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Resonant Pulse Power Converter with a Self-Switching Technique

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Abstract

In this paper, a resonant pulse power converter (RPPC) is proposed. The proposed RPPC transfers the pulse-shape power from a DC source to a load periodically. The RPPC consists of a resonant circuit and a resonant pulse converter driven by a self-switching circuit. Depending on the magnitude difference between the input and output voltages, the operations of the RPPC are divided into 4 modes; boost mode, hybrid mode, direct mode and cut-off mode, respectively. The main switch of the RPPC turns on in the ZCS condition and off in the ZVS condition spontaneously. The operational principles of a RPPC using the self-switching technique are analyzed and verified in experiments. An example of a RPPC application is demonstrated in the area of thermoelectric energy harvesting.

Key Words: MOSFET, Resonant pulse power converter, Self-switching, Resonance, Thermoelectric energy harvesting

I. Introduction

In order to achieve a high conversion efficiency with low switching loss, various topologies for resonant converters have been investigated.[1] To utilize the resonance for power conversion requires detecting the peak value or the zero instant of the voltage/current, which can be realized with additional circuit components such as sensors or switching ICs. However, especially in the very small power area, additional circuit components increase both the cost of the circuit and the volume of the circuit, and they require an additional power source to drive them properly.[2],[13,[14]

Various types of self-switching techniques have been proposed to decrease the cost and volume of the circuits and to eliminate the requirement of an additional power source. [3]–[5] Most of the previous techniques used a transformer and a control circuit to turn on/off the power switches.[6],[7] Resistive sensors were also equipped in order to detect the current/voltage magnitude. However, the sensors also consume energy for their operation. Other techniques without an auxiliary winding circuit were proposed, where the switching processes originated from the current and/or voltage surge protections.[8]–[10]

In the field of the energy harvesting, the self-switching technique is especially important. The available power from energy harvesting devices such as thermoelectric, piezoelectric or electromagnetic devices is below 0.1[W] [11],[12], which may not be sufficient to drive the control IC of the power converter. Hence, it has been proposed to eliminate the control IC in the area of the energy harvesting for harvesting power efficiently.[13]

In order to harvest energy from piezoelectric devices, a self-powered switching circuit with BJTs was proposed which extracts energy from an AC source and transfers it to a DC load, and needs a current flowing from the base to the emitter.[14] The BJT switches of the self-powered switching circuit turn on at the peak of the input voltage and turn off at zero voltage.

In this paper, a novel resonant pulse power converter (RPPC) with a MOSFET self-switching technique is presented, which extracts the energy from a DC source and transfer it to a DC load. The operation principles of the RPPC are fully analyzed and four operation modes are defined as, boost mode, hybrid mode, direct mode and cut-off mode. Experimental results are presented to verify the operation of the proposed RPPC for power-transferring and to demonstrate the potential of the RPPC for the thermoelectric energy-harvesting.

II. Topology of a Resonant Pulse Power Converter

Fig. 1 is the topology of a resonant pulse power converter (RPPC) with a self-switching circuit. The RPPC consists of a resonant circuit and a resonant pulse converter driven by the self-switching circuit in Fig. 2. The self-switching circuit consists of a P-MOSFET S_2, two diodes D_2 and D_3, three resistors R_s, R_{s1} and R_p, and a capacitor C_S.

The resonant inductor L_{in} is designed to be much larger than the inductor L. The RPPC transfers the pulse energy from a

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Fig. 1. Resonant pulse power converter with self-switching circuit.

Fig. 2. Self-switching circuit in RPPC.

DC voltage source V_{in} to a DC voltage load V_o as the self-switching circuit turns on and off the N-MOSFET S_1 of the RPPC under the ZCS/ZVS condition.

The switching frequency f_S of the MOSFET S_1 in Fig. 1 is determined by the resonant inductor L_{in} and the self-switching capacitors C_{in} and C_S as follows:

$$f_S = \frac{1}{\pi\sqrt{(C_{in}+C_S)L_{in}}}. \tag{1}$$

The Q factor of the resonant circuit with an inductor L_{in} and capacitors C_{in} and C_S is designed to be high enough to reduce the power conversion loss. The capacitor voltage of C_{in} and C_S can be increased to twice as high as the DC input voltage through the resonance.

