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Research on Simulation Speed of Continuous System Based on SimPowerSystems

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Abstract

Simulation speed is a noteworthy issue in the simulation of continuous system. Although previous research has to some extent obtained some achievements, it is still very slow for complex system simulation. A schematic diagram is formulated to describe and analyze the simulation process of continuous system in SimPowerSystems environment. Three simulation methods are proposed based on different ways of discretization mathematical model, namely continuous method, discrete method and hybrid method, and their implementation approaches are presented as well. Meanwhile, the characteristics of modules in Simulink and SimPowerSystems are also studied. Simulation performance of three methods are illustrated by theory analysis and case verification, the results show that discrete method can obviously improve simulation speed. And when sampling time is 5us, discrete method meets precision requirement generally. It has important significance for the simulation of large system.

Keywords*: continuous system, SimPowerSystems, simulation speed, continuous method, discrete method, hybrid method*

1. Introduction

SimPowerSystems is a simulation toolbox of Power System based on interface of Simulink, which is used in the simulation of variously continuous systems, for instance, power electronics, motor control and power transmission [1]. We can utilize circuit diagram to construct simulation model which is consisted by modules in Simulink and SimPowerSystems. It will automatically become a mathematic model when simulation starts, and then be analyzed and calculated in MATLAB. In recent years, many literatures have been studied electrical system using SimPowerSystems [2-5] and obtained the results of high credibility. But simulation speed is still very slow even paralysis for complex system which contains too many nonlinear links and state variables. In order to solve the issue, many scholars have did research. Ref[7-8] are represented for eliminating algebraic loop of simulation model to enhance simulation speed, but algebraic loop has various forms, leading to difficult elimination. In ref [9-10], many algorithm improved are introduced to accelerate simulation speed, but it does not get obvious effect.

Although SimPowerSystems provides three simulation types for continuous system, their performances are not same. Especially for complex electrical system, the difference of simulation results is more obvious. However, the distinction has not been deep studied. Moreover, two kinds of modules are supplied for the same link in SimPowerSystems and Simulink, namely continuous module and discrete module. But the applicability of two kinds of modules has not been analyzed. As a result, modules are free to build simulation model.

In order to improve simulation speed, this paper will commence from two simulation types and two kinds of modules. Three simulation methods are proposed, namely

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continuous method, discrete method and hybrid method, and their implementation approaches are presented as well. The performances of different simulation methods are compared. It is concluded that discrete method not only has higher computing stability, but also very fast simulation speed with meeting precision requirement. This means that the problem of simulation speed for complex electrical system is radically solved.

The remainder of this paper is organized as follows: In section 2, it is proposed that simulation object in SimPowerSystems is continuous system rather than discrete event system. Section 3 presents implementation way of three simulation methods. Section 4 compares simulation performance. In section 5, a case is studied to evaluate these simulation approaches. Section 6 gives the conclusion remarks.

2. Continuous System Simulation

According to whether the change of state variable is continuous or not, system is divided into continuous system and discrete system, the state of continuous system is consecutively changing with time. According to whether the change of state variable is regular or not, discrete system is classified into discrete time system and discrete event system, the state of discrete event system is discretely changing at random time.

Simulation is based on model which directly influences implementation of emulation, so modeling is fundamental to realize simulation. Modeling is split into system modeling which is establishing mathematical model and simulation modeling. According to different motion laws of system, mathematical model is divided into the model of continuous system and that of discrete event system. It should be noted that mathematical model of discrete time system could be included the model of continuous system, the reason is that original mathematical model must be discretized when used with digital simulation technique and eventually becomes discrete-time model. Simulation modeling, also known as simulation approach, is establishing simulation model on the computer and selecting simulation algorithm to solve output. According to the different characteristics of mathematical model of system, system simulation is classified into the emulation of continuous system and that of discrete event system. To summarize what has been mentioned above, a diagram of system simulation process is shown in Figure 1.

