A Novel Quasi-Resonant ZCS-PFM DC-DC Switching Regulator with Loosely-Coupled Flyback Inductors

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Abstract —This paper presents a novel topological prototype of voltage source series quasi-resonant zero current soft-switching pulse frequency modulated dc-dc power converter circuit using IGBTs which incorporates a high-frequency flyback transformer link. Its steady-state operating principle is described on the basis of simulation analysis, along with the open loop controlled power regulation characteristics of the multi-functional coupled inductors linked dc-dc power converter operating under a principle of zero current soft switching commutation.

Index Terms —DC-DC power converter, series resonant chopper type, flyback transformer, zero current soft switching, pulse frequency modulation.

I. Introduction

RECENTLY, there are many efforts to develop the efficient switch mode dc-dc power converters for utility AC power supply interfacing to clean energy such as Lithuim battery, PEFC, PV panel, EDLC, and so forth. Among these, the downsized isolated high frequency link soft-switching dc-dc power converters with low noises and high-efficiency are able to be more effective and acceptable.

This paper proposes a novel topological circuit of stable voltage source dc-dc power converter using the latest IGBTs which is able to operate on the basis of series quasi-resonant type soft-switching PFM controlled theory. This dc-dc power converter can achieve zero current soft-switching(ZCS) with the aid of multi-functional loosely -coupled high-frequency flyback transformer such as resonant inductor, voltage and current transformation, extended boost voltage range, dc voltage smoothing filter and current commutation inductor. Its steady state circuit operation and the output voltage regulation characteristics in steady-state open loop scheme are quantitatively evaluated and discussed herein. Finally, the effectiveness of this power converter is proved on the basis of the computer aided simulation.

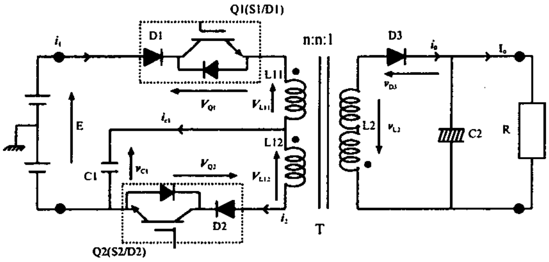


Fig. 1. A soft-switching converter with a flyback transformer

II. Circuit Topology

The main circuit topology of the high-frequency flyback transformer linked ZCS-PFM series resonant chopper type DC-DC power converter using IGBTs is shown in Fig.1. This new circuit topology using the voltage source series resonant chopper is composed of the series quasi-resonant flyback coupled inductors(L_{11}, L_{12}, L_1) at the primary side of the flyback transformer, two reverse-blocking active power switching blockings $Q(Q_1, Q_2)$, a single series resonant capacitor C_1 as the voltage source of the second series resonant circuit, a voltage/current step-up and step-down transformer with a high frequency electrical isolation, a soft recovery diode switch required to store and transfer the magnetic energy stored into the flyback resonant coupled inductors;D_3, a capacitor C_2 and typical input load resistance R of electronic appliances.

III. Operating Principle in Steady State

A. Tightly-Coupled Flyback Transformer

Fig.2(a) illustrates steady-state operating waveforms of the dc-dc power converter with high-frequency tightly-coupled flyback transformer ($k = 1$) in the operating period of $T_S > t_S$. Observing these waveforms of the active power switches and so forth, it is obvious that the summation t_S of the conducting time t_1 of $Q(Q_1, Q_2)$ and the conducting time t_2 of D_3 has the quantitative relationship for the chopper output period T_S as shown below.

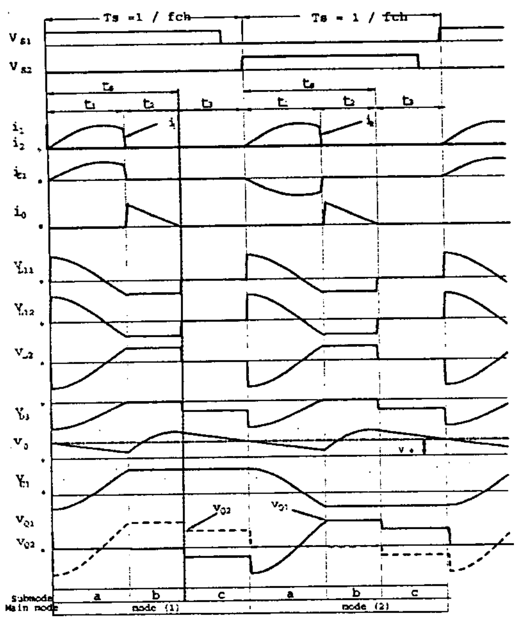
(1) $T_S > t_S$ ($t_3 > 0$, when t_3 is a Q and D cut-off time.)
(2) $T_S = t_S(t_3 = 0)$
(3) $T_S < t_S(t_3 = 0)$

