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Acceleration of PSO for Designing Class E Amplifier

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Abstract– Class E amplifier, which is a power amplifier with switching characteristics, is known to be efficient in conversion. However, since the switching conditions must be satisfied on the steady state, determining the values of the circuit elements included is difficult. The PSO algorithm has been applied to the optimization problem. However, the high-Q nature prevents the PSO from determining the optimum values efficiently. On the other hand, the computation with respect to a particle is almost independent to the others. Namely, the positions and velocities of the particles can be calculated in parallel. We take advantage of this feature and develop the program suitable for current multi-core processor using OpenMP, which is an API for multi-platform shared-memory parallel programming. It is confirmed that the proposed method accelerates the PSO.

1. Introduction

There are many applications of drivers with sinusoidal waveform for power electronics systems. 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].

To make the circuit behave as a class E amplifier, switching constraints on the steady-state are satisfied. The designers have to adjust the passive elements of the circuit and the device parameters of MOSFET in order to minimize the switching losses. The fundamental idea of automatic tuning of the class E amplifier was presented in [3], which would be the first attempt of automatic design of the circuit. This method was improved to consider the model of MOSFET [4] using the circuit simulator. However, the constraints on the steady-state are evaluated by the transient analysis, which make the procedure less robust. In [8], the PSO algorithm was introduced for the optimization problem, where the constraints on the steady-state were directly evaluated by using a commercial tool.

In this paper, the PSO algorithm [4] for designing the class E amplifier is improved. First, the objective function is defined as the conditions of class E amplifier are satisfied. Next, an OpenMP directive is appended to the original code in order to accelerate the optimization suitable for multi-core processor. Using the proper parameters of the PSO [7], the efficiency of the parallel implementation is confirmed.

2. Optimization of Class E Amplifier

A basic circuit configuration of class E amplifier is shown in Fig. 1. The circuit consists of a dc voltage source V_D, a dc-feed inductor L_C, a switch S, which is n-channel power MOSFET, a shut capacitor C_S to the MOSFET, a series resonant circuit composed of the inductor L_0, the capacitor C_0, and the output resistor R. To achieve the high-efficiency, all the losses occur during the switching of S must be minimized, which requires the drain-source voltage to be zero when the MOS switch closes. It is also required that the time derivative of the switch voltage, which is equal to the current flowing through the capacitor C_0, is to be zero at the switching instant. Therefore, the conditions as class E amplifier are represented by

$$v_S(0) = 0 \tag{1}$$

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

The conditions (1) and (2) are called the class E conditions. The conditions (1) and (2) are certainly switching ones and must be satisfied on the steady-state, which makes the design of class E amplifier difficult. Therefore, the closed form expression with an ideal treatment in [1] and [2] gives a useful guidance to design the class E amplifier. Following the guidance, the designers may find the suitable circuit parameters by repeating the circuit simulations. However, the mathematical model of MOSFET is so complicated that the idealization to obtain the closed form expression is not always valid and suitable operation of class E amplifier is not always achieved. In order to satisfy (1) and (2), values of the passive elements and device parameters of the MOSFET should be optimally adjusted. In [4], an optimization method was proposed to tune these parameters. This method is an extension of the shooting Newton method [3], where the behavior of class E amplifier is analyzed by a SPICE simulator and all the effects of MOSFET within the device model are taken into account.

Figure 2 shows typical waveforms of class E amplifier. The input D_r is driving the MOSFET and a square waveform is given. When the class E conditions are satisfied, the voltage v_S of the shunt capacitor C_S switches very softly at T and $2T$ so that the switching losses are very small. Then, an almost sinusoidal waveform v_{out} is observed at the output resistance R. Therefore, class E amplifier has a high quality factor. The transition time is very long until the circuit reaches the steady-state, which means that there are two difficulties of the optimization method proposed in [4]. One is that the optimization requires huge computational time since the circuit simulation becomes long. The other is that the judgment whether the circuit reaches the steady-state is difficult. A class E amplifier may not have a steady-state solution with a period T of Fig. 2, depending on the passive components. In this case, it is hard to judge whether the circuit has a long transition time or does not have the steady-state solution with a period T. To eliminate the weaknesses, the steady-state analysis with the commercial simulator [5] is used in [8], instead of the transient analysis. In the analysis, the steady-state solution, which is assumed to be a period T, is found by the Newton method.

