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# Design of Resonant Class E DC/DC Converter by PSO

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**Abstract–** This paper presents design of resonant class E DC/DC converter with class E switching circuits. To achieve high power conversion efficiency at high frequencies, we apply particle swarm optimization using a circuit simulator to adjust the passive elements including the circuit. In the illustrative examples, we confirm the validity of the proposed method.

## 1. Introduction

Appropriate DC voltage is required for various building blocks in a circuit. Therefore, it is necessary to convert a DC level to another. The switching DC/DC converter attains this purpose. It features being fabricated with small size and high power conversion efficiency. However, since the circuit is switched, the electromagnetic interference (EMI) level is high.

Alternatively, resonant class E DC/DC converter is proposed [1]. It is known that the class E switching circuits are noiseless, when the switching conditions satisfy. Therefore, resonant class E DC/DC converter is of low EMI level, which is an advantage in comparison to other switching converters. However, the design is difficult, because the switching conditions satisfy on the steady state.

In this paper, our aim is to determine the passive elements included in resonant class E DC/DC converter by using particle swarm optimization (PSO) [3]. Calculating the steady state response by a circuit simulator, the objective function associated with the switching conditions is minimized. Then, we can obtain the designed circuit with the optimized passive elements.

This paper is organized as follows. In Sect. 2, we review resonant class E DC/DC converter. In Sect. 3, the class E inverter and rectifier are provided. In Sect. 4, the optimization method is provided. In Sect. 5, the illustrative examples are presented. Section 6 is conclusions.

## 2. Resonant DC/DC Converter

Figure 1(a) shows block diagram of resonant DC/DC converter. Resonant DC/DC converters consist of two parts, inverter and rectifier. Both inverter and rectifier must be realized so that they have high power-conversion efficiency at high frequencies to obtain an efficient DC/DC converter. Using the inverter and rectifier with class E switching conditions as shown in Fig. 1(b), we can obtain a DC/DC converter with high power-conversion efficiency [1]. When the class E switching conditions satisfy, the EMI level is extremely low. This is the most advantageous feature of the resonant DC/DC converter with class E switching conditions.

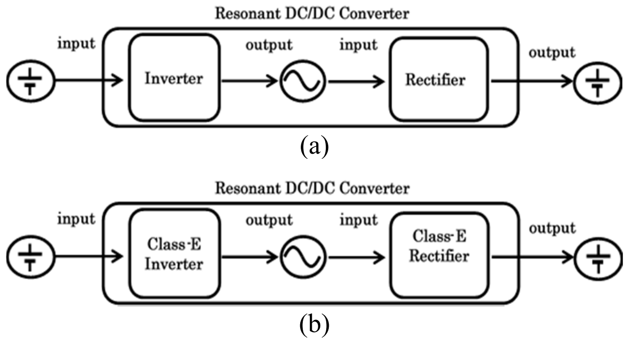



Figure 1: Block diagram of resonant DC/DC converters. (a) General configuration. (b) Converter with class E switching conditions.

## 3. Class E Inverter and Rectifier

Figure 2 shows the basic configuration of class E inverter. Class-E inverter is composed of input DC voltage $V_{DD}$, capacitors $C_S$, $C_o$, inductors $L_C$, $L_O$, resistor $R$, and MOSFET. The circuit is switched by applying a clock voltage $V_C$ to the MOSFET. Since DC voltage $V_D$ is converted to AC voltage $V_O$, the circuit is an inverter. When the MOSFET is turned on, the drain-source voltage becomes almost zero. On the other hand, when the switch is turned off, the drain-source voltage is amplified. Behavior of the class E inverter is constrained by switching of the MOSFET. In other words, it is necessary to minimize loss when the drain-source voltage is switched.

Class E inverter must satisfy the class E switching conditions. Figure 3 shows an ideal waveform of class E inverter that satisfies the switching conditions. Class E switching conditions for class E inverter is defined so that when the switch is turned on, the switch voltage $V_s$ across the capacitor $C_s$ is zero and the slope is also zero. These conditions are mathematically expressed as

$$V_S(T) = 0 \tag{1}$$

$$\left.\frac{dV_S}{dt}\right|_{t=T} = 0 \tag{2}$$

where T is the period of input voltage source $V_C$. The conditions (1) and (2) are called zero voltage switching (ZVS) and zero derivative switching (ZDS) conditions. However, since these conditions must satisfy in the steady state, adjustment of passive elements is a tremendous task.

