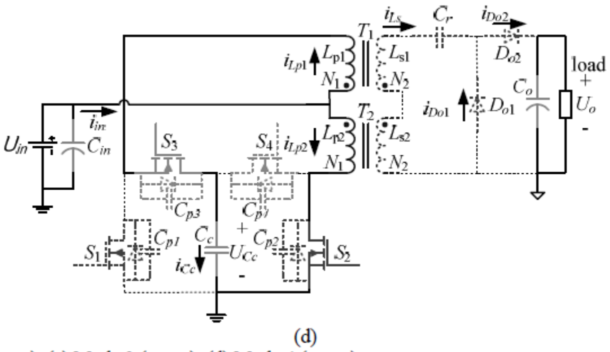

Fig.2. Operation modes of the proposed converter. (a) Mode 1 (t_0 ~ t_1). (b) Mode 2 (t_1 ~ t_2). (c) Mode 3 (t_2 ~ t_3). (d) Mode 4 (t_3 ~ t_4)

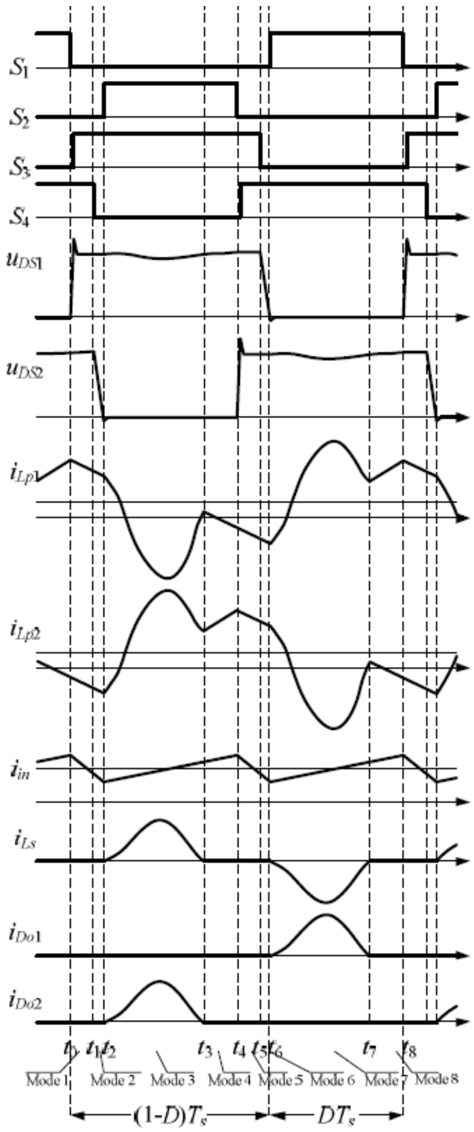

Fig.3. Key waveforms for D<0.5.

III. ANALYSIS AND DESIGN OF RESONANCE:

There are huge high stride up topologies, for example, current-nourished push-pull [12], fly back-forward [14], [18] and double help [15]. Reverberation is an essential interim of these converters. Suitable resounding parameter can get delicate exchanging execution. Essential overwhelming reverberation is utilized as a part of [1], [11], [14-16] and ZVS on of essential fundamental MOSFETs is accomplished. Optional predominant reverberation is utilized as a part of [12], [13], [17] and auxiliary redressing diodes are killed delicately. Reverberation model of this converter and relationship between two sorts of resonances will be introduced and investigate.

A.Analysis of equivalent resonant circuit:

Current of primary winding is composed by magnetizing component (iLp(t)) and resonant component (N2iLs(t)/N1).