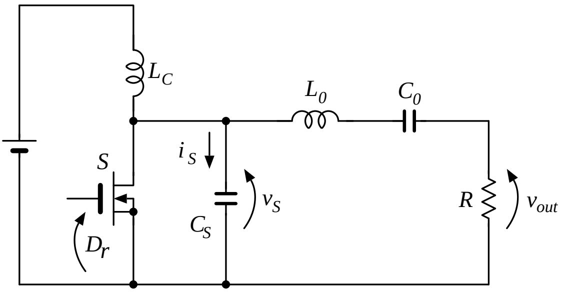


Figure 1: Class E amplifier.

In [8], the objective function was taken as $|v_S(0)|^2$ or $|dv_S/dt|_{t=0}|^2$. Namely, the class E conditions of (1) and (2) are not satisfied. The reason why either of (1) and (2) is considered on the objective function for the optimization is due to mismatch in magnitude between (1) and (2). Generally, the time derivative (2) is much larger than the value of (1). If (1) and (2) are simultaneously evaluated, $|v_S(0)|^2$ or $|dv_S/dt|_{t=0}|^2$ should be multiplied by a scaling factor and they are added to make the function. To meet the class E conditions fully, we choose the value of the shunt capacitor C_S as the scaling factor. Then, $C_S dv_S/dt$ is equal to the capacitor current i_S. Therefore, the class E conditions are translated by the minimization of the objective function:

$$f_1(\lambda_1,\ldots,\lambda_n)=|v_S(0)|^2+|i_S(0)|^2, \qquad (3)$$

where $\lambda_1, \ldots, \lambda_n$ are the design parameters.

Figure 3(a) and 3(b) show the profiles of the objective function (3) seen from two view points, where the parameter space is selected to the two capacitors C_S (x-axis) and C_0 (y-axis). The function is certainly multimodal one, which says that the optimization for designing the class E amplifier is not easy. In Figs. 3(a) and 3(b), a part with the highest value shows that the objective function has infinity, where 0.895 percent of all the sample points in the parameter region have infinity. Infinity means that the steady-state solution is not obtained by using the steady-state circuit simulator. The steady-state solution not being found is reported by the simulator. Also, the simulation is forced to be terminated by the user even if the simulation time is long. In such cases, the objective function has infinity. There are two possibilities that the report is issued or the simulation time is long. The class E amplifies may not have the steady-state solution with the period T essentially. There may be an interesting nonlinear phenomenon. In the other case, it may be too difficult for the simulator to find the solution of the circuit. Anyway, the objective function has infinity frequently, even though the parameter region is narrow (the parameter region of Figs. 3(a) and 3(b) is $10^{-9} < C_S$, $C_0 < 10^{-10}$). Therefore, the objective function for determining the parameters of the class E amplifier is not well-defined.

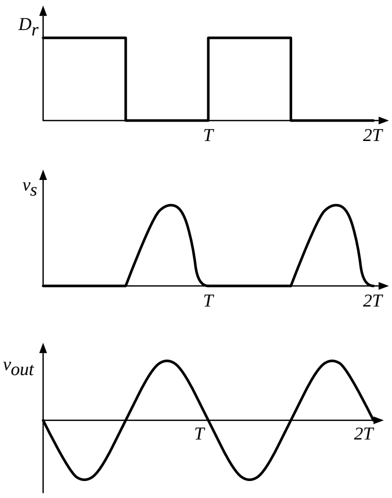
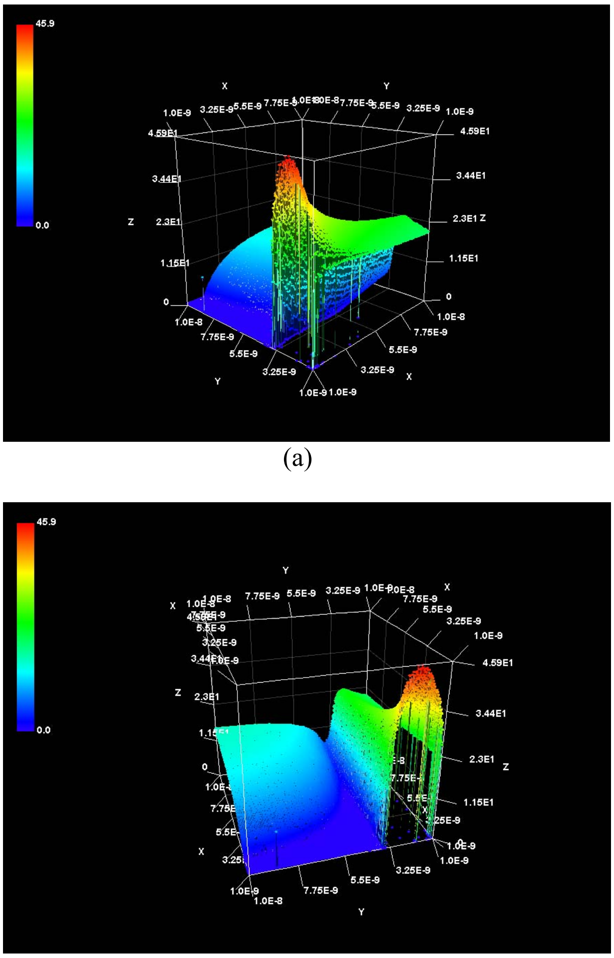