Hence, t_S is the summation of the main active power switch $Q(Q_1, Q_2)$ conducting time t_1 and current overlapping commutation time from Q_1(or Q_2) to D_3 defined as t_u. Where, $T_S = 1/f_{ch}$:f_{ch} is the switching frequency of chopper current via D_3.

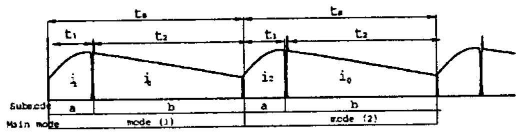
Inspecting Fig.2(a), the operation modes in steady-state are divided into the main mode(1) and main mode(2) in accordance with the gate pulse voltages supplied to the $Q(Q_1, Q_2)$. Each main mode is also catagorized into submode (a),(b) and (c) according to on-off state of D_3. The equivalent circuits of these operation modes are shown in Fig.(4). Hence, all the equivalent circuits are represented each by operating mode in Fig.2(a). The submodes (a),(b) and (c) of the main mode(1) are respectively described below.

Submode(1(a))[$0 \leq t \leq t_1$]

When $Q_1(S_1/D_1)$ is on, the first resonant circuit composed of $(E - Q_1 - L_{11} - C_1)$ loop is established. The series resonant

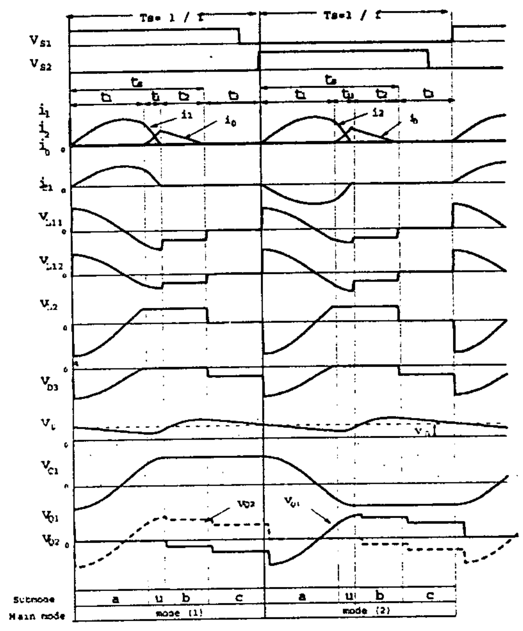


(a) $k \approx 1, T_S > t_S$

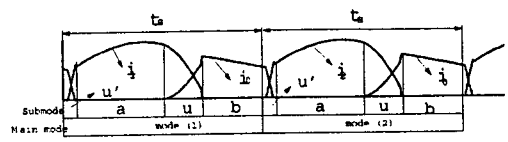


(b) $k \approx 1, T_S < t_S$

Fig. 2. Steady-state operating waveforms with tightly coupling



(a) $k \neq 1, T_S > t_S$



(b) $k \neq 1, T_S < t_S$

Fig. 3. Steady-state operating waveforms with loosely coupling

current i_1 occurs which is determined by $L_{11} = L_1$ and C_1 with series resonant frequency:$f_r = 1/2\pi\sqrt{L_1 C_1}$. Q_1 is turned on under ZCS condition. When i_1 of Q_1 is subsequently changed from $di/dt \geq 0$ to $di/dt \leq 0$, the voltage across $L_2(v_{L2})$ in the secondary side of the transformer changes its direction. This submode ends when v_{L2} equals to V_0 across C_2

Submode(1(b))[$t_1 \leq t \leq t_1 + t_2$]

