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A New Spice Model and Optimization Method of an Arbitrary Periodical Waveform Generator

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Abstract: The construction and corresponding optimization method of a new SPICE model for generating arbitrary periodical waveform are presented. Unlike the model based on rectangular wave source, the new model is composed of periodical oblique wave sources. The periodical oblique wave source is built by using fundamental pulse sources connected in series with matched parameters. A nonuniform sampling algorithm based on the secondorder derivative of sampling points is proposed to optimise the model. The availability of the model and the effect of the model optimization are shown from circuit simulations.

Key words: SPICE, arbitrary waveform, biomedical circuits, nonuniform sampling

INTRODUCTION

Simulation is of great importance in modern circuit designs. Since a SPICE circuit simulator has become an industry standard(Vladimirescu, 1999), SPICE model for circuit elements (e.g., Complementary Metaloxide Semi-conductor (CMOS) (Panagopoulos *et al*., 2013) is indispensible. In such designs as biomedical circuit design, to obtain simulation results that agree with actual tests as far as possible, a general arbitrary waveform generator to output waveform of odd and irregular shapes as real signal (e.g., Electrocardiograph (ECG) (Yoo *et al*., 2009) or Electroencephalogram (EEG) (Filipe *et al*., 2011) is often required.

It seems that the simplest solution to the above problem is using the Piecewise Linear Model (PLM) (Norbiato dos Santos and Diniz, 2011). Although PLM can produce complex waveform but the waveform generated by PLM is limited in duration, so it is not suitable for producing periodical waveform, which is unlimited in duration.

Blazek *et al*. (1975) presented a function generator for biomedical applications. The model of the generator is based on rectangular waveform that is acted as the basic element for approximating the target waveform. Since then, several solutions to the problem reported (Josko and Rak, 2005; Sun *et al*., 2008; Deniau *et al*., 2011) are all derived from Blazek's model. For convenience, we call the model based on the rectangular waveform rectangular-wave-based model (RWBM). RWBM will become less accurate when the number of sampling points used to construct the generator becomes smaller. To get a smooth waveform, low pass filters or other measures (e.g., Quasi-PID Controllers) are usually employed. However, these measures can not increase simulation accuracy fundamentally compared with PLM.

Generators reported above belong to analog generators. With the development of digital technology, complex waveform generators tend to be implemented by using digital circuit elements. For example, Qasim and Abbasi (2007) proposed a FPGA-Based approtch for digital waveform generation. Generally the digital-based generator is more flexible than the analog generators in generating complex waveform, because its output can be easily controlled by modifying embedded program. However, from the perspective of circuit simulation, such generators are hard to be implemented by SPICE, so they can not be used directly in popular circuit simulation sofewares (e.g., Dxp, TINA, etc.,).

This study proposed a new SPICE model of arbitrary periodical waveform generator for circuit simulation in which a complex periodical waveform is required. The new model is based on the periodical oblique wave source. For convenience, this model was called Oblique Wave-based Model (OWBM).

First the construction of OWBM is described, then a nonuniform sampling algorithm based on the secondorder derivative of sampling points for optimizing the model is presented and results follows before discussion and conclusion.

MATERIALS AND METHODS

Construction of RWBM: The construction of traditional RWBM is shown in Fig. 1 (The figure just shows the first period of waveform). The target periodical waveform is

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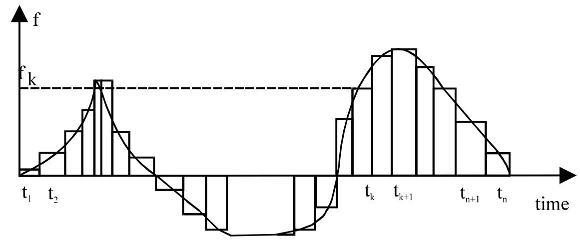