The self-switching circuit in Fig. 2 operates as an envelope detector, an energy storage device, a comparator, a discharge path and a pull-down resistor. The capacitors C_S and C_{in} and the diode D_2 take the role of a peak detector. The capacitor C_S stores enough energy to ignite the P-MOSFET S_2 and the N-MOSFET S_1. The capacitor C_{in} also stores the input energy and takes the role of ignition of the P-MOSFET S_2. At the turn-on instant of the P-MOSFET, the stored energy of the capacitors is respectively described as:

$$E_{(stored)C_{in}} = \frac{1}{2}\left(V_{in} - V_D - V_{S2_{th}}\right)^2 \tag{2}$$

$$E_{(stored)C_s} = \frac{1}{2}\left(2V_{in} - V_D\right)^2 \tag{3}$$

where V_D is the forward voltage drop of the diode and V_{th} is the threshold voltage of the MOSFET. Both parameters are critical for realizing the self-switching technique.

The forward voltage drop of the diode V_D in Eq (2) and (3) is usually lower than the threshold voltage of the MOSFET V_{th} in Eq (2). Assuming that C_{in} is equal to C_S, the relationship of the stored energies is:

$$E_{(stored)C_s} >> E_{(stored)C_{in}}. \tag{4}$$

Hence, assigning a capacitance of C_S that is bigger than that of C_{in} is better from the view point of the transferrable power.

The pull-down resistor R_p is for dissipating the noise of the parasitic capacitor at the gate of S_1 especially when the switch S_1 turns off. It also dissipates a small amount of energy during the turn-on interval of S_2.

III. Operational Principles

For a simple analysis of the RPPC operation, it is assumed that the parasitic resistors of all the passive elements are zero, and that the self-switching capacitor C_S is much larger than the resonant capacitor C_{in} Hence, the resonance frequency is mainly determined by C_S.

The capacitor voltage of the resonant circuit is:

$$v_{C_{in}}(t) = V_{in}\left(1 - \cos\left(\frac{1}{\sqrt{L_{in}C_S}}t\right)\right)[0 < t < T/2] \tag{5}$$

The peak value of the capacitor voltage is two times as high as the input voltage.

Depending on the relative voltage difference between the input voltage and the load voltage, there are 4 operating modes for the proposed circuit; hybrid mode, boost mode, direct mode and cut-off mode.

Fig. 3 shows the operation region of each mode.

A. Cut-off Mode

In order to turn on the main MOSFET switch, S_1, the magnitude of the gate-source voltage of S_1 must be higher than the threshold voltage, and it should be kept in this condition while the P-MOSFET S_2 is turned on. Hence, the minimum voltage of the self-switching capacitor, v_{CS}, is V_{S1th} which is equal to $v_{Cin} - V_D$. Therefore, the RPPC cannot transfer the input power to a load with under the following condition:

$$V_{in}\left(\cong \frac{VC_{in}(max)}{2}\right) < \frac{V_{S1_{th}}V_D}{2}V_O. \tag{6}$$

B. Direct Mode

Since the magnitude of V_{in} is always greater than the magnitude of V_o in the direct mode, the diode D_1 is always turned on and the self-switching circuit does not operate. An equivalent model of this mode is presented in Fig. 4.

Fig. 3. Operation region of Cut-off, Boost, Hybrid and Direct mode.

Fig. 4. Equivalent circuit of RPPC operation for the direct mode.

C. Boost Mode

In the boost mode, the magnitudes of V_{in} and V_o are satisfied with the following condition:

$$\frac{V_{S1th}V_D}{2} < V_D\left(\cong \frac{V_{C_{in}}(\max)}{2}\right) < \frac{V_O}{2}. \tag{7}$$

The operation of the boost mode, which follows the solid line arrows in Fig. 5, can be divided into 6 intervals: the intervals 1, 3, 4, 5, 6 and 7. The waveforms of the voltage and the current are depicted in Fig. 6.

Interval 1($t_0 \sim t_1$): At t_0, the voltages and currents of the passive elements are zero and all of the switches are off. The capacitors C_S and C_{in} begin to be charged by the resonance of L_{in}, C_{in} and C_S. The capacitor voltage is expressed as:

$$v_{C_S}(t) = v_{C_{in}}(t) - V_D = V_{in}\left\{1 - \cos\left(\frac{1}{\sqrt{L_{in}(C_{in}+C_S)}}t\right)\right\}. \tag{8}$$

From (8), the length of interval 1 can be considered as half of the resonant period of L_{in}, C_S and C_{in}. Interval 2 ends at t1 when the voltage magnitude of C_{in} becomes twice as big as the magnitude of V_{in}.