When D_3 is on, the current i_1 flowing through L_{11} is immediately transferred to the inductor L_2 in the secondary side of the flyback transformer on the basis of the electromagnetic flux conservation law. The current i_1 is transferred into $i_0 = i_1/n(i_0 = i_2/n)$;n is a turn ratio of the flyback transformer specified by $\sqrt{L_2/L_1}$. At this moment, the current i_1 through Q_1 is instantly commutated into the secondary-side inductor L_2 with a zero current transition. After that, the voltage across Q_1 holds a zero voltage interval with the aid of the $v_{11} = V_0/n$. Under $v_{L2} = V_0$, D_3 is turned on and the voltage across L_{11} is clamped to a load voltage V_0 determined by the total voltage $v_{L1} = \frac{V_0}{n}$. According to the KVL, the closed loop circuit including v_{L1}, the resonant voltage v_{C_1} across C_1 and E, the voltage across Q_1 is kept to be zero. The active switch Q_1 commutated under zero current and zero voltage condition is still in off-state even if it is triggered with a broad pulse width gate voltage signal V_{g1}. At that time, the magnetic energy stored into L_{11} due to i_1 is estimated as $w = L_{11}i_1^2(t_2)/2$ and transferred into L_2. This transferred energy is efficiently converted into the output dissipated energy $(v_0^2/R)T_S$, where T_S;chopper switching period in the output circuit in parallel with C_2 and R during a conducting mode of D_3. This submode ends when the transferred magnetic energy becomes zero.

Submode(1(c))[$t_1 + t_2 \leq t \leq t_1 + t_2 + t_3 = T_S$]

When the transferred magnetic energy of L_2 becomes zero, D_3 is naturally turned off with a ZCS transition. All the active and passive power switching devices in this sub-mode is in off-state and this submode ends completely when Q_2 is turned on.

Similarly, when Q_2 is turned on, the successive submodes(a)(b) and (c) mentioned above begin to operate again and one cycle operation of the power converter treated here is to be completed.

According to the PFM control scheme of Q_1 and Q_2, the period of submode 1(c) and submode 2(c) can be zero. Consequently, due to the law of the electromagnetic flux conservation, the final value of i_0 becomes the initial value of i_1 or i_2. Then, the active switch Q_1 and Q_2 is able to be operated under the condition of hard switching. Fig.2(b) illustrates the circuit operation waveforms when $T_S < t_S(k \approx 1)$.

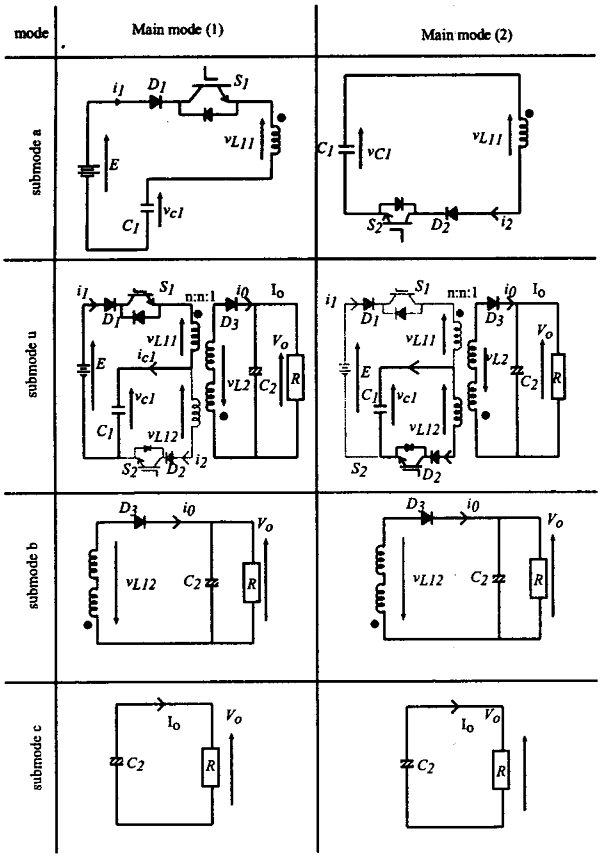


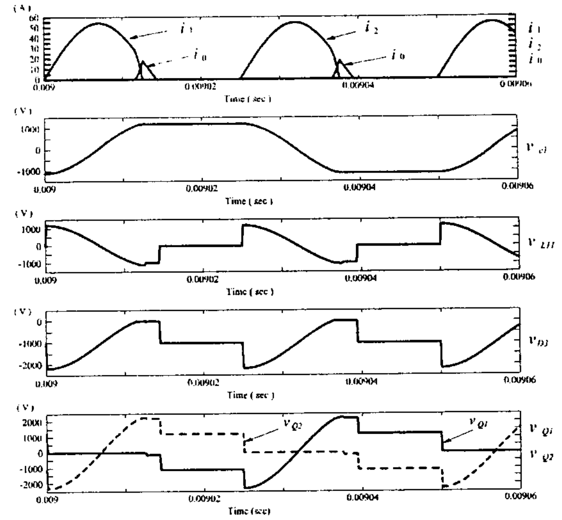
Fig. 4. Operation modes and equivalent circuits