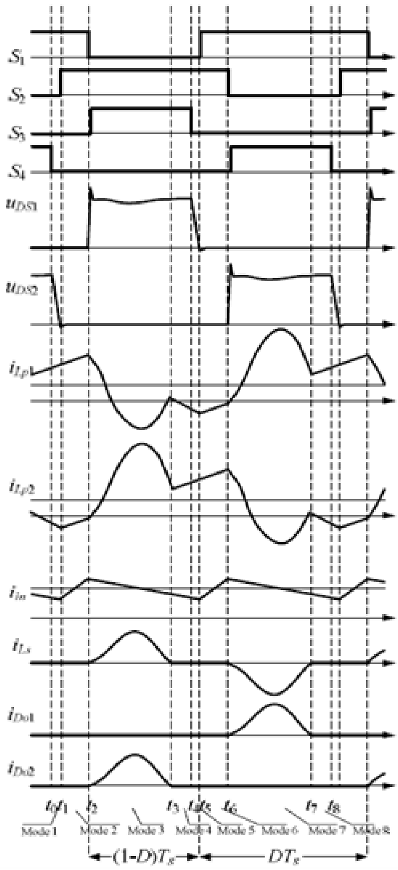

Fig.4. Key waveforms for D>0.5.

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Hence, equivalent circuit of resonant interval is shown as Fig.5. State equations are listed as (4) to (11).

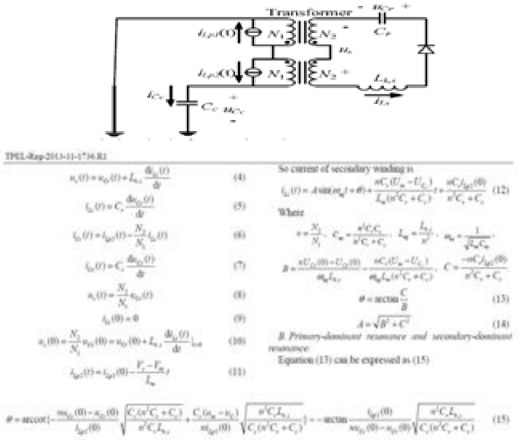

Fig.5. Equivalent circuit of resonant interval.

Condition (15) demonstrates that thunderous parameter and introductory status of Cc, Cr, Lk,s make commitment to the period of reverberation. Contrasting Cr and Cc, θ has a tendency to be - π/2 when Cr is generally sufficiently extensive. The current of optional twisting then is a cosine-like bend. Cr is too huge to have any impact on the reverberation so it can be named as essential prevailing reverberation. Auxiliary current is only the impression of essential thunderous current. Fig.6 indicates waveforms of recreation for essential overwhelming reverberation. Current of essential spillage inductor ik,p is turned around and achieves trough after portion of thunderous.

In the event that assistant switch is killed as of now, essential spillage inductor will release capacitor Cds of fundamental MOSFET [14]. ZVS on of primary MOSFETs can be accomplished when reverse current is adequately expansive. Then, optional current is close to its top at the exchanging minute. Thusly, invert recuperation issue of auxiliary diodes is remained and just reduced by optional spillage inductor.

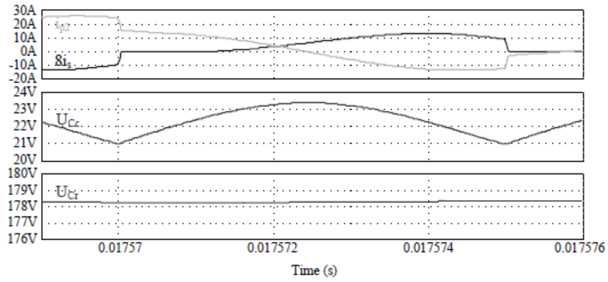

Fig.6. Primary-dominant resonance.

(N_2/N_1=8, C_c=10μF, C_r=47μF, $L_{k,s}$=10.74μH L_{p1}=L_{p2}=3μH)

θtends to be zero when Ccis generally sufficiently vast. Thecurrent of auxiliary twisting then is a sine-like bend. Cc is too substantial to have any impact on the reverberation so it can be named as optional prevailing reverberation. Essential thunderous current is only the impression of optional resounding current. Fig.7 indicates waveforms of reenactment for auxiliary predominant reverberation. In an unexpected way, current of essential spillage inductor ik,pis switched and comes to troughafter a fourth of thunderous cycle t =π2Leq,s Cr auxiliary current scopes to zero right now and resounding circuit is cut off by optional diodes so diodes are killed delicately [12].

