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Design of Class E Amplifier Using Particle Swarm Optimization

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Abstract— Class E amplifier is known as a switching type power amplifier which has a high efficiency and output power. However, the design is very difficult, since the constraints on the steady-state must be satisfied. In this paper, an optimization procedure of class E amplifier is proposed, where the particle swarm optimization is used. In the proposed approach, the design parameters or the optimal solution is evaluated by a standard commercial circuit simulator. Therefore, we can determine the parameters considering the nonlinear characteristics of MOSFET included in the circuit fully. We define a new cost function for determining the design parameters of class E amplifier. By the simulation, it is confirmed that the adjusted circuit behaves as a class E amplifier certainly.

1. Introduction

There are many applications of drivers with sinusoidal waveform for power systems. A class E amplifier is the best choice as a circuit configuration of the drivers, since it is capable of combining a high efficiency ($> 50\%$) with a resonant output power (30 dBm) [1]. On the other hand, the design of class E amplifier is very difficult. To make the circuit behave as a class E amplifier which has switching constraints on the steady-state, the designers have to adjust the passive elements in the circuit and the device parameters of MOSFET in order to minimize the switching losses.

To overcome its difficulty, an optimization procedure based on the shooting Newton method is proposed in [2]. In this method, the class E amplifier is idealized by two linear circuits on the on/off state of the nMOS switch, and the passive elements are determined simultaneously so that the class E conditions are satisfied. This idea is extended to the design considering the nMOS model fully, using circuit simulator [3], [4]. These methods determine the design parameters and the steady-state responses simultaneously, which degrades the robustness of the algorithms.

In this paper, we propose an optimization procedure of class E amplifier using Particle Swarm Optimization (PSO). PSO is known as a global optimization procedure. Therefore, the proposed method is robust to find the design parameters of class E amplifier. In our approach, the behavior of the class E amplifier is analyzed by HSPICERF [5], which is a standard commercial steady-state circuit analysis tool. Therefore, we expect to include the characteristics of MOSFET included in the class E amplifier fully. We define a cost function for determining the design parameters of class E amplifier. Some passive elements of the circuit are determined by the PSO. By the simulation, it is confirmed that the adjusted circuit behaves as a class E amplifier certainly. The proposed method is very simple, which would make the design of class E amplifiers easy.

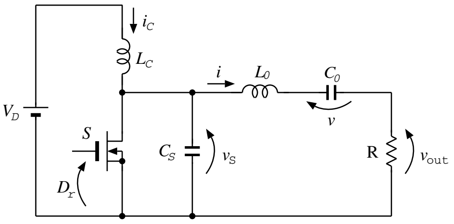


Figure 1: Class E amplifier.

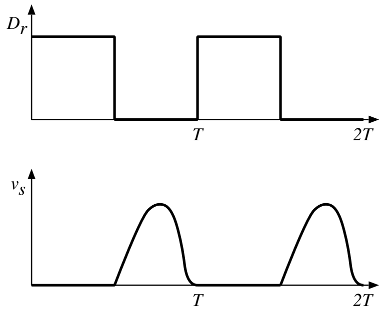


Figure 2: Capacitor voltage of class E amplifier.

2. Class E Amplifier

A class E amplifier is basically configured as shown in Fig. 1. The circuit consists of an input voltage V_D, a dc-feed inductor L_C, an nMOS switch S, a shut capacitor C_S to the nMOS switch, a series resonant circuit composed of the inductor L_0 and capacitor C_0, and the output resistor R. To achieve the high-efficiency, all the losses occur during switching must be minimized, which demands that the drain-source voltage becomes zero when the switch closes. Furthermore, it is necessary that the time derivative of the switch voltage, which is equal to the current flowing through the capacitor C_0, is also to be zero at the switching moment [1]. As a result, the conditions as a class E amplifier are obtained by

$$v_s(0) = 0, \quad (1)$$

$$\left.\frac{dv_s}{dt}\right|_{t=0} = 0. \quad (2)$$

Figure 2 shows a typical waveform of the switch voltage v_s which smoothly lands into the ground at T and $2T$ without switching losses. In oder to fulfill the conditions (1) and (2), the design parameters such as values of the passive elements and device parameters of the MOSFET S should be adjusted optimally. Moreover, the conditions must be satisfied on the steady-state, which make the design of class E amplifier difficult.