B. Loosely-Coupled Flyback Transformer Linked Converter

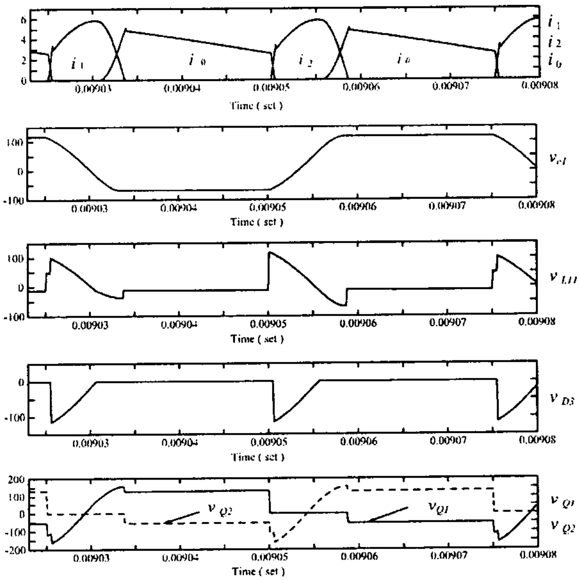
Practically, the inverter systems of the flyback transformer T is not completely coupled. When D_3 is turned on, due to its leakage inductance, both Q_1 and D_3 are both in on-state condition between the transition period for the submode(a) and the submode(b), the resulting currents generated from both sides exist at the same time(submode(μ)) . Due to the gate pulse width, Q_1 is close to the half length of inverter cycle, D_3 is turned on and Q_1 is turned off with ZCS & ZVS(Zero Voltage Switching) respectively. If k is close to $1(k \rightarrow 1)$, the current overlapping time t_u is also close to zero. Under a condition of ZCS which implies that $T_S > t_S$, the operation voltage current waveforms of the proposed series resonant chopper circuit is illustrated in Fig. 3(a). In this case, both the main mode (1) or (2) is completely divided into submode (a)(b)(μ) and (c), respectively. Although the submode (c) does not always exist in accordance with PFM control scheme, the hard switching commutation has to be avoided since submode (μ') occurs corresponding to submode(μ). This assures the complete ZCS operation eventhough the submode(c) does not exist. Fig.3(b) depicts the circuit operating waveforms when $T_S < t_S(k \neq 1)$.

IV. Simulation Results and Discussions

The design specifications and circuit parameters on the converter simulation are given by Table 1.



(a) Light load ($R = 2000\Omega, f_{ch} = 40kHz$)

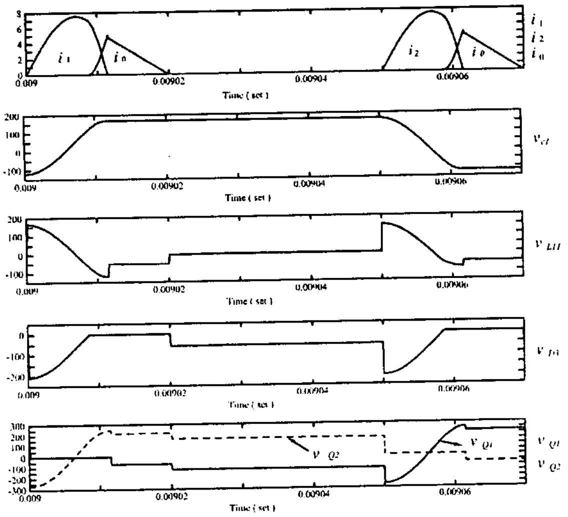


(b) Heavy load ($R = 5\Omega, f_{ch} = 40kHz$)