In the event that insignificant covering (D>0.5) or non-covering (D<0.5) interim is longer than half of the thunderous cycle, ZCS off will be gotten inside the entire operation range. Henceforth from past examination, ZVS on of fundamental MOSFETs and ZCS off of optional diodes can't be gotten all the while at the same working conditions. In essential overwhelming reverberation, full segment of current will comes back to zero after a whole thunderous cycle t □ 2π Leq,p Cc. Be that as it may, helper switch is as yet directing so essential full circuit is not cut off and another thunderous cycle starts. Subsequently, turn around recuperation issue of optional diodes is remained. Waveforms for this circumstance are appeared as Fig.8.

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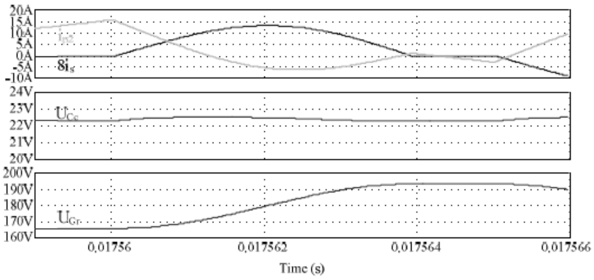

Fig.7. Secondary-dominant resonance.

(N_2/N_1=8, C_c=40μF, C_r=150nF, $L_{k,s}$=10.74μH L_{p1}=L_{p2}=3μH)

Unfortunately, ZVS on of main MOSFETs can't be achieved when D is <0.5. Shown as Fig.9, resonance is terminated when S_2 is turned off. Then current flows from primary leakage inductor to clamping capacitor C_c before S_1 is turned on. Hence there is no reverse current to discharge capacitor C_{ds} of S_1.

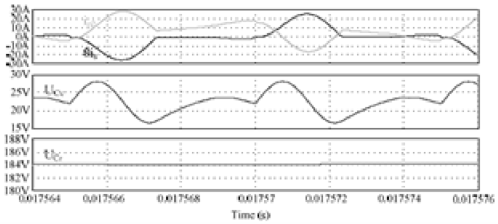

Fig.8. Primary-dominant resonance cannot achieve ZCS off

(N_2/N_1=8, C_c=1.25μF, C_r=100μF, $L_{k,s}$=10.74μH L_{p1}=L_{p2}=3μH)

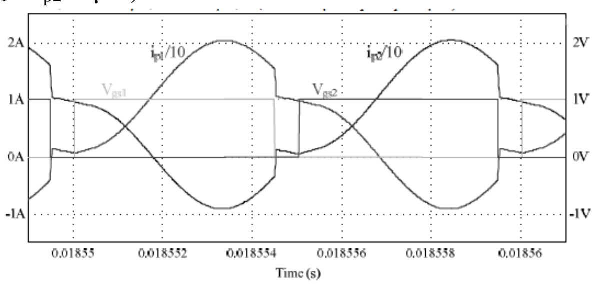

Fig.9. Resonant waveforms for D <0.5.

(N_2/N_1=8, C_c=6μF, C_r=47μF, $L_{k,s}$=10.74μH, L_{p1}=L_{p2}=5μH)

In light of the investigation above, correlation of two sorts of resonances is exhibited as TABLE II. So it goes to a tradeoff between essential exchanging misfortune and optional opposite recuperation misfortune in the specific application. ZVS on ought to be gotten if essential exchanging misfortune rules. ZCS off is favored when reverse - recuperation misfortune is generally high. Outline of circuit parameter is easy to figure out which delicate exchanging execution will be used. In this converter, the outline uses reverse charging streams of Lp1 and Lp2 because of their little inductances which acquire ZVS on of fundamental MOSFETs. In this way ZVS on of the fundamental MOSFETs does not have connection with thunderous interim so it can be acknowledged without the confined scope of obligation proportion in [8], and can coincide with ZCS off of auxiliary diodes.