Fig. 1: Construction of RWBM

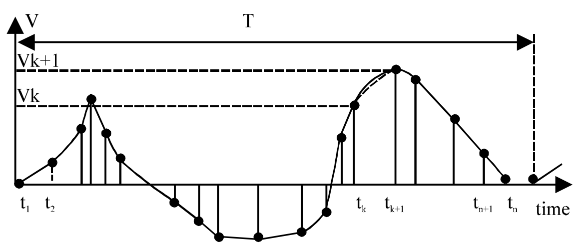

Fig. 2: Construction of OWBM

imagined as the summation of multiple rectangular wave. During the time from t_k to t_{k+1}, the target waveform is approximated by a constant. It is obvious that the accuracy of this model will decrease when the target waveform in $[t_k, t_{k+1}]$ is abrupt.

Construction of OWBM: Unlike traditional RWBM, OWBM uses an oblique line rather than a constant to approximating the target waveform in the interval $[t_k, t_{k+1}]$, which can increase model accuracy obviously. Fig. 2 illustrates the construction of OWBM. The target waveform can be imagined to be consisting of a summation of periodic oblique wave voltage sources (basic elements of OWBM) in stead of retangular-wave voltage souces, the basic elements of RWBM.

Use lv_k (k = 1, 2, ..., n-1) to represent the k'th basic element of OWBM, v_k to represent the sampling value of the target waveform at the moment t_k and T o represent the period of the target waveform, then the output of OWBM is:

$$v(t) = \sum_{k=1}^{n} lv_k = \sum_{k=1}^{n} lv(t_k, v_k, t_{k+1}, v_{k+1}, T) \quad , t_{n+1} = T - t_1, v_{n+1} = v_1 \tag{1}$$

Here, the oblique wave voltage source lv_k is a linear source determined by two sampling points ((t_k, v_k) and (t_{k+1}, v_{k+1}) of the target waveform and the period T. Fig. 3 is the circuit model of OWBM.

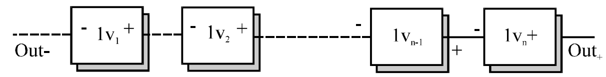

Fig. 3: Circuit model of OWBM

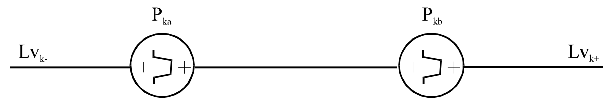

Fig. 4: Construction of periodic oblique wave source (lvk, k = 1, 2, ..., n-1)

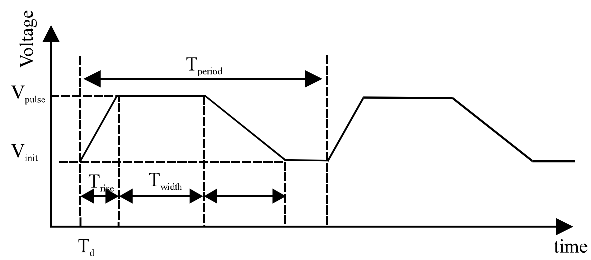

Fig. 5: Parameters and waveform of a pulse voltage source

In SPICE element library, the rectangular waveform can be generated by a fundamental pulse source, while the periodical oblique source can not be generated by any fundamental element directly. To address the problem, we use two fundamental pulse source to form the periodical oblique source lv_k, as shown in Fig. 4.

Here, lv_k (k = 1, 2, ...n-1) is used to approximate target waveform in $[t_k, t_{k+1}]$. P_{ka} and P_{kb} are two pulse voltage sources. The parameters to determine a pulse voltage source is shown in Fig. 5.