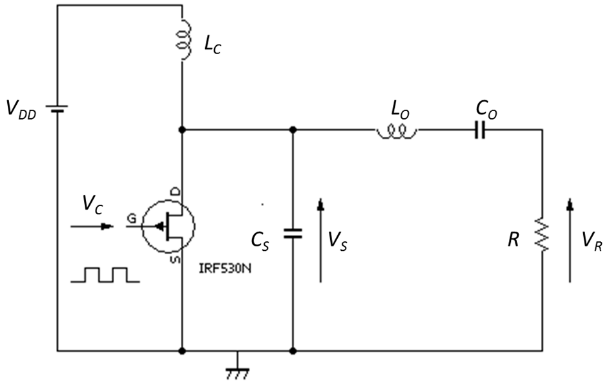



Figure 2: Configuration of class E Inverter.

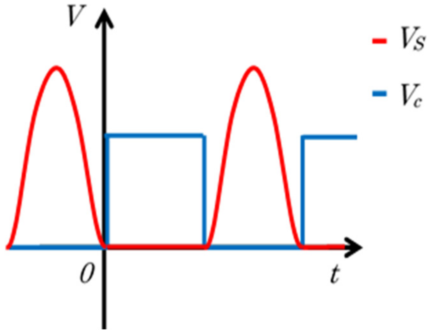



Figure 3: Ideal waveform of class E inverter.

Figure 4 shows the configuration of class-E rectifier. Class-E rectifier is composed of input AC current $I_R$, capacitors $C_D$, $C_f$, inductor $L_f$, resistor $R_l$ and Schottky barrier diode as the switching device. The input AC current is rectified in a half-wave by the diode and is converted to DC voltage by the low-pass filter consisting of $L_f$ and $C_f$. The class E switching conditions must satisfy in the rectifier, but it is different from class E inverter. The class E switching conditions of class-E rectifier is defined that when the switch is turned off, the diode voltage $V_s$ and the slope are both zero. Figure 5 shows an ideal waveform of class E rectifier.

Class E rectifier can achieve high power conversion efficiency when the class E switching conditions satisfy. The values of passive elements do not have to be adjusted, because the E class switching conditions satisfy, when the diode is off. However, since magnitude of the output voltage is constrained by the passive elements, we need to give appropriate values for a specified DC output.

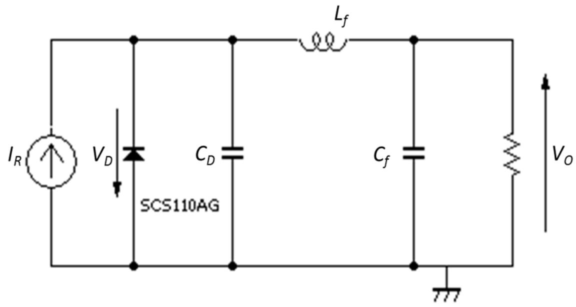



Figure 4: Configuration of class E rectifier.

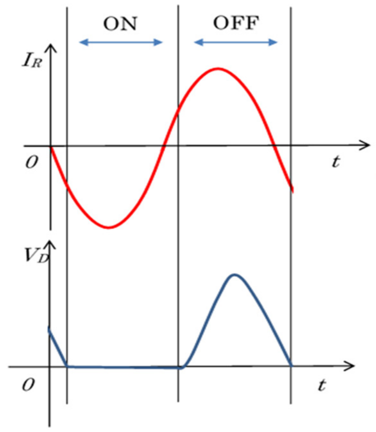



Figure 5: Ideal waveform of class E rectifier.