TABLE II
COMPARISON OF TWO KINDS OF RESONANCES

Resonant timing point	ZVS on of main switches	ZCS off of secondary diodes
Primary -dominant resonance	After $T_r/2=\pi\sqrt{L_{eq,p}C_c}$ (D>0.5)	Cannot be achieved
Secondary-dominant resonance	After $T_r/4=\frac{\pi}{2}\sqrt{L_{eq,s}C_r}$ (D>0.5)	After $T_r/2=\pi\sqrt{L_{eq,s}C_r}$

A. Design of the optimized resonance:

In this specific vehicle inverter application, operation point at D=0.5 is favored as a result of minimized info current swell. ZVS on of fundamental switches can be accomplished while polarizing inductances are sufficiently little. In the mean time, ZCS off of auxiliary diodes is planned inside the entire information voltage and burden range. Because of moderately high turn proportion of transformer, Cc should be uncommonly extensive to get auxiliary predominant reverberation. In the outlined converter, a public cinching capacitor Cc is utilized and its capacitance is legitimately not huge because of the configuration of upgraded reverberation. In this way, the planned reverberation is between the previously mentioned two resonances and the volume of capacitor is diminished. Three elements ought to be considered for outline of this streamlined reverberation.

1) Duration of resonance. In order to achieve ZCS off of secondary diodes, duration of resonance should be shorter than minimal overlapping interval (D>0.5) or non-overlapping interval (D<0.5). However when duration of resonance is shortened, the peak of

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resonant current rises to transfer equivalent energy. That means C_c and C_r should be sufficiently large to alleviate current stress of both primary and secondary side.

2) Ripple of clamping voltage. Main MOSFETs will sustain high voltage stress if C_c is too small. Hence, C_c should restrict the ripple of clamping voltage into an acceptable range.

3) Capacitor volume. After taking the previous two into consideration, a combination of C_c and C_r should be adopted to get minimal volume of capacitors.

In this converter, C_r is 47nF and C_c is 3μF while turn ratio of transformer is 3:3:24. Waveforms of simulation for resonance are shown as Fig.10. Obviously, the resonance is the one between primary-dominant resonance and secondary-dominant resonance.

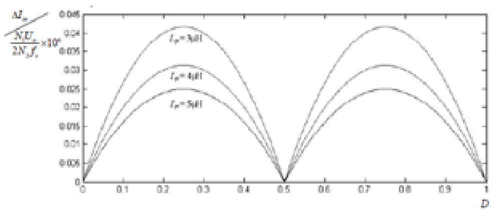


Fig.10. Waveforms of simulation for designed resonance.

(N_2/N_1=8,C_c=3μF,C_r=47nF, $L_{k,s}$=10.74μH, L_{p1}=L_{p2}=3μH)

IV. ANALYSIS AND DESIGN OF CIRCUIT

A. Design of ZCS of secondary diodes:

Secondary circuit is conducting at non-overlapping interval (D<0.5) or overlapping interval (D>0.5). When D is smaller than 0.5, the minimal non-overlapping period is

$t_{min1} = T_s D_{min}$ (16)

When D is greater than 0.5, the minimal overlapping periodis

$t_{min2} = T_s(1-D_{max})$ (17)

If the clamping capacitor C_c is large enough to make little contribution to the resonance, the current of secondary side can be written as

$i_{Ls}(t) = I_{Ls\_peak} \sin \omega_{eq} t$ (19)

Where $\omega_{eq} = \frac{1}{\sqrt{(L_{k,s1} + L_{k,s2})C_r}}$

$L_{k,s1}$and $L_{k,s2}$are equivalent leakage inductances ofsecondary side.

Thus, the period of resonance is

$t_{res} = \pi/\omega_{eq} = \pi\sqrt{(L_{k,s1} + L_{k,s2})C_r}$ (20)

To ensure ZCS off of secondary diodes can be obtained throughout the entire operation range, the period of resonance should be restricted. $t_{res} \le \{t_{min1}, t_{min2}\}_{min}$ (21) Given the leakage inductance of the transformers T_1 and T_2, voltage doubler capacitor C_r can be sketched from (17) to

Fig.11. Peak-to-peak value of magnetizing ripple current with respect to duty ratio.

A. Analysis of input ripple curren

Because of small inductors L_{p1} and L_{p2}, large ripple currents of i_{Lp1} and i_{Lp2} are obtained. However, due to interleaved control of S_1 and S_2, input ripple current is decreased remarkably. Input ripple current can be derived as follows.

