早稲田大学大学院情報生産システム研究科

博 士 論 文 概 要

論 文 題 目

Study on Numerical Integration Algorithms and Time-Step Control Methods in Pseudo-Transient Analysis for Solving Nonlinear DC Circuit Equations

申 請 者
Xiao WU

情報生産システム工学専攻

2017 年 4 月

Recently, engineering productivity in integrated circuit product design and development is limited largely by the effectiveness of the computer-aided design (CAD) tools, in which the SPICE-like simulators are perhaps the most important one. The circuit simulation combines (a) mathematical modeling of the circuit devices, (b) formulation of the circuit equations, and (c) numerical analysis algorithms for solution of these equations. As circuits of more complexity and mixed types of functionality, these equations are much more difficult to be solved. Therefore, the study on improving the convergence of the numerical analysis algorithms for solving the integrated circuit equations is an important task.

For the circuit simulation, the most important and difficult task is to find the DC operating point. In DC analysis, the numerical analysis algorithms are used to solve the system of nonlinear algebraic equations. The most typical algorithm is the Newton-Raphson (NR) method. This method has the very desirable property of quadratic convergence. However, it may fail to converge if the initial guess is not sufficiently close to the real solution. Until now, the pseudo-transient analysis (PTA) methods are considered as the most practical methods to solve this non-convergence problem. The main idea of the PTA methods is to insert the pseudo-element (capacitor and inductor) into the original circuit to form a pseudo-circuit. After that, the DC problems are converted to the transient problems. The efficiency of the conventional PTA methods is not very satisfactory. Moreover, the insertion of the pure pseudo-element is easy to form an oscillator. In order to overcome the oscillation problem in PTA method, the compound element PTA (CEPTA) method is proposed (Hong Yu, IEICE Trans 2006) from the pseudo-element viewpoint. Instead of using pure reactance element as the pseudo-element, compound elements in CEPTA are composed of time-varying resistor and capacitor, time-varying conductor and inductor. More recently, based on CEPTA, a new SPICE3 implementation method and embedding method of pseudo-element are proposed (Zhou Jin, IEICE Trans 2013). In addition, the time-step control method of the numerical integration algorithm used in PTA greatly affects the convergence performance of PTA. The simple iteration count method that based on the number of Newton's iterations, and Switched Evolution / Relaxation (SER) (Kelley, SIAM J.1998) method that based on the residual of equations are well known. However, the conventional methods cannot make all circuits converge especially some large-scale circuits. Therefore, to propose a practical numerical analysis algorithm that has a better convergence performance and easy to be implemented is very important.

In this research, a practical method which can succeed in all the cases mentioned before is needed. All the research studies previously published are from the pseudo-element viewpoint. To address these issues from the different viewpoint (numerical integration algorithm viewpoint), (1) a Damped PTA (DPTA) and (2) a time-step control method for DPTA are proposed. All the proposed methods are implemented in Waseda SPICE (WSPICE), and have been applied to the practical and large-scale circuits to verify the effectiveness.

The dissertation contains the following five chapters.

Chapter 1, "Introduction", presents the background of the circuit simulation. Then, the importance of circuit simulation in integrated circuit design is introduced. After that, the conventional numerical analysis methods for solving the nonlinear DC circuit equations and the related algorithms are reviewed. At last, the challenges and purposes of this research are described.

Chapter 2, "Preliminaries", introduces some related methods, which will be used in later chapters. The commonly used numerical integration algorithms and the conventional time-step control methods are reviewed. Moreover, the convergence of PTA method is analyzed.

Chapter 3, "A PTA Method Using Numerical Integration Algorithms with Artificial Damping for Solving Nonlinear DC Circuit Equations", proposes a new PTA method, which uses numerical integration algorithms with artificial damping effect. This new PTA method solves the oscillation problem from the different viewpoint (numerical integration algorithm viewpoint), other than the pseudo-element viewpoint. Firstly, the k-step (k=1, 2, 3 ...) numerical integration algorithms are proposed. Step k=1 is the backward Euler method. As k increases, the damping effect is artificially enlarged. The consistency, convergence and stability of the proposed numerical integration algorithms are analyzed. By using the proposed numerical integration algorithms, the new PTA method is capable to reduce the oscillation. After that, a switching algorithm is proposed to control the step k. It considers the convergence of NR in each time-point to change the step k smoothly. With varying degrees of damping effect, the convergence performance of the proposed PTA method is improved.

The proposed algorithms are implemented in the Waseda spice (WSPICE) and applied to practical large-scale analog circuits. Numerical examples demonstrate that compared with conventional PTA method (Zhou

Jin, IEICE Trans 2013), the proposed method can reduce the CPU time (computational time to convergence in PTA procedure) for practical analog circuits. Using DPTA for the practical and large-scale analog circuit (1516 MOSFETs), the CPU time has 4.79X speedup, and the number of NR iterations is reduced to 18.03% of the iterations by using conventional CEPTA. Moreover, with the proposed method, 100% test circuits in INOUE Lab. are solved (62/62) including practical and large-scale circuit (>1516 MOSFETs) that is difficult to converge by using conventional PTA method and commercial circuit simulator.

Chapter 4, "An Adaptive Time-Step Control Method in Damped Pseudo-Transient Analysis for Solving Nonlinear DC Circuit Equations", proposes an adaptive time-step control method for DPTA, which includes an increment algorithm and a decrement algorithm. At the beginning, the demands of time-step size for different situations during the pseudo-transient analysis are analyzed. Based on these demands, the new time-step control method considers the residuals of pseudo-circuit equations, the relative change of node voltages and currents, and the iteration count of Newton-Raphson together to increase the time-step size. When NR fails to converge, the decrement algorithm uses a gradually reduced ratio to reduce the time-step size. Therefore, the proposed method has ability to adapt the time-step size without constant upper limit which means that it can obtain the damping effect as large as possible. Moreover, the proposed method has a wider applicability to the pseudo-capacitor value since it can automatically and effectively adapt the time-step size according to the circuit state during the simulation.

The proposed algorithms are implemented in the Waseda spice (WSPICE) and the effectiveness is verified by applying to practical large-scale analog circuits. Numerical examples demonstrate that compared with conventional DPTA, the proposed method has 0.86X~104.82X speedup of CPU time. Compared with conventional SER (Kelley, SIAM J.1998), the proposed method has 1.22X~76.34X speedup of CPU time. It is also proved that, DPTA with the proposed time-step control method has the ability to 100% solve all test circuits in INOUE Lab. and the benchmark circuits (113/113). Moreover, the robustness of DPTA is enhanced. Compared with other time-step control methods, the proposed method can expand the range of capacitor value used in the pseudo-element.

Chapter 5, "Conclusions", concludes the dissertation and gives the future work.