Interval 3($t_1 \sim t_2$): After t_1, v_{C_S} maintains the peak value and the resonant frequency is changed, because C_S is disconnected by D_2. The magnitude of v_{Cin} decreases rapidly with the resonance of L_{in} and C_{in} until the gate-source voltage of the P-MOSFET v_{gs} is equal to the threshold voltage $V_{S2_{th}}$. At t_2, the following condition is satisfied:

$$V_{in}\left\{1 - \cos\left(\frac{1}{\sqrt{L_{in}C_{in}}}t_2\right)\right\} = V_{C_s}(\max) - V_{S2_{th}}. \tag{9}$$

Interval 4($t_2 \sim t_3$): This interval is very short when compared to the resonance frequency. The voltage difference between v_{CS} and v_{Cin} turns on the P-MOSFET S_2 and immediately the capacitor voltage v_{C_S} turns on the N- MOSFET S_1 with the ZCS condition.

Interval 5($t_3 \sim t_4$): At t_3, the closed current path consists of L, C_{in}, C_S, S_1 and S_2. The stored energy of the capacitors is transferred to the boost inductor L. The energy transferred from the capacitor to the inductor in this interval is written as:

$$E = \frac{C_S}{2}\left[V_{in}\left\{1 - \cos\left(\frac{1}{\sqrt{L_{in}C_{in}}}t_2\right)\right\}\right]^2 - \frac{C_S}{2}V_{S1th}{}^2. \tag{10}$$

The switch S_1 turns off at t_4 when v_{gs} of S_1 equals $v_{S1_{th}}$. This interval is approximately a quarter of the self-switching resonant period as follows:

$$T_{self} \cong \frac{\pi\sqrt{LC_S}}{2} \tag{11}$$

Interval 6($t_4 \sim t_5$): The diode D_1 turns on at t_4. The energy of L is transferred to the load. The slope of the current i_L is:

$$\frac{d}{dt}i_L = \frac{V_O + V_D}{L} \tag{12}$$

The length of interval 6 is approximately written as:

$$t_5 - t_4 >> \frac{\sqrt{LC_S(2V_{in} - V_D)}}{V_O + V_D} \tag{13}$$

The voltage of the capacitors drops below zero.

$$v_{C_{in}}(t_5) = v_{C_S}(t_5) + V_D = \frac{1}{C_S}\int_{t_4}^{t_5} i_L\,dt \tag{14}$$

Interval 7($t_5 \sim t_{0'}$): In this interval, $i_{L_{in}}$ flows reversely to the charge capacitors through the body diode of S_1. This interval is as short as interval 3.

As mentioned above, interval 1 is much longer than the other intervals. The resonant inductor L_{in} and the self-switching capacitor C_S determine the switching period. The switching period of the boost mode is approximately written as:

$$T_{Boost} \cong \pi\sqrt{L_{in}C_S}. \tag{15}$$

The transferred energy of (3) can be approximately rewritten as:

$$E_{Boost} = \frac{1}{2}CV^2 = \frac{C_S}{2}\left\{(2V_{in} - V_D)^2 - V_{S1_{th}}{}^2\right\}. \tag{16}$$

D. Hybrid mode

In the hybrid mode, the input voltage and the output voltage should be satisfied with the following condition:

$$\frac{V_O}{2} < V_{in}\left(\cong \frac{V_{C_{in}}(\max)}{2}\right) < V_O. \tag{17}$$

The operation of the hybrid mode, which follows the dotted-line arrows in Fig. 5, can be divided into 7 intervals.

Fig. 5. Operation principle of RPPC with self-switching circuit (Dotted line for Hybrid mode and Solid line for Boost mode).

Interval 1($t_0 \sim t_C$): The voltages and currents of the passive elements are zero and all of the switches are off at t_0. Interval 1 continues to the instant of t_C when the voltage magnitude of C_{in} is equal to the magnitude of the load voltage V_O. Then, the diode D_1 turns on at t_C which is expressed as:

$$t_C = \sqrt{L_{in}C_S}\cos^{-1}\left(\frac{V_{in}-V_O-V_D}{V_{in}}\right) \quad [\frac{T}{4} < t_C < \frac{T}{2}]. \quad (18)$$

Interval 2($t_C \sim t_1$): The input source connects directly through the diode D_1 to the load. The voltage magnitude of C_{in} is equal to the magnitude of V_o until $i_{L_{in}}$ drops to zero at t_C. Fig. 7 (d) and (e) show the voltage and current waveforms of interval 2.