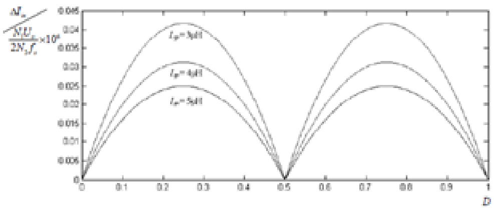
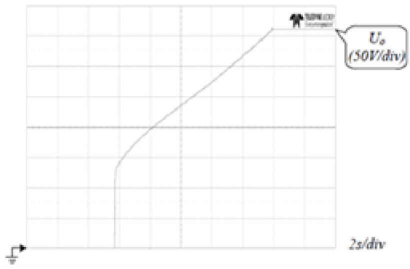


Fig.12. Peak-to-peak value of input ripple current with respect to duty ratio.



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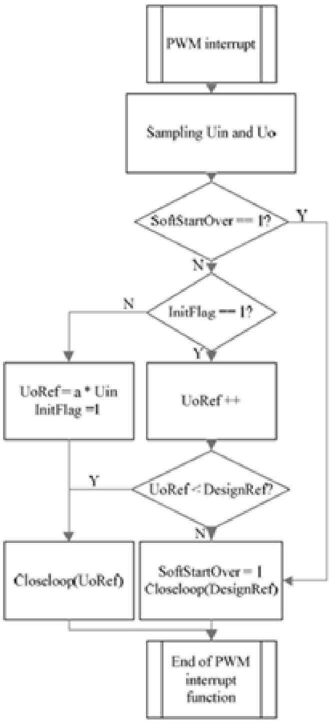
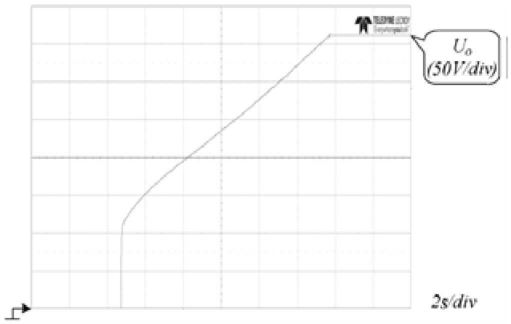
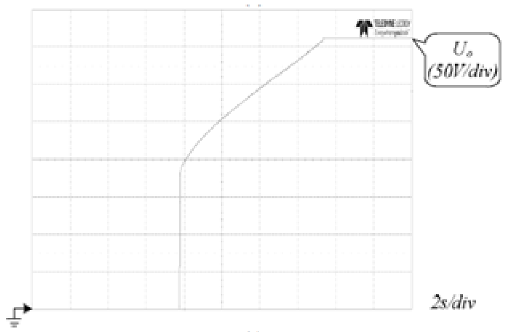


Fig.13. Flow chart of soft start-up.

A. Scheme of soft start-up:



(a)



(c)

(b)

Fig.14. Waveforms of soft start-up. (a) U_{in}=10.8V. (b) U_{in}=12V. (c) U_{in}=16V.

V. EXPERIMENTAL RESULTS

To confirm the hypothetical investigation and outline proceduresa model for vehicle inverter is actualized. The information voltage scope of the converter is from 10.8 V to 16 V and yield voltage is 360 V. The full load is 150W and exchanged. Fig.15a - Fig.15c are waveforms of the converter at full load. A swell recurrence of the help inductor is twice as high as the exchanging recurrence. As per Fig.7b, however swell current of iLp1 is expansive, information swell current is surprisingly minor which approves the configuration. To accomplishing high proficiency on wide information voltage and burden conditions, reverse charging current is not sufficiently huge at full load in view of generally extensive attractive inductance and high DC segment of information current. Along these lines, reverse polarizing current can lessen turn-on loss of the fundamental MOSFETs however ZVS on is not accomplished at full load.