Use superscripts ka and kb to denote the parameters of the two pulse sources P_{ka} and P_{kb} respectively, then the two sources should match each other on parameters as follows:

$$\begin{cases} V_{init}^{ka} = v_k, V_{pulse}^{ka} = v_{k+1} \\ T_d^{ka} = t_k, T_{rise}^{ka} = t_{k+1} - t_k, T_{width}^{ka} = T - T_{rise}^{ka} \\ , T_{fall}^{ka} = 0, T_{period}^{ka} = T \end{cases} \tag{2}$$

$$\begin{cases} V_{init}^{kb} = 0, V_{pulse}^{kb} = -V_{k+1} \\ T_d^{kb} = t_{k+1}, T_{rise}^{kb} = T_{fall}^{kb} = 0 \\ T_{width}^{kb} = T - T_{rise}^{ka}, T_{period}^{kb} = T \end{cases} \tag{3}$$

As an example, supose t_k = 0.2, v_k = 1, t_{k+1} = 0.5, v_{k+1} = 2.5, T = 3, according to Eq.-, the waveform of P_{ka} and P_{kb} and lv_k can be drawn, as shown in Fig. 6.

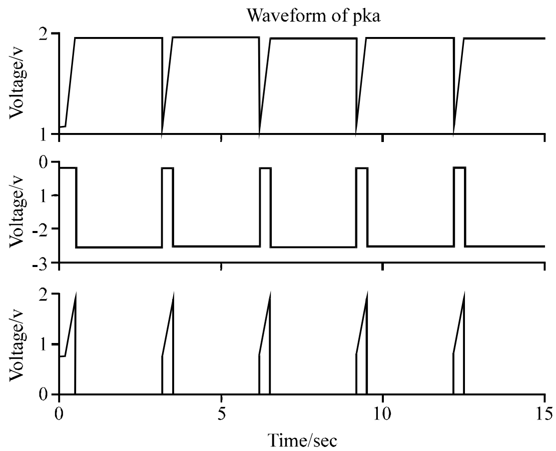

Fig. 6: Periodical oblique waveform of pka, pkb, lvk when tk = 0.2, vk = 1, tk+1 = 0.5, vk+1 = 2.5, T = 3

Figure 6 shows that, the output voltage of lv_k during the first period is not the same as the output voltage during subsequent periods, because during the time from 0 to t_k, the voltage is v_k, not 0 V as the others, which is a character of OWBM rather than a special case only to this example. The output voltage during first period of OWBM may exceed the input voltage range of the circuit to be simulated, so measures should be taken to limit the range. A effective measure is using a limiter in parallel with the generator as shown in Fig. 7.

The output range of the limiter is as follows:

$$V_{out^1} = V_{out^1_+} - V_{out^1_-}$$
$$= \begin{cases} V_{bias1} + V_{on}, V_{out} \geq V_{bias1} + V_{on} \\ V_{out}, -V_{bias2} - V_{on} < V_{out} < V_{bias1} + V_{on} \\ -V_{bias2} - V_{on}, V_{out} \leq -V_{bias2} - V_{on} \end{cases}$$
$$V_{out} = V_{out_+} - V_{out_-}$$

where, V_{on} is the voltage drop in forward conduction of the diodes (for silicon diodes, V_{on} is about 0.6~0.8V, for germanium diodes, V_{on} is about 0.1~0.3V).

Model optimization: According to section 2.2, if the n sampling points $\{(t_k, v_k) \mid k = 1, 2, \ldots, n\}$ on one period of the target waveform are given, then OWBM can be implemented. The more the sampling points, the more the model become accurate and the more the simulation takes time and memory. The aim of model optimization is to construct OWBM with as less points as possible on the premise of model accuracy.

Usually the original n sampling points of target waveform are collected by the same sampling interval (T_s, uniform sampling). According to Shannon's sampling theorem, the sampling frequency ($F_s = 1/T_s$) for a certain signal should be at least twice the maximum frequency (F_{max}) of the signal. Limited by the theorem, the equal-interval sampling leads to data redundancy under many circumstances. For example, for some signal such as ECG, EEG, etc, usually the frequency components spread in a very wide range, so uniform sampling will leads to much more serious data redundancy and the decrease of the simulation speed. Therefore, if the number of basic elements is reduced as far as possible, the model will be optimized, which will help to decrease memory and computational cost effectively. In such contexts, nonuniform sampling (Bose and Sircar, 1998; Kerestecioglu and Tokat, 2003; Feizi *et al*., 2012) naturally is preferable to uniform sampling. Although, Maymon and Oppenheim (2011) has proposed the implementation of a nonuniform sampling strategy, which was based on the estimation of Autoregressive Power Spectral Density (AR-PSD) for each divided block of original data, however, it involves complex computation. Furthermore, how the original data is divided to several blocks is still a problem.