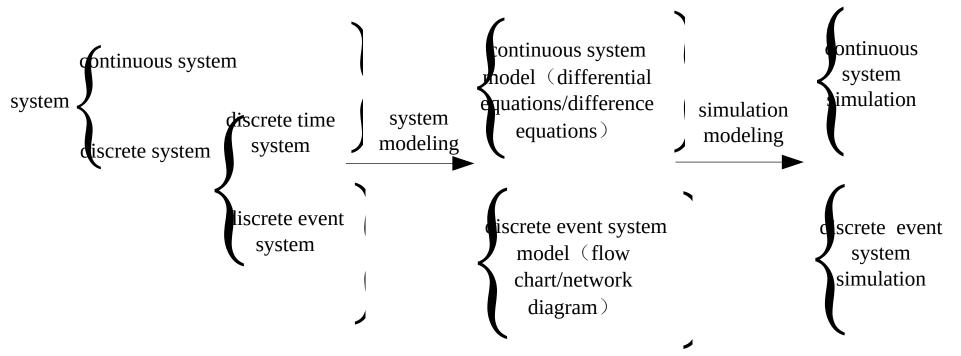


Figure 1. Schematic Diagram of System Simulation Process

The computer simulation of discrete event system does not have practical significance, and does not belong to its modules in SimPowerSystems. Therefore, this paper is merely studying the simulation of continuous system.

The mathematical model of continuous system must be discretized when used with digital simulation technique as digital computer can only do finite computations for sets of numbers of finite word length, but that of continuous system not only contains infinitude number, but allows infinite multiple operations, such as integral and derivation. The mathematical model of continuous system is represented in different ways, such as differential equation and transfer function. Due to different ways of discretization for mathematical model, disparate simulation types are produced in SimPowerSystems.

3. Implementation of Simulation Approaches using Simpowersystems

SimPowerSystems provides three simulation types for continuous system, namely continuous type, discrete type and phasor type. Continuous type is used for discretization of differential equations, discrete type is applied to discretization of transfer functions, phasor type discretizes mathematical model in complex field. In ref [12], phasor way is described in detail, due to space limitation, there will no longer discuss it.

In order to improve simulation speed, this paper will commence from two simulation types and two kinds of modules that are continuous module and discrete module, and propose three simulation methods, namely continuous method, discrete method and hybrid method.

3.1. Continuous Method Based on Simpowersystems

Continuous method is realized by establishing continuous simulation model and selecting simulation algorithm.

3.1.1. Construction of Continuous Simulation Model

In order to build simulation model, MATLAB provides many model libraries which include various links used in specific field. One of the most basic is Simulink model library which contains unit module that is used for constructing link. These modules are divided into three types: continuous module, discrete module and hybrid module. The output of continuous module is consecutively changing with input, discrete module output is altered at fixed time intervals, and the output of hybrid module is depending on the type of input. Model libraries used for electrical system are Simulink and SimPowerSystems. Moreover, a link sometimes may be separately expressed using continuous module and discrete module which represents the link of discretization.

Continuous method is based on successive simulation model which is built by the non-discrete module in Simulink and the continuous module in SimPowerSystems.

3.1.2. Choice of Simulation Algorithm

The category of simulation model determines selection of simulation algorithm, continuous simulation model uses numerical integration algorithm to solve output. There are many common numerical integration algorithms, euler, trapezoidal and runge-kutta etc. they are developed from the view of solving differential equation, which have rigorous thought and complete system, and their calculation principle is: firstly, differential equations are changed into different iterative formulas, then approximate solution of system is gotten by recalculating coefficients of iterative formulas at each step [13].

Suppose that a continuous system is described using a first-order differential equation, as shown in Equation (1):

$$\begin{cases} \dot{y} = f(t, y), t \in [a, b] \\ y(a) = y_0 \end{cases} \tag{1}$$

Where t is time, y is state vector of system.

The calculation process of numerical integration algorithm is illustrated in Figure 2.