Due to the small size of the boost inductor L, the energy stored in L can be neglected. Therefore, the energy transferred to the load for interval 2 is expressed as:

$$E_{Hybrid(1)} = \frac{1}{2}LI^2 = \frac{L_{in}}{2} i_{L_{in}}(t_C)^2. \quad (19)$$

Interval 3∼7($t_1 \sim t_{0'}$): The operations from interval 3 to interval 7 in the hybrid mode are exactly the same as those in the boost mode as depicted in Fig. 5.

TABLE I
EXPERIMENTAL SETUP

Parameters	Symbol	Value	Unit
Capacitor of resonant circuit	C_{in}	1	nF
Capacitor of self-switching circuit	C_S	1	uF
Inductor of resonant circuit	L_{in}	4	mH
Inductor of resonant converter	L	3.3	μH

From (16) and (19), the total transferred energy of the hybrid mode is written as:

$$E_{Hybrid} = \frac{L_{in}}{2} i_{L_{in}}(t_C)^2 + \frac{C_S}{2}\left(V_O - V_{S1_{th}}\right)^2. \quad (20)$$

IV. EXPERIMENT

In order to verify the operation of the RPPC with a self-switching circuit, several experiments were performed. The circuit parameters of the RPPC are presented in Table I.

The magnitude of the output voltage is set to 12[V] and the magnitude of the input voltages are respectively 2, 5 or 8[V] for each experiment. In order to investigate the effect of the

Fig. 6. Waveforms of boost mode operation. (a) Capacitor C_{in} Voltage. (b) Inductor L_{in} current. (c) Inductor L current. (d) Capacitor C_S and C_{in} voltage. (e) MOSFET S_1, gate-source voltage. (f) MOSFETS S_1 drain voltage and (g) Inductor L current.

Fig. 7. Waveforms of hybrid mode operation. (a) Capacitor C_{in} voltage. (b) Inductor L_{in} current. (c) Inductor L current. (d) Capacitor C_{in} and C_S voltage and (e) Inductor L_{in} and L current.

magnitude of the MOSFET threshold voltage, a low threshold MOSFET and a high threshold MOSFET are selected for each experiment.

Fig. 8 shows the results of the experiment for the low threshold case of 1[V]. NTGS3103N (*On semiconductor*) is selected for the N-MOSFET and NTF6P02T3 (*ON semiconductor*) is selected for the P-MOSFET. All of the diodes in the self-switching circuits are accomplished by Schottky diodes MBRS540T3 (*ON semiconductor*, V_D=0.5[V]). In Fig. 8, (a) is for the hybrid mode, (b) is for the boost mode and (c) is for the boost mode with low input voltage of 2[V]. The waveforms are very close to the analysis results in Fig. 6 and Fig. 7. In Fig. 8, the switching period of S_1 is approximately 0.2ms, which is very close to two times the resonance frequency of L_{in} and C_S.

In Fig. 9, the self-switching intervals in the boost mode are expanded: mode 3, mode 4, mode 5, mode 6 and mode 7. It shows that the P-MOSFET turns on when the voltage difference between the gate and the source equals the threshold voltage of 1[V] and the N-MOSFET turns on immediately after that moment. The period of self-switching in Fig. 9 (a) is equal to a quarter of the resonance frequency of L and C_S. However, Fig. 9 shows that the turn-on interval of the N-MOSFET in Fig. 9 (b) is shorter than in Fig. 9 (a). The reason is that the stored energy of C_S at low input voltage of 2[V] is not sufficient to turn on S_1 completely, when compared with input voltage of 5[V].

In order to investigate the effects of the high threshold voltage of the MOSFET, HUF75343P3 (*FAIRCHILD*) of $V_{th} = 3$[V] is selected for the N-MOSFET and FQP27P06 (*FAIRCHILD*) of $V_{th} = -4$[V] is selected for the P-MOSFET. Fig. 10 shows the resulting waveform when V_{in} is 5[V] and V_O is 12[V]. The P-MOSFET is turned on when the voltage difference between the gate and the source of the P-MOSFET is 4[V]. Since the N-MOSFET is turned off when the gate

(a)

(b)

(c)

Fig. 8. Experimental result waveforms with low threshold MOSFET. (a) hybrid mode operation at V_{in}=8[V], V_O =12[V]. (b) boost mode operation at V_{in}=5[V], V_O =12[V] and (c) boost mode operation at V_{in}=2[V], V_O =12[V].

(a)

(b)

Fig. 9. Experimental result waveforms of self-switching intervals with low threshold MOSFETs in boost mode operation. (a) V_{in}=5[V], V_O =12[V] at self-switching moment. (b) V_{in}=2[V], V_O =12[V] at self-switching moment.