Figure 2: Typical waveforms of class E amplifier.

3. PSO

PSO is a good choice for the optimization problem in which the objective function is not well-defined. PSO has many particles which are trials to obtain a best position fitting into the problem specification. Therefore, unless a set of parameters provides steady-state responses of the class E amplifier, the optimization proceeds discarding the trials. This is why we select the PSO for the optimization.

In many variants of PSO algorithms, we use the PSO with star topology, where the neighborhood of each particle is the entire swarm and the PSO is referred to as the gbest PSO. Other type of neighborhood topologies may be effective. However, this paper is restricted to the gbest PSO.



(a)

(b)

Figure 3: Objective function for the optimization.

Let $\boldsymbol{x}_i(k)$ and $\boldsymbol{v}_i(k)$ respectively represent the position and velocity vectors of ith particle ($i = 1, .., m$) at iteration step k. The position $\boldsymbol{x}_i(k)$ is an n-dimension vector, which is the solution of problem. In the dynamics of the standard PSO, two kinds of the best positions are memorized. If the fitness of a position is better than its previous best position, it is stored as the local best position $\boldsymbol{p}_i(k)$. If the local best position $\boldsymbol{p}_i(k)$ is better than the global best positions $\boldsymbol{p}_g(k)$, it is updated by $\boldsymbol{p}_i(k)$.

The dynamics of the gbest PSO used in this paper is written in a set of difference equations:

$$\begin{aligned} v_{ij}(k+1) = \eta v_{ij}(k) + \varphi_1 U(0,1)\left(p_{ij}(k) - x_{ij}(k)\right) \\ + \varphi_2 U(0,1)\left(p_{gj}(k) - x_{ij}(k)\right) \end{aligned} \tag{4}$$

$$x_{ij}(k+1) = x_{ij}(k) + v_{ij}(k+1) \tag{5}$$

where $i = 1, ...m$, $j = 1,... n$. $U(0,1)$ represents uniformly distributed random numbers in the range of [0,1]. φ_1 and φ_2 are acceleration coefficients and η is an inertia weight.

The calculation of (1) and (2) associated with a particle is independently done to the other particles. Therefore, the updating of particles has parallel computation nature. After updating the particle's positions, fitness of each particle is evaluated. Fitness of a particle is also independent to those related with the other particles. Although the parallel nature in the computation of position and velocity is interesting, most of the CPU power is used for the circuit simulations in the optimization. Therefore, the evaluation of fitness, precisely, the steady-state analysis to assess fitness of the particles by using a commercial tool, is done in parallel to accelerate the PSO.

To run some simulations in parallel, OpenMP is used. Calling the simulator multiply is only to append a directive to the original code. Assessment of fitness is a little complicated. The arguments of (3) are obtained from the simulator in a text file. If the simulation time is longer than a user-defined criterion, the simulator is forced to be terminated, which can be done with some unix commands and is written by a perl script. In the code of the PSO, the perl script is called by a system call.