Parameters	Symbols	Values
Input voltage	U_{in}	10.8~16V
Output voltage	U_o	360V
Output power	P_o	0~150W
Switching frequency	f_s	100kHz
Inductance of primary winding	L_{p1}, L_{p2}	4μH
Inductance of secondary winding	L_{s1}, L_{s2}	256μH
Secondary equivalent leakage inductance	$L_{k,s1}$, $L_{k,s2}$	5.4μH
Primary winding turns	N_1	3
Secondary winding turns	N_2	24
Clamping capacitor	C_c	3.3μF
Resonant capacitor (voltage doubler capacitor)	C_r	47nF
Input capacitor	C_{in}	1000μF
Output capacitor	C_o	220μF
Components	Symbols	Part numbers
Main switches	S_1, S_2	IPP023NE7N3_G
Auxiliary switches	S_3, S_4	IPP015N04NG
Secondary rectifying diodes	D_{o1}, D_{o2}	MUR460
Transformer core	T_1, T_2	PQ26/20
Driver IC		IR2110
DSP		DSPIC33FJ06GS101

By the by, ZVS on of the primary MOSFETs can be accomplished inside the most scope of operation when DC part of info current is littler than an appropriate quality. Fig.16a - Fig.16c are waveforms of the delicate exchanging at appropriate operation focuses with various information voltages. Polarizing current of essential inductor is opposite when the principle MOSFET S1 is going to turn on. ZVS on of the principle MOSFETs is acknowledged at these operation focuses. Moreover, when Uin is 10.8V, ZVS on can be picked up with Po lower than 95.6W (63.73% burden). At the point when Uin is 12V, ZVS on can be picked up with Po lower than 105W (70%

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burden) . As to Uin = 16V, it is the extent lower than 114W (76% burden). It is likewise evident that the current of auxiliary diode declines to zero delicately. Subsequently, turn around recuperation issue of auxiliary diode is expelled inside the whole operation range, in the mean time ZVS on of primary MOSFETs is still acquired.

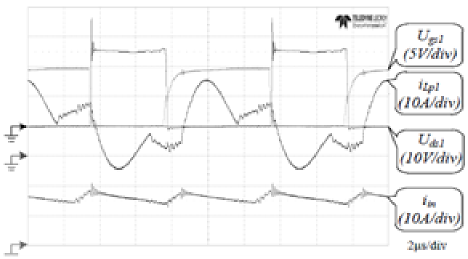

Fig.15a. Waveforms of the converter at full load (U_{in}=10.8V).

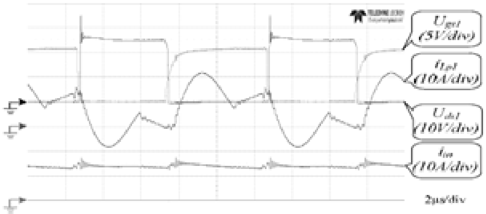

Fig.15b. Waveforms of the converter at full load (U_{in}=12V).

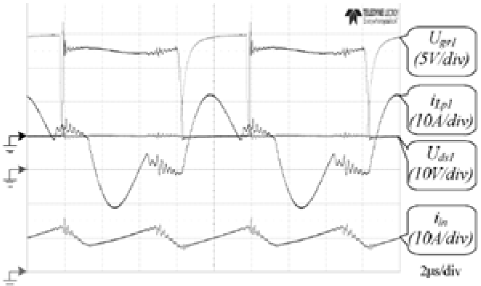

Fig.15c. Waveforms of the converter at full load (U_{in}=16V).

Fig.17 shows the measured efficiency curve of the prototype. Compared with efficiency of 10.8V input, 12V input, 14V input and 16V input, the efficiency of 12V input within the entire operation range is relatively high which is above 92%. The highest efficiency of 12V input is 94.88%. The efficiency of the proposed converter is superior to the current-fed push-pull converter [8].

The converter can certainly achieve ZVS on of all the MOSFETs at the whole load conditions with small enough magnetic inductance according to (22). But the concomitant large input current

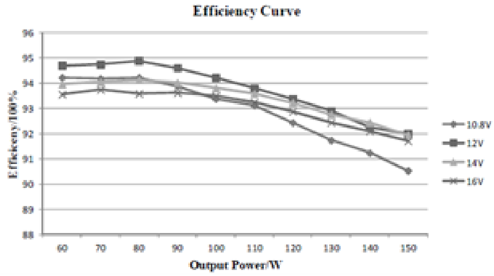

Fig.17. Efficiency curves of the prototype at different loads and input voltages.