## 4. Optimization

### 4.1. PSO

PSO is a method for optimization without making use of explicit information of gradient of objective function. PSO consists of many particles, the vertex of which is corresponding to optimized variables. PSO is used to determine optimum parameters of the DC/DC converter. Updating the position and the velocity of particles of PSO is performed by

$$\boldsymbol{x} \leftarrow \boldsymbol{x} + \boldsymbol{v}, \tag{3}$$
$$\boldsymbol{v} \leftarrow \omega \boldsymbol{v} + c_1 r_1 (\hat{\boldsymbol{x}} - \boldsymbol{x}) + c_2 r_2 (\widehat{\boldsymbol{x}_g} - \boldsymbol{x}), \tag{4}$$

where $\boldsymbol{x}$ and $\boldsymbol{v}$ are position and velocity of particle, respectively, $\omega$ is an inertia, $c_1$ and $c_2$ are acceleration coefficients of particles, and $r_1$ and $r_2$ are random numbers in [0,1]. $\hat{\boldsymbol{x}}$ is the current best position in the particle. $\widehat{\boldsymbol{x}_g}$ is the best position for all the particles.

### 4.2. Objective Function

The objective function is required to execute PSO associated with the class E switching conditions (1) and (2). Since (2) is more sensitive than (1), we use (1) only and define the objective (cost) function by

$$\mathrm{cost} = \sqrt{V_S^2(T)}\,. \tag{5}$$

PSO provided in Sect. 4.1 finds the minimum point where (5) is minimized. To obtain (5), the steady state response have to be calculated. We use the time-domain shooting method of HSPICERF [4] to obtain $V_S$.

## 5. Results

We calculated the transient response of the resonant DC/DC converter shown in Figure. 6, where as a specification, $V_{DD}$=5V, $C_S$=3nF, $C_o$=3nF, $L_C$=7.96mH, $L_O$=7.96µH, $C_D$=2.35nF, $C_f$=470µF, and $L_f$=318µH were given. Figure 7 shows the transient response of the switch voltage $V_S$, where the class E switching conditions do not apparently satisfy. Although the class E conditions satisfy for the class E inverter only, the operating conditions are disturbed by connecting a rectifier to the inverter. This implies that we need to adjust values of passive elements. Hence, we applied PSO provided in Sect. 4.1, where $\omega$ = 0.729 and $c_1$=$c_2$=1.494. As a result, $Cs$=2.1127nF, $Co$=98.8555nF were obtained. The transient response of the circuit with these capacitances is shown in Figure. 8(a). We also show the diode voltage $V_D$ in Fig. 8(b). Form Figs. 8(a) and 8(b), we can see that the class E switching is achieved for both the switch voltage $Vs$ and the diode voltage $V_D$. Accordingly, we can say that the designed DC / DC converter is that the switching loss and electromagnetic interference are small.

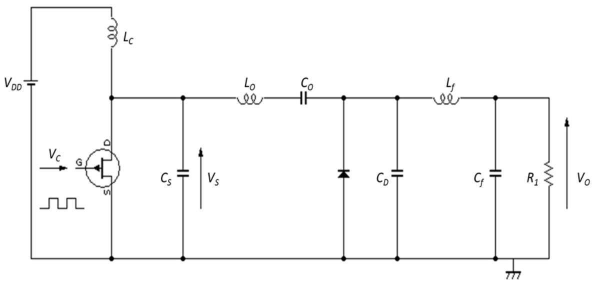


Figure 6: Configuration of class E DC/DC converter.