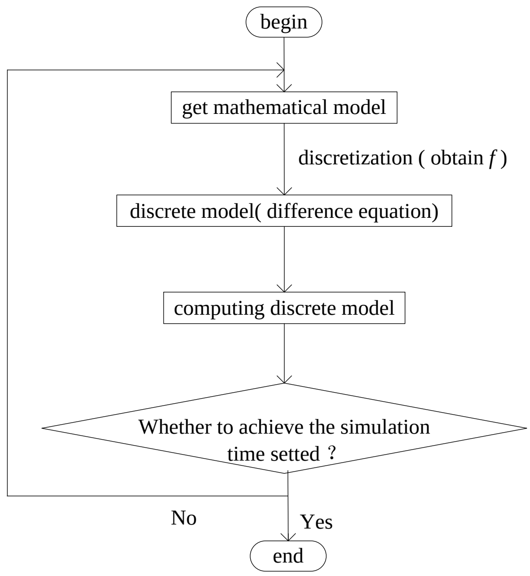


Figure 2. Flowchart of Numerical Integration Algorithm

The algorithms are classified into fixed step and variable step. The fixed step algorithm solves system at equal time interval which can be manually specified. Although we can improve simulation precision by reducing step, simulation speed will become very slow due to increase the number of step computed. Increasing step can accelerate simulation speed, but excessive step may lead to error out of control, resulting in diverging results.

The variable step algorithm solves system at different time interval. According to error value setted, the step size keeps constant within the range of error. Once exceeding the range, the step size will be reduced. It makes reduce the step size to improve simulation accuracy when the state of system changes quickly, and increase the step size to avoid unnecessary calculations when that of system changes slowly. Moreover, the variable step algorithm comes with zero-crossing detection to improve simulation precision. When using continuous method to simulate system, the variable step algorithm can bring better simulation effect, the reason is that the state of continuous system is consecutively changing with time.

3.2. Discrete Method Based on Simpowersystems

Discrete method is realized by discretizing transfer function, establishing discrete simulation model, and selecting simulation algorithm.

3.2.1. Discretization Of Transfer Function: Discretization of differential equation is implemented by calculating at each integration step. However, discretization of transfer function is realized by Tustin substitution method. So-called Tustin, is changing the transfer function G (s) of continuous system into the transfer function G (z) of discrete system using a replacement formula, and then solves the inverse transformation of G(z) to get difference equation.

3.2.2. Construction of Discrete Simulation Model

Discrete method is based on straggling simulation model which is built by non-continuous module in Simulink and discrete module in SimPowerSystems.

Structure of discrete module is derived from comparison with successive module, namely continuous links are changed to discrete taches. Although discrete modules in SimPowerSystems have correction links, discrete method has higher stability shown from following analysis. Therefore, the influence of removing correction links is negligible for continuous system simulation, which can reduce computational complexity. In order to accelerate simulation speed, the discrete modules should delete correction links.

3.2.3. Choice of Discrete Algorithm

Discrete simulation model utilizes discrete algorithm to solve output. Discrete algorithm is used for system without continuous states. It solves difference equation at a fixed time. The calculation process of discrete algorithm is illustrated in Figure 3.

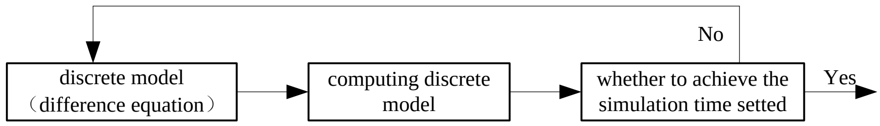


Figure 3. The Calculation Process of Discrete Algorithm

Discrete algorithms are classified into fixed step and variable step as well. The variable step algorithm can avoid unnecessary calculation when it is used for discrete simulation models with different sampling time. The fixed step algorithm is applied to calculate the systems which have not continuous states or not states. It is noteworthy that discrete approach does not need to execute zero-crossing detection, the reason is that discrete algorithm can well match update time of a discrete signal.

3.3. Hybrid Method Based On Simpowersystems

As applicability of continuous modules and discrete modules has not be studied, their are free to build simulation model, leading to producing hybrid method. The construction of hybrid simulation model is combined with continuous modules and discrete modules. Continuous link replaced by continuous module is discretized using numerical integration algorithm. Discrete module represents the link of discretization, so discrete link replaced by discrete module is just calculating difference equation. The principle of hybrid way is illustrated in Figure 4.