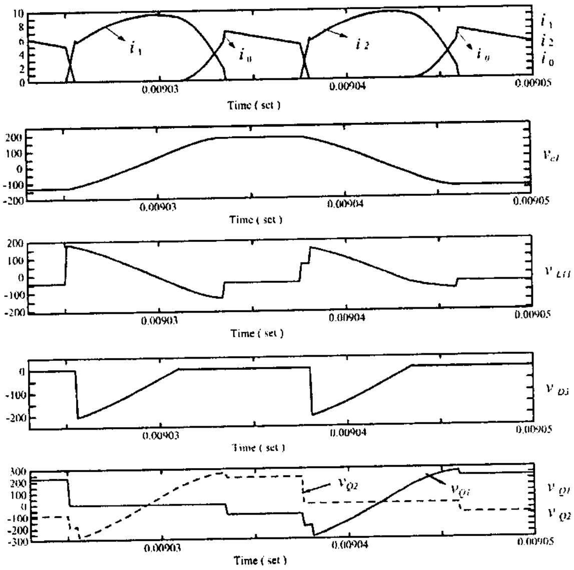
Fig. 5. Steady-state operating waveforms for various loads(Case of Loosely-coupled Flyback Transformer)

TABLE I
Design Value Specifications

Item	Value
Transformer coupling rate n	1
Series quasi-resonant inductor L_{11}, L_{12}, L_1	100 μH
Series quasi-resonant capacitor C_1	0.2 μF
Output smoothing capacitor C_2	100 μF
DC input voltage source E	50 V



(a) Low frequency ($R = 100\Omega, f_{ch} = 20kHz$)

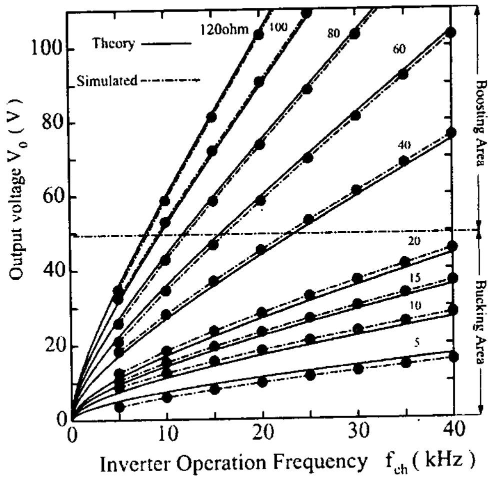


(b) High frequency ($R = 100\Omega, f_{ch} = 80kHz$)

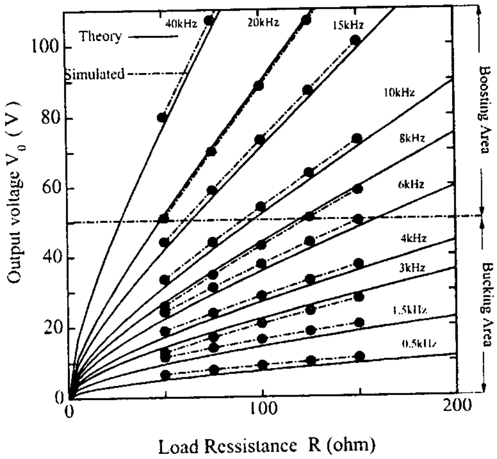
Fig. 6. Steady-state operating waveforms for various loads(Case of Loosely-coupled Flyback Transformer)

A. Tightly-coupled Flyback Transformer

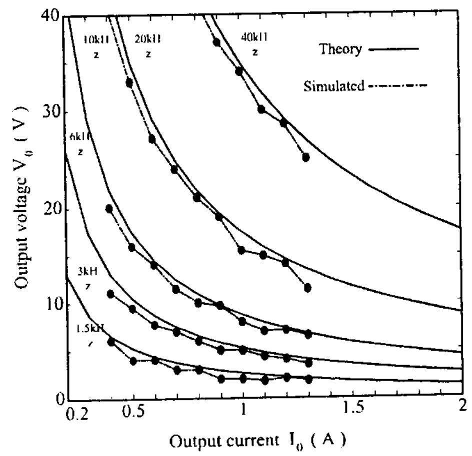
In case of applying tightly-coupled flyback transformer in the proposed converter system(electromagnetic coupling coefficient $k = 0.995$). When operating with $T_S > t_S$, the main active power switch block $Q(Q_1, Q_2)$ are turned on with ZCS and turned off with ZCS & ZVS. Moreover, it is controlled within chopper frequency range under wide load variations from light to heavy load. In the other words, the soft-switching operations can be completely acheived in spite of voltage regulation. However, when operating with $T_S < t_S$, main switch block Q_1, Q_2 are operated on hard-switching conditions for the tightly coupled flyback transformer design. It is obvious that this hard-switching condition can be overcome by employing loosely-



(a) Characteristics of output voltage and inverter operation frequency



(b) Characteristics of output voltage and load resistance



(c) Load characteristics

Fig. 7. Voltage Regulation Characteristics in open loop control system

coupled flyback transformer instead of tightly-coupled flyback transformer as disscussed from the beginning.