Fig. 10. Waveforms of self-switching intervals with high threshold MOSFETs.

voltage is less than the high threshold voltage of 3[V], the turn-on interval of S_1 becomes shorter than 3[μs] in Fig. 9 (a).

Fig. 11 shows the waveforms of the self-switching intervals for different magnitudes of C_{in} with V_{in}=5[V], V_O=12[V], L_{in}=4[mH], L=3.3[μH] and C_S=1[μF] respectively. C_{in} is 1[nF] for Fig. 11 (a), and C_{in} is 10[nF] for Fig. 11 (b). The turn-on instant after the peak detection instant of Fig. 11 is delayed depending on the magnitude of C_{in} because the period of the interval 3 is determined by the resonant capacitor C_{in} and L_{in}.

Fig. 12 shows the powers transferred to the load: one is estimated by the analysis and the other is measured in the experiment. The peak current, I_{peak}, of S_1 for various values of L is also depicted in Fig. 12. The experiment is performed with V_{in} of 5[V] and a load of 6[kΩ] in parallel with a capacitor 10[μF]. For the estimation of P_{OUT}, the forward voltage drop of the diode is 0.7[V], and the threshold voltage of the MOSFET is 1[V]. C_S is 0.1[μF] for Fig. 12(a), 1[μF] for (b) and 10[μF] for (c), respectively. As C_S is decreased, the

Fig. 11. Waveforms of self-switching intervals with variation of resonant capacitor C_{in}. (a) V_{in}=5[V], V_O=12[V], C_{in}=1[nF] at self-switching instant in boost mode operation and (b) V_{in}=5[V], V_O =12[V], C_{in}=10[nF] at self-switching instant in boost mode operation.

Fig. 12. The measured P_{OUT}, the estimated P_{OUT} and the measured I_{peak} with the various inductances of L. (a) V_{in}=5[V], C_S=0.1[μF]. (b) V_{in}=5[V], C_S=1[μF] and (c) V_{in}=5[V], C_S=10[μF].

power transferred to the load is decreased. As L is increased, the peak current value of L is decreased linearly. However, the maximum point of the power transferred to the load is not linearly changed. The difference between the estimated P_{OUT} and the measured P_{OUT} is caused by a switching loss and a conduction loss due to the parasitic resistor, which are mainly affected by I_{peak}. The switching loss and the conduction loss by the parasitic resistor decrease linearly when I_{peak} is decreased.

V. Thermoelectric Energy Harvesting

In order to demonstrate the usefulness of a RPPC with a self-switching circuit, an experiment on thermoelectric energy harvesting is performed. A thermoelectric device converts thermal energy into DC electric energy. Since the harvestable energy from a thermoelectric device is below 10mW, low threshold MOSFETs (N-MOSFET *ON semiconductor* NTZD3154N, V_{th}=0.6[V], P-MOSFET *ON semiconductor* NTR4101P, V_{th}=-0.72[V]) and low forward voltage drop diodes (*ON semiconductor* NSR0320, V_D=0.35[V]) are chosen. A TEC-12712 is used for the thermoelectric device. A 6[V] lead-acid battery is used at the output.

The parameters for the experiment on thermoelectric energy harvesting are presented in Table 2. Fig. 13 shows the resulting waveforms. An energy of 2[mW] at 1[V] of the thermoelectric device is transferred to the battery in the form of a pulse. The efficiency of the proposed converter is about 50%.

TABLE II
Parameters of Thermoelectric Energy Harvesting Experiment

Parameters	Symbol	Value	Unit
Capacitor of resonant circuit	C_{in}	1	nF
Capacitor of self-switching circuit	C_S	1	μF
Inductor of resonant circuit	L_{in}	4	mH
Inductor of resonant converter	L	150	μH

VI. Conclusion

In this paper, a resonant pulse power converter (RPPC) with a self-switching circuit is proposed and the operation modes

Fig. 13. Voltage/current waveforms obtained from the thermoelectric energy harvesting experiment with V_{in}=1[V] and V_O =5.5[V].

of this RPPC are analyzed in detail. The RPPC has 4 operation modes, which are classified by the relative magnitude difference between the input voltage and the output voltage.

In order to drive the RPPC, a self-switching circuit is chosen. The self-switching circuit turns on/off the main MOSFET switch under the zero current/voltage condition without requiring a gate driving IC. The self-switching circuit and the resonant circuit determine the switching frequency of the RPPC.

It is verified with the several experiments including a thermoelectric energy harvesting experiment that the proposed RPPC with a self-switching circuit is able to transfer the available power of a DC voltage source to a DC load.

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