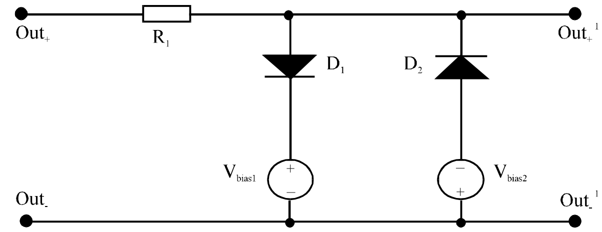

Fig. 7: Limiter circuit to limit the output volatage range of OWBM

From the perspective of linear interpolation (this is one of methods used in circuit simulations), if the target waveform in a local time-domain is a strait line (the secondorder derivative is zero), then only the two ends need to be sampled, which means a relatively low frequency can be used here; if the target waveform in a time-domain is a wave (a local extremum arises, the secondorder derivative is also a local extremum), to capture the change near the extremum, the relatively high sampling frequency should be used.

Based on the above facts, a practical nonuniform sampling algorithm is proposed, which bases on the secondorder derivative of every uniform sampling point of the target waveform. The strategy is described as follows:

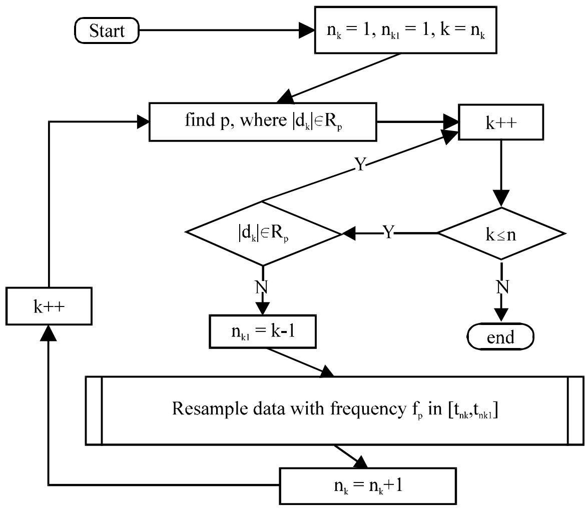

Fig. 8: Flow chart of nonuniform sampling

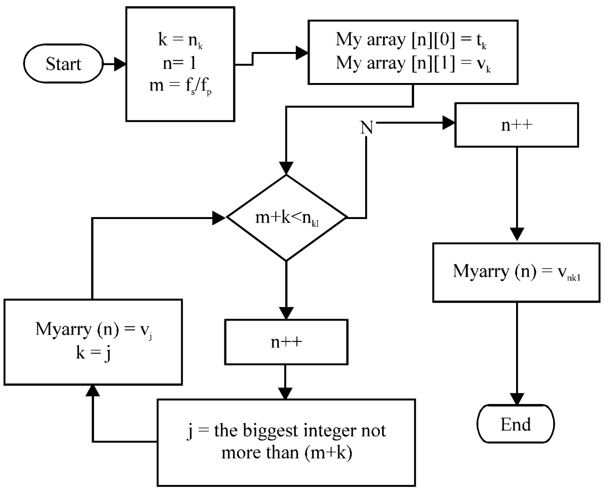

Fig. 9: Flow chart of resampling subroutine (myarray is an 2-D array used to store the value of resampling points)