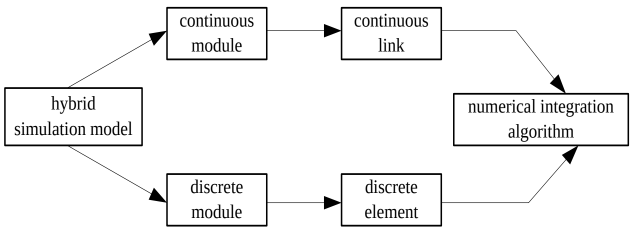


Figure 4. Schematic of Hybrid Simulation

This section detailed analyzed implementation way of three simulation approaches. The differences and relations are shown in Table 1.

Table 1. Comparison Implementation Way

simulation approach	continuous method	discrete method	hybrid method
discretization way	calculation at each integration step	Tustin substitution method	continuous module is discretized by calculation at each integration step. discrete module represents the link of discretization and is just calculating difference equation.
simulation model	continuous simulation model	discrete simulation model	hybrid simulation model

simulation algorithm	numerical integration algorithm	discrete algorithm	numerical integration algorithm
simulation system	continuous system		

4. Comparison of Simulation Effect

4.1. Computing Stability

Continuous method has low computational stability as numerical integration algorithm exists the problem of stability, Although the system is stable, simulation results are still divergent without appropriate algorithm or integral step[14]. The range of appropriate value of integral step is diverse for different algorithm, the integral step size of forward euler algorithm must be less than two times of system time constant, the stability region of runge-kutta algorithm is slightly increasing with rising of the order. It is noteworthy that the integral step of trapezoidal algorithm does not limit, while oversize step can reduce simulation precision.

Suppose that the formula of trapezoidal algorithm can be described as shown in Equation (2):

$$y_{n+1} = y_n + \frac{T}{2}\left[f\left(t_n, y_n\right) + f\left(t_{n+1}, y_{n+1}\right)\right] \qquad (2)$$

Take Laplace transform on Equation (2). Set $z = e^{sT}$ and substitute it into Equation (2), then we get Tustin transformation formula shown in Equation (3):

$$s = \frac{2}{T}\frac{z-1}{z+1} \qquad (3)$$

Set $s = \sigma + \mathrm{j}\omega$ and substitute it into Equation (3), then solve the square of $|z|$ in Equation (4):

$$|z|^2 = \frac{\left(1+\frac{\sigma T}{2}\right)^2 + \left(\frac{\omega T}{2}\right)^2}{\left(1-\frac{\sigma T}{2}\right)^2 + \left(\frac{\omega T}{2}\right)^2} \qquad (4)$$

From Equation (4), if $\sigma < 0$, then $|z|$<1. If σ=0, then $|z|$=1. if $\sigma > 0$, then $|z|$>1. It is obvious that left half plane of s is mapped in unit circle using Tustin transformation formula.

Discrete method discretizes mathematical model of continuous system using Tustin substitution formula. From Eqs. (2), (3), we can see that the formula is directly derived from trapezoidal integral equation. It shows that if the original G(s) is stable, then G (z) is steady as well.

Hybrid method discretizes continuous links replaced by continuous modules based on numerical integration algorithm. Therefore, it is still obtaining divergent results without appropriate algorithm or integral step.

4.2. Simulation Precision

Discrete method has low simualtion precision, one of the reasons is that Tustin formula is directly derived from the equation of trapezoidal integral of which the precision is not high in all numerical integral algorithms. There are many algorithms with high precision, such as runge-kutta, adams etc. The second reason is that discrete approach deals with nonlinear component using piecewise linearization that introduces error.

For linear system, the precision of discrete method is the same with that of continuous method based on trapezoidal integral algorithm. However, for nonlinear system, the simulation accuracy of discrete method is lower than that of continuous method using trapezoidal integral algorithm. Moreover, continuous method has error control and zero-crossing detection. These show that continuous method has higher simulation accuracy.

As for hybrid method, its simulation precision is lower than continuous approach. Although it should be higher than discrete way in theory, the numerical integral algorithms cannot calculate difference equation at a fixed time, leading to the conclusion that the precision of hybrid method is not always higher than that of discrete approach.