Class E amplifier has a high Q value, which means that long transition continues until it reaches the steady-state. Therefore, we need an expensive computational cost of the analysis of class E amplifier to confirm whether the class E conditions (1) and (2) are satisfied or not. This is prohibited from using the transient simulation based on a numerical integration formula, thus, a method for finding the steady-state solution would be used. The methods of steady-state analysis of nonlinear circuits are categorized into time and frequency-domain methods. In the frequency-domain method, all the waveforms are assumed by sum of kernel functions such as Fourier series. The input of class E amplifier is a pulse waveform. Hence, we should not use the frequency-domain methods to the analysis of class E amplifier. The shooting Newton method, which is a time-domain method, is suitable for this analysis. In the proposed optimization procedure, HSPICERF is used [5]. HSPICERF includes not only the shooting Newton analysis (.SN) but also some useful functions for evaluating the class E conditions of (1) and (2).

3. Determining Design Parameters

3.1. PSO

PSO is a method for optimization without explicit knowledge of the gradient of problem to be optimized. Since the class E amplifier is analyzed by a circuit simulator in our approach, a cost function for the optimization can not be explicitly written [2]. Since the gradient is not easily obtained, PSO becomes a good tool for finding the optimum design parameters of the class E amplifier.

The update rule of PSO used for determining the design parameters of class E amplifier is described by

$$\boldsymbol{x} \leftarrow \boldsymbol{x} + \boldsymbol{v}, \quad (3)$$

$$\boldsymbol{v} \leftarrow w\boldsymbol{v} + c_1 r_1(\hat{\boldsymbol{x}} - \boldsymbol{x}) + c_2 r_2(\hat{\boldsymbol{x}}_g - \boldsymbol{x}), \quad (4)$$

where $\boldsymbol{x}$ and $\boldsymbol{v}$ are respectively the position and velocity of particle. w is a inertia. c_1 and c_2 imply the ratio of particles in a group which turn to a good position. r_1 and r_2 are random numbers in $[0, 1]$. $\boldsymbol{x}_g$ is the best position for all the particles. $\hat{\boldsymbol{x}}$ is the current best position of the particle.

3.2. Implementation

To apply the PSO to determining the design parameters, it is necessary to define the cost function. The conditions as a class E amplifier are related with $v_s(0)$ and $dv_s/dt|_{t=0}$ as (1) and (2). However, $dv_s/dt|_{t=0}$ is more sensitive to the parameter changes than $v_s(0)$. Therefore, the cost function including $|dv_s/dt|_{t=0}|$ can not be defined to determine the design parameters to be optimal. We use v_s only and define the cost function.

The cost function is defined by

$$cost = \frac{1}{N}\sqrt{v_s(0)^2 + ...v_s(T_1)^2}, \quad (5)$$

where T_1 is the pulse width of the input voltage D_r of Fig. 2 and N is the number of time points in $[v_s(0), v_s(T_1)]$. The PSO algorithm minimizes (5) changing the design parameters. The way to evaluate (5) is summarized below.

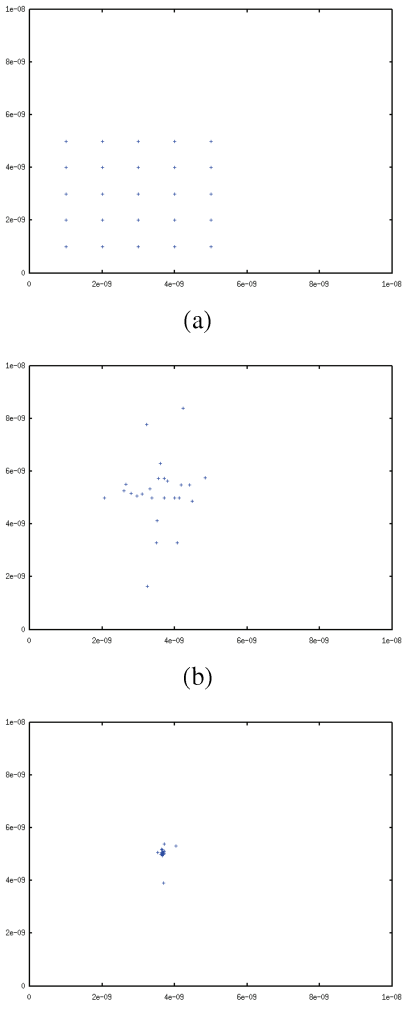
1. A new position is selected by (3) and (4).
2. If components of the position of particle correspond the passive elements of the class E amplifier and are all non-negative, the shooting Newtown analysis (.SN) of HSPICERF is carried out. Otherwise the update is skipped.
3. If the shooting Newton method converges, the root mean square value (5) which defines how the position is optimal, is automatically calculated using a HSPICERF command (.Measure). Otherwise the update is skipped.