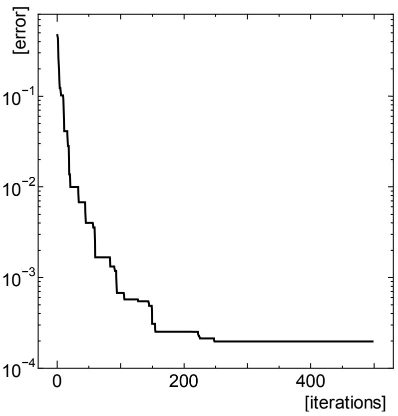


Figure 4: Convergence process of the PSO.

4. Results

To design the class E amplifier, we defined the the following parameters [2]: 1)$\omega=2\pi f$, 2) $\omega=2\pi f_0 =1/(L_0C_0)^{1/2}$, 3)$Q = \omega L_0/R$, 4)$A=f_0/f$, 5)$B=C_0/C_S$, 6)$H=L_0/L_S$. As a specification, f = 1.0 [MHz], V_D = 5.0 [V], R = 5.0 [Ω], Q = 10.0, H = 0.001, L_C=7.96 [mF], and L_0=7.96 [μH] were given. Therefore, C_S and C_0 are selected as the design parameters.

As the PSO parameters of (4), φ_1= φ_2=1.6, η=0.7, and m=24 were set. Figure 4 shows the convergence process of the PSO. After the convergence of the PSO, the optimum capacitor values, C_S = 5.58 [nF] and C_0=3.56 [nF], are obtained. Using these parameters, we analyzed the class E amplifier. Figure 5 shows the steady-state responses, where the voltage v_S of the shut capacitor switches smoothly and the class E conditions are almost satisfied.

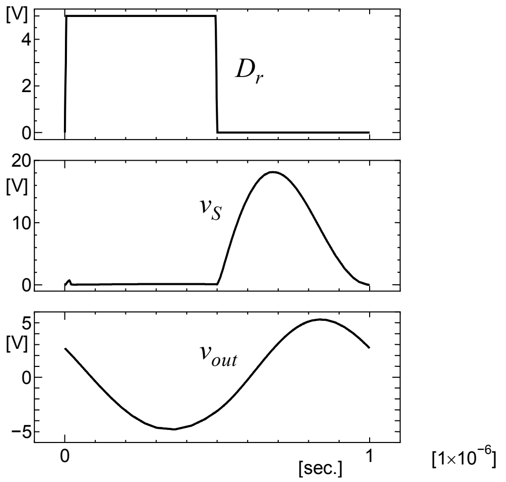


Figure 5: Steady-state responses of the class E amplifier.

To investigate the effects of parallel computation, the optimization program was run on the workstation with Intel Xeon X5472 (3GHz) or Sun UltraSPARC-T2 (1.1GHz) processors. The workstation of Intel processor has 8 cores and the sun's workstation has 32 cores. Therefore, the maximum thread size is 8 for the Intel's processors and 32 for the sun's processors. Tables 1 and 2 show the CPU comparisons with number of threads which are used for evaluation of the objective function. Since the number of particles is 24, the fitness is at most evaluated for 24 different parameters at an iteration step. The OpenMP directive `#pragma omp for` was appended to the original code to utilize multi-threading. From Table 1, we can see that the directive becomes effective when the number of threads is an aliquot of 24. Due to stochastic nature of PSO, the efficiency is not proportional to the number of threads as seen in Table 2. However, the optimization is certainly accelerated by using a lot of CPU cores.

Table 1: CPU time comparisons with number of threads used (Intel Xeon X5472).

num. of threads	CPU times [sec.]	Num. of threads	CPU times [sec.]
1	32,113	5	13,579
2	20,370	6	13,234
3	16,588	7	13,428
4	13,814	8	11,304

Table 2: CPU time comparisons with number of threads used (Sun UltraSPARC-T2).

num. of threads	CPU times [sec.]	Num. of threads	CPU times [sec.]
1	79,816	8	17,967
2	50,753	12	20,249
4	30,831	24	15,342

5. Conclusion

The PSO algorithm for designing class E amplifier has been presented. To reduce the computational cost of the optimization, the parallel nature of the PSO was used. The evaluation of fitness of the PSO is computed in parallel, where OpenMP is used in developing the code. It is confirmed that the optimization of the class E amplifier via the PSO algorithm is accelerated. However, the improvement of the algorithm is further required since the objective function become more complicated when the other specifications are appended.

Acknowledgments

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