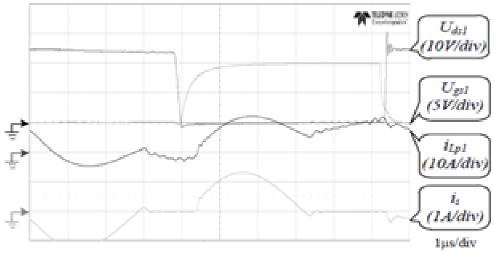

Fig.16a. Waveforms of soft switching (U_{in}=10.8V, P_o=95.6W).

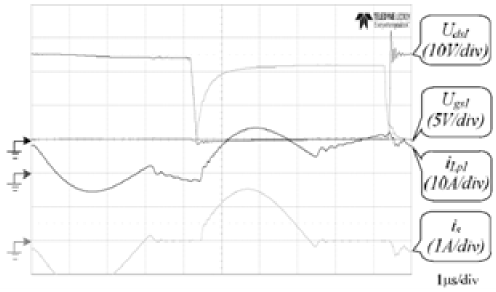

Fig.16b. Waveforms of soft switching (U_{in}=12V, P_o=105W).

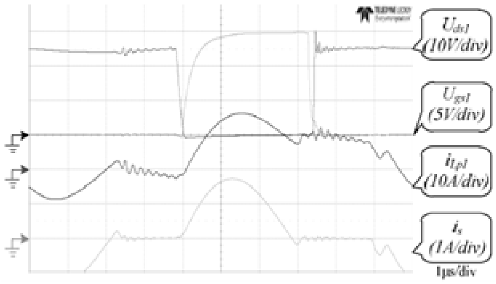

Fig.16c. Waveforms of soft switching (U_{in}=16V, P_o=114W)

Ripple results in worse alternating current (AC) copper losses which bring down the efficiency of the converter, which can be seen in Fig.18. Fig.19 is the hardware circuit of the prototype.The experimental results are consistent with the design. However, the proposed design is not applicable in high-power field because the large magnetizing ripple current increases the current stress of MOSFETs. It is suitable for low-power application such as vehicle inverters.

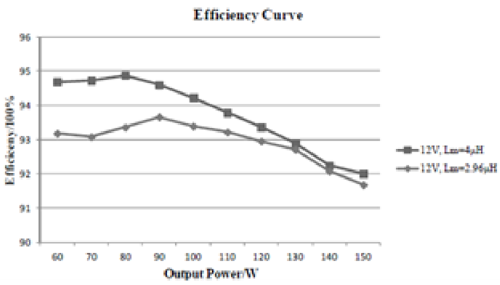

Fig.18. Efficiency curves of the prototype at 12V input voltage with different magnetic inductances.

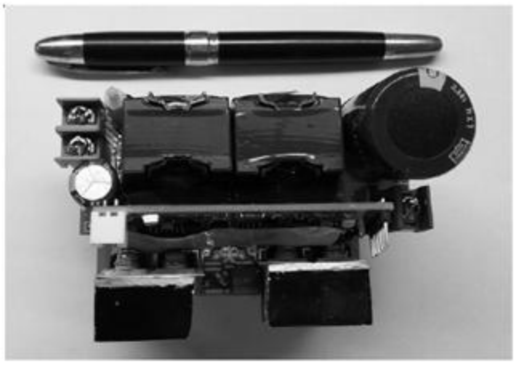

Fig.19. Hardware circuit of the prototype.

VII. CONCLUSION:

In this paper, reverberation investigation and delicate exchanging outline of a segregated support converter with coupled inductors are exhibited. Two sorts of reverberation are broke down to get ZVS on of principle switches or ZCS off of auxiliary amending diodes. Relationship between the resonances is outlined and a streamlined reverberation between the two sorts of resonances is utilized to build power thickness and lower converter cost. In addition, by picking suitable attractive inductance of the coupled inductors, ZVS one of the primary MOSFETs and ZCS off of the auxiliary diodes can be accomplished by and large at the same working conditions with no extra gadgets. Also, limited scope of obligation proportion is evacuated and an ideal operation point with zero information swell current is picked up. Finally, a 150W, 12V-360V high productivity model converter is worked to confirm the examination, and the test comes about outline that the proposed converter is an aggressive contender for low power and high stride up applications with disengagement necessities.

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