4. Results

To design the class E amplifier, we defined the the following parameters [2]:

1. $\omega = 2\pi f$.
2. $\omega_0 = 2\pi f_0 = 1/\sqrt{L_0 C_0}$.
3. $Q = \omega L_0/R$.
4. $A = f_0/f = \omega_0/\omega$.
5. $B = C_0/C_S$.
6. $H = L_0/L_C$.

As a specification, $f = 1.0$[MHz], $V_D = 5.0$[V], $R = 5.0[\Omega]$, $Q = 10.0$, $H = 0.001$, $L_C = 7.96$[mF], and $L_O = 7.96[\mu\text{H}]$ were given. As a result, C_S and C_O have to be determined only.



(a)

(b)

(c)

Figure 3: Positions of particles of the PSO. (a)Initial positions. (b)Positions at the 5th iteration. (c)Positions at the 30th iteration.

In (3) and (4), $c_1 = c_2 = 1$ were used and w_1 was a random number in $[0, 1]$. Using 25 particles, the PSO was carried out until 30 iterations, where all the particles were updated at 1 iteration, that is, a particle was updated 30 times maximum. Figures 3(a)-3(c) show the positions of particles of the PSO algorithm. The particles concentrates in a position with increase of the iterations. After 30 iterations, we obtained the best position (solution); $C_S = 3.64[nF]$ and $C_O = 5.09[nF]$. Figure 4 shows the simulation results of the class E amplifier using HSPICERF. The switching voltage v_s dumps smoothly around $t = 0$ so that the switching losses are almost zero. The output voltage is almost sinusoidal waveform. The circuit adjusted by the PSO certainly behaves as a class E amplifier.

To design the class E amplifier, the cost function (5) was used. However, the cost function is related with one of the class E conditions only, that is, (1). On the other hand, in oder to investigate the effect of (2) for the optimization, we defined the cost function:

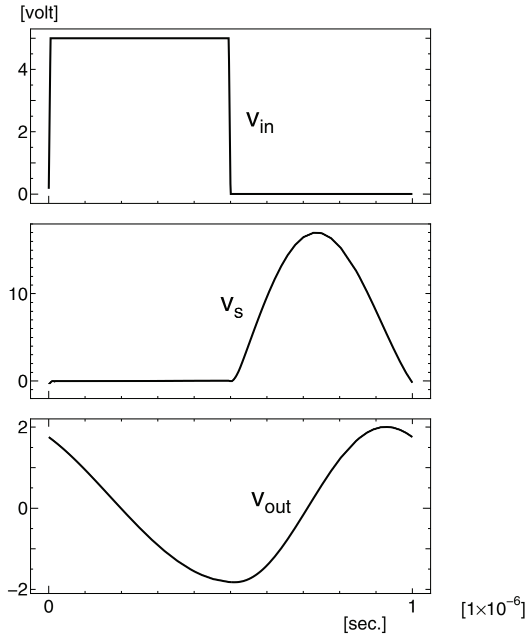


Figure 4: Simulation results of the class E amplifier after optimization by the PSO.