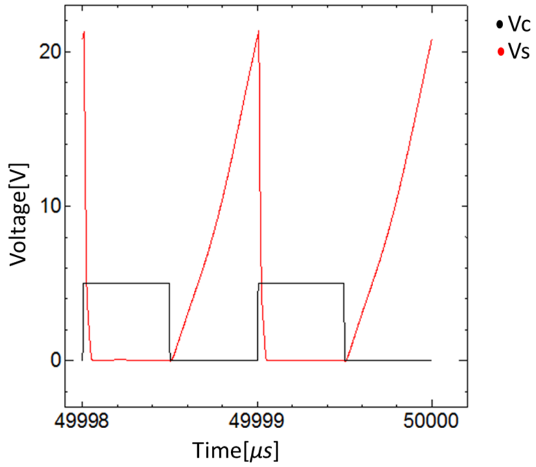
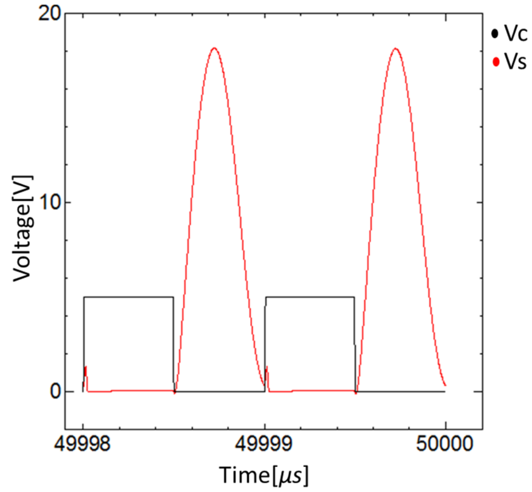
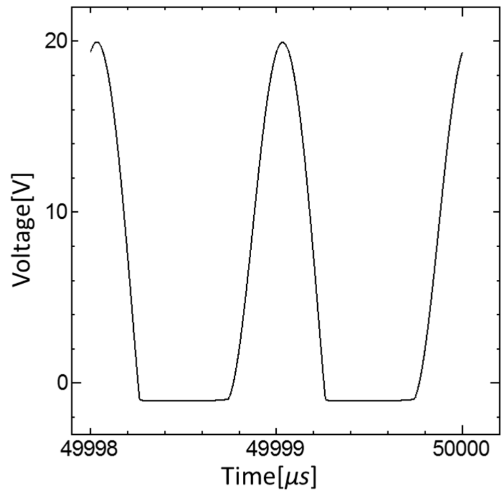



Figure 7: Transient response of DC/DC converter, the passive elements of which are not optimized.




(a)




(b)

Figure 8: Transient response of class E DC/DC converter that is optimized by PSO. (a) Switch voltage. (b) Diode voltage.

The output voltage *Vo* is shown in Figure. 9. Since it has a DC value, the designed DC/DC converter converts the input DC voltage to an AC voltage and converts again into a DC voltage. This validates that the resonance DC/DC converter behaves correctly.

However, PSO with (5) cannot change the output voltage freely. Hence, we applied PSO again to change the output voltage. The specified voltage was assumed to be 10V, and $C_D$, $L_f$, and $R_1$ were selected as optimization variables. The cost function is redefined by

$$\text{cost} = \sqrt{(10 - V)^2} \, . \tag{6}$$

As a result, $C_D$=3.8275nF, $L_f$ =379.4785μH, and $R_1$ = 128.8611Ω were obtained. The output voltage of optimized circuit is shown in Fig. 9. We can see that the output voltage is roughly 10V.

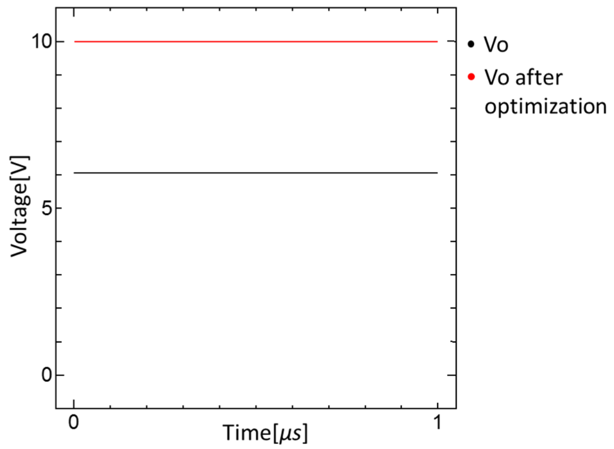



Figure 9: Output voltage of class E DC/DC converters.

## 6. Conclusion

We have presented an optimization method for designing the resonant class E DC/DC converter, applying PSO. The method is used to satisfy the class E operating conditions. Further, we apply PSO again to obtain the desired output voltage. Behavior of the optimized circuit was confirmed by transient analysis. The class E switching conditions then are broken due to changing some parameters in order to obtain the desired output voltage. Hence, we should consider satisfying the class E switching conditions by changing the duty ratio of clock voltage.

## References

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