4.3. Simulation Speed

Continuous method has slower simulation speed for complex system as it solves differential equation using numerical integration algorithm. From Fig.2, we can see that recursive difference equations should be built firstly to calculate the output of system. However, the difference equations must be rebuilt at each step, as its coefficients, namely derivative, are not same at different time. The calculation amount of continuous method is too large as it is more difficult to obtain derivative, which leads to slower simulation speed. Moreover, continuous method has error control and zero-crossing detection,which make slow down as well.

As for discrete method, it changes transfer function into difference equation that can be directly calculated by computer. Obviously, the change is easy. From Fig.3, we can see that the computer only needs to solve the difference equation to get the output at each step. There are leading to the conclusion that discrete method has faster simulation speed.

The calculation amount of hybrid method is between the continuous method and discrete approach. Thus the speed is in between as well.

This section detailed analyzed simulation performance of three simulation approaches. The comparison results are shown in Table 2.

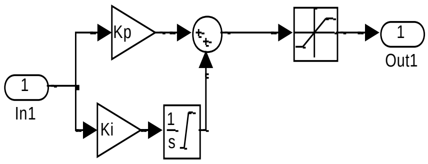
Table 2. Performance Comparison of Three Simulation Methods

simulation approach	continuous method	discrete method	hybrid method
computational stability	determined by the simulation algorithm and integration step	stabilization	determined by the simulation algorithm and integration step
simulation precision	relatively high. it is codetermined by algorithm, error control, and zero-crossing detection.	lower than continuous method. it is determined by sampling time.	lower than continuous method. it is codetermined by algorithm, error control, and zero-crossing detection.
simulation speed	the speed is very slower for complex system as it is more difficult to obtain derivative that requires to recalculate at each integration step.	the speed is much faster than continuous way. it is determined by the sampling time, 5us can meet precision requirement generally.	the speed is in between. it is determined by the number of discrete modules in simulation model.

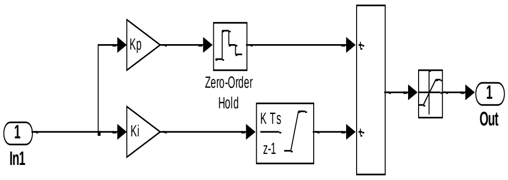
5. Case Study

A case in ref [15] is used to evaluate and compare the three simulation methods discussed in previous sections. The condition required is: on the basis of increasing capacitor voltage and local balance control, changing inductive load into capacitive load at 0.55s. In order to better compare simulation effect, this paper only analyzes the grid current of A phase.

The simulation model is continuous in ref [15]. In order to compare the three methods, this paper builds the discrete simulation model and the hybrid simulation model. The differences in simulation models are shown in Figure 5 and Figure 6.

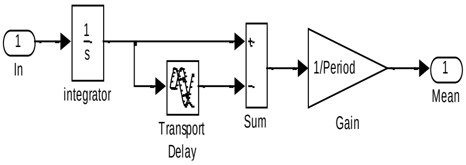


(a) PI module in continuous simulation model

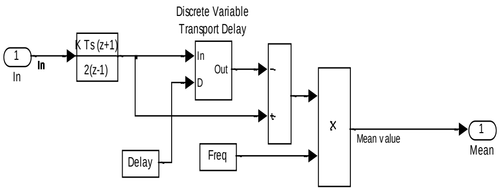


(b) PI module in discrete simulation model

Figure 5. PI Module in Different Simulation Models



(a) Mean value module in continuous simulation model



(b) Mean value module in discrete simulation model

Figure 6. Mean Value Module In Different Simulation Models

In addition, the discrete simulation model utilizes discrete 3-phase PLL module without correction links. The hybrid simulation model is obtained by changing 3-phase PLL in the continuous simulation model into discrete 3-phase PLL without correction links.

The parameters of all modules are the default values in ref [15], and the simulation parameters are shown in Table 3.

Table 3. Simulation Parameters

simulation method	continuous method	discrete method	hybrid method
algorithm	ode23s	variable-step discrete	ode23s
relative tolerance	1e-3		1e-3
sampling time		5e-6s	5e-6s
simultaion interval	0-1s		

It should be noted that other simulation parameters are default values in MATLAB.