- At first, calculate secondorder derivatives of each original sampling point (t_k, v_k) by using equation as follows:

$$d_k = v_{k+2}+v_{k-2}-2v_k,\ k = 1, 4,\cdots,n \tag{5}$$

- Here, $v_0 = v_n$, $v_{-1} = v_1$, $v_{n+1} = v_1$, $v_{n+2} = v_2$

Assume that the range of the absolute value of the secondorder derivatives $\{d_2(k)|k = 2, 3, \ldots, n\text{-}1\}$ is $[s_{min}, s_{max}]$, divide the interval equally into N (N = 2) subintervals: $[s_0, s_1)$, $[s_1, s_2)$ … $[s_{N-1}, s_N]$ ($s_0 = s_{min}$, $s_N = s_{max}$. To facilitate the presentation, use R_1, R_2 … R_N respectively to represent these N subintervals). Take a suitable sampling frequency f_{up} (= $2F_{max}$, usually take $f_N = F_s$, the original equivalent interval sampling frequency) and a frequency f_{down} less than f_{up}, then divide $[f_l, f_u]$ into N-1 sampling frequency subintervals $[f_1, f_2]$, $[f_2, f_3]$, …, $[f_{N-1}, f_N]$ ($f_1 = f_{down}$, $f_N = f_{up}$) with the same length.

Divide the first period of the target waveform to several time-domains: $[t_1, t_2)$, $[t_2, t_3)$, ...$[t_k, t_{k+1})$ …$[t_M, t_{M+1}]$ (represent them by T_1, T_2, … T_M respectively), which meet the following conditions:

- The absolute values of secondorder derivatives for all sampling points that belongs to a certain time-domain T_m (1 = m = M), fall into a certain single interval R_p (1 = p = N)
- Figure 8 shows the nonuniform sampling process
- The division of time-domains is finished in resampling. The resampling process in Fig. 8 is a subroutine, its realization is shown in Fig. 9

When f_{down} and f_{up} are given, N is the only parameter that affects the precision of the nonuniform sampling algorithm. It is obviously that with the increase of N value, the precision will be improved, while the number of sampling points will become larger. To get the appropriate N value, define the following error equation:

$$\mathrm{Err}(n) = \sqrt{\frac{\sum_{k=1}^{L}(z_k - y_k)^2}{L}} \tag{6}$$

where Z_k, is the value evaluated by interpolation based on the nunuiform samples when N = n corresponding to the k'th samples (y_k) of the original uniform sampling. Take model error constant δ>0, with the increase of n, when the following condition Eq. 6 is satisfied, chose N = n:

$$\frac{\mathrm{Err}(n) - \mathrm{Err}(n+1)}{\mathrm{Err}(n)} \le \delta$$

As an example, Fig. 10 shows the comparison between data by uniform sampling and data by the proposed nonuniform sampling. The ratio of the number of sampling points between uniform sampling and nonuniform sampling is 4.175, which means the number of circuit elements used by the nonuniform sampling will be much less than that used by the nonuniform sampling.

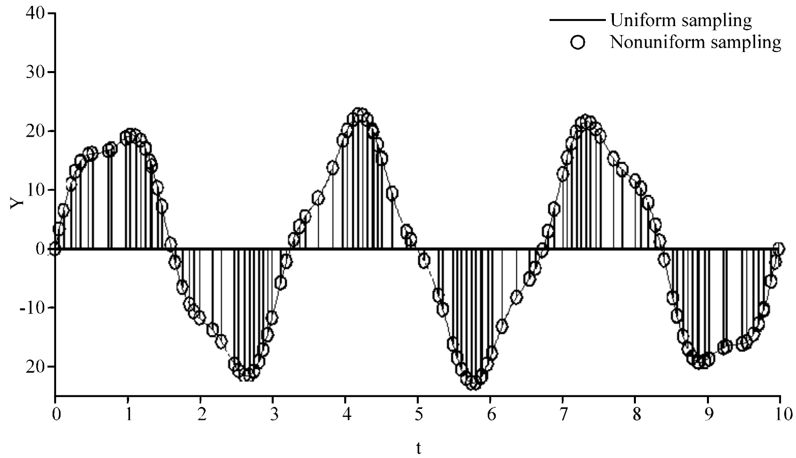

Fig. 10: Comparison of the proposed nonuniform sampling with sampling with equal sampling interval(ratio of number of points between uniform sampling and nonuniform sampling is 4.175)