B. *Loosely-coupled Flyback Transformer*

Fig.5 and Fig.6 illustrate the voltage and current waveforms of the steady state operation in case of applying loosely-coupled flyback transformer in the proposed converter system(electromagnetic coupling coefficient $k = 0.95$). The operating waveforms are obtained under the different load R and chopper frequency f_{ch} conditions. When operating with both $T_S > t_S$ and $T_S < t_S$, the main active power switch blocks $Q(Q_1, Q_2)$ are turned with by ZCS and turned off with ZCS & ZVS. D_3 is also turned on and turned off with ZCS. It is noted that for light load and no load operations, the overvoltage for the power devices and components can occur with ZCS operation. Therefore, a protection control scheme is needed to protect the whole converter system. Moreover, when electromagnetic coupling coefficient $k \neq 1$, the main active power switches Q_1/Q_2 conducting times can overlap with the conducting time of D_3. The overlapping time can be increased and results in the increase of the absolute value of voltage and current in each part of the system. In Fig.5(b) and Fig.6(b), when $T_S < t_S$, it is obvious that the overlapping time between D_3 and Q_1/Q_2 is required. Commutation times between D_3 and Q_1/Q_2 are very sudden that di/dt stresses of Q_1 and Q_2 produce voltage surges and noises that are undesired on the condition of $T_S < t_S$.

C. *Output Voltage Regulation Characteristics*

Fig.7(a) shows the operating characteristic of the output voltage and chopper operating freqency as controlled parameter under various load conditions. Similarly, Fig.7(b) shows the characteristics of the output voltage and the load condition R with chopper operating frequency f_{ch} as controlled parameter. Finally, Fig.7(c) displays the chracteristics of the output voltage and the output current I_0 with chopper operating frequency for the controlled parameter. The characteristics of adjusting output voltage in accordance with chopper control frequency, the relationship is linear when considering high chopper control frequency. Furthermore, since the output characteristics of this proposed converter has a large voltage regulation factor, it is important to operate this power converter using the feedback control scheme. From Fig.7(a), it is obvious that the chracteristics of dc buck-boost property can be confirmed.

V. CONCLUSIONS

This paper has presented the series resonant zero current soft-switching PFM push-pull type IGBT dc-dc power converter with flyback transformer. The circuit topology was analyzed under the condition that the flyback transformer is designed for the tightly coupled structure. The analysis was conducted on the basis of both theoretical concepts and simulation methods. Both results match each other. Moreover, this ZCS PFM-controlled DC-DC power converter with a flyback transformer was quantitatively investigated by using high-frequency chopper switching frequency, resonant circuit parameter including flyback transformer parameter, load resistance parameter. It was noted that the proposed power converter is different from typical high-frequency linked series resonant inverter type DC-DC converter since its main active power semiconductor switches (IGBTs) and rectifying diode in the secondary side of the flyback transformer were able to be operated under ZCS principle regardless of switching frequency control range and load variations. Therefore, the recovering time of the diode in the secondary side of the flyback transformer became small and the problem of electromagnetic noises was alleviated. All the voltages across the main active power switch and the resonant capacitor were clamped to the output voltage to limit the high voltages for high Q factor. Moreover, the circuit operation was stable even when no current flows through smoothing capacitor. The flyback transformer also had some functions such as energy storage inductor, voltage and current transformation and series resonant low pass filter which can be acheived by simple and low cost electrical circuit compositions. Magnetizing inductance of flyback transformer does not affect the ZCS operation of MOS-type power gate controlled switching semiconductor switches such as IGBTs. On the other hand, its leakage inductance supports ZCS operations at wide range of control frequency and load variations. In the future, more works will be needed for comparing this proposed series resonant chopper type converter circuit employing a flyback transformer with non-resonant type converter.

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