The waveforms of the grid current of A phase are shown in Figure 7, 8 is the local enlargement of Figure 7, and Figure 9 is the simulation time of cascaded H-bridge SVG.

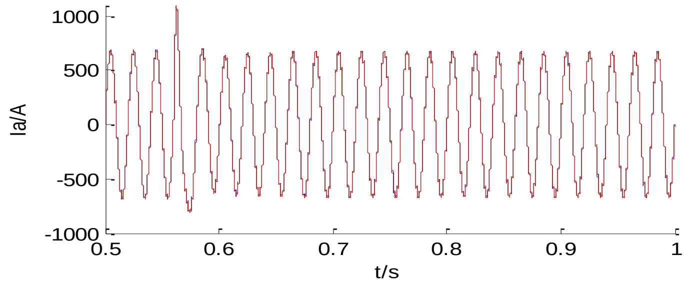


Figure 7. Ia Waveforms in Three Simulation Methods

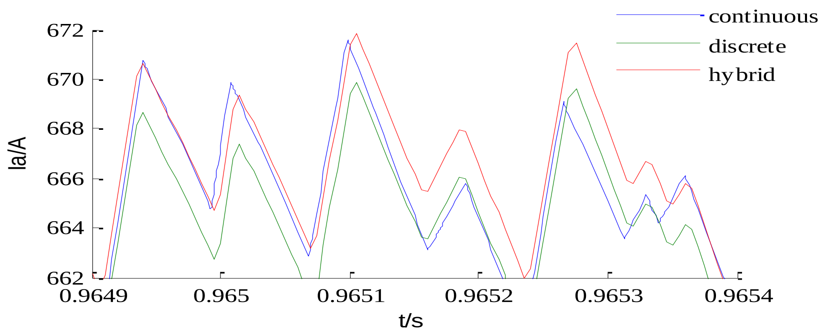


Figure 8. Local Enlargement of Ia Waveforms

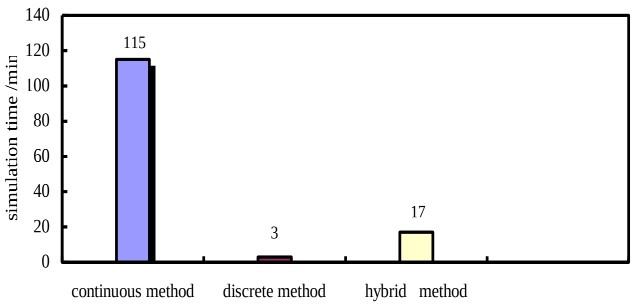


Figure 9. Simulation Time in Three Simulation Methods

The grid current of A phase is represented by Ia. From Fig.7, we can see that Ia waveforms are the same as ref [15] and almost entirely overlap in three simulation methods. These show that the three simulation methods proposed are correct. Moreover, the results will be divergent if continuous method chooses ode23t or ode23tb, it shows that computational stability of continuous method is not high. From Fig.8, when sampling time is 5us, discrete method has higher precision that can meet requirement of the simulation system. In particular, we can see that discrete method can obviously shorten simulation time from Fig.9.

The results coincide with the theory mentioned above, showing that discrete method proposed can accelerate the speed obviously.

6. Conclusions

A diagram of system simulation process is proposed firstly as a theoretical basis, which leads to the conclusion that the simulation in SimPowerSystems is only aimed at continuous system.

Model libraries used for the simulation of electrical system are Simulink and SimPowerSystems, of which the modules are studied. It should be noted that a link sometimes may be separately expressed using continuous module and discrete module which represents the link of discretization.

In order to improve simulation speed, this paper commences from two simulation types and two kinds of modules that are continuous module and discrete module, and proposes three simulation methods, namely continuous method, discrete method and hybrid method. Their implementation approaches are studied and performances are discussed in terms of computing stability, simulation precision, simulation speed as well.

The analysis of theory and the case shows that discrete method not only has higher computing stability and not low precision, but also can accelerate the speed obviously. It means that the problem for complex electrical system of slow simulation speed is radically solved.

Acknowledgements

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