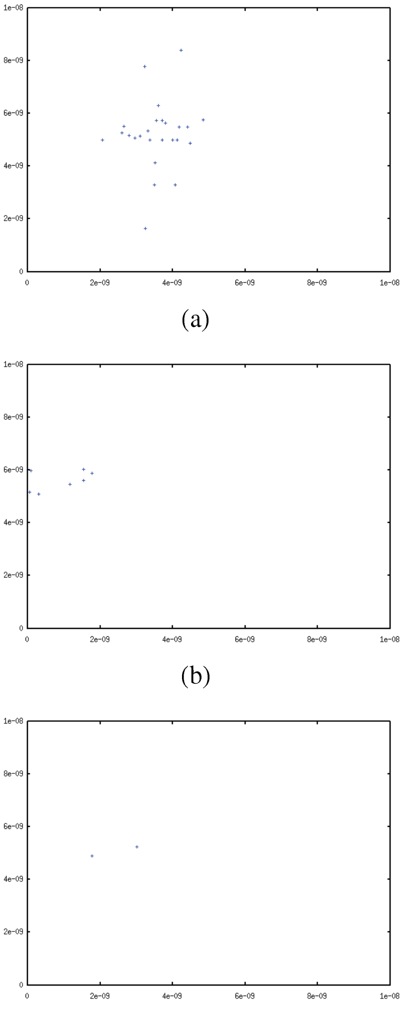
$$cost' = \frac{1}{N}\sqrt{i_s(0)^2 + ...i_s(T_1)^2}, \tag{6}$$

and run the PSO algorithm. In (6), i_s is the current which flows through the capacitor C_S in Fig. 1. Therefore, the cost function is associated with (2). The figures 4(a)-4(c) show the positions of the particles. We can see that the PSO fails to capture the optimal position. PSO is known as a global optimization method. Hence, a problem which PSO fails is difficult or the cost function of which is not suitable. This means that the condition (2) may not be necessary for optimization algorithms to design a class E amplifier.

The simulation of class E amplifier needs a large cost, even if HSPICERF is used. The PSO algorithm needed 4,477 [sec.] on Intel Pentium 4 CPU 2.40 [GHz] with 2 [GByte] memory, where CentOS 5.4 was used. In this example, we provided suitable initial positions as shown in Fig. 3(a), thus, the particles concentrate at the 30th iteration. However, if suitable values were not given, many iterations would be necessary to get a good solution. Therefore, we should improve efficiency of the PSO algorithm for designing the class E amplifier.

5. Conclusions

The optimization procedure of class E amplifier has been proposed, where the PSO algorithm is used. To adjust the design parameters of class E amplifier, the cost function for the optimization is defined. In our approach, a standard



(a)

(b)

(c)

Figure 5: Positions of particles in the PSO using the cost function (6). (a)Positions at the 5th iteration. (b)Positions at the 10th iteration. (c)Positions at the 30th iteration.

commercial steady-state analysis tool is used. Since the device model is realistic, we can determine the design parameters suitably. HSPICERF includes various functions, for example, including scattering parameter. Therefore, our approach can include the physical effects of the circuit in detail. However, when the circuit is analyzed considered such effects, the simulation needs a lot of CPU times. Therefore, we must improve efficiency of the PSO algorithm. This is our future work.

References

[1] P. Reynaert, K. L. R.Mertens, and M. S. J. Steyaert, “State-space behavioral model for CMOS class E power amplifiers,” *IEEE Trans. TCAD*, vol. 22, no. 2, pp. 132-138, Feb. 2003.

[2] H. Sekiya, I. Sasase, and S. Mori, “Computation of design values for class E amplifiers without using waveform equations,” *IEEE Trans. Circuits and Systems-I*, vol. 49, no. 7, pp. 966-978, July 2002.

[3] Y. Tanji, H. Sekiya, and H. Asai, “Optimization procedure of class E amplifiers using SPICE,” Proc. of 2005 European Conference on Circuit Theory and Design, Aug. 2005.

[4] H. Sekiya, T. Ezawa, and Y. Tanji, “Design procedure for class E switching circuits allowing implicit circuit equations,” *IEEE Trans. Circuits and Systems-I*, vol. 55, no. 11, pp. 3688-3696, Dec. 2008.

[5] User Guide: RF Analysis, Synopsys, 2009.

[6] J. Kennedy and R. C. Eberhart, “Particle swarm optimization,” Proc. of IEEE Int. Conf. on Neural Networks, pp. 1942-1948, 1995.

[7] M. Lovbjerg, T. Krink, “Extending particle swarm optimisers with self-organized criticality”, Proc. of the Fourth Congress on Evolutionary Computation (CEC), vol. 2, pp. 1588-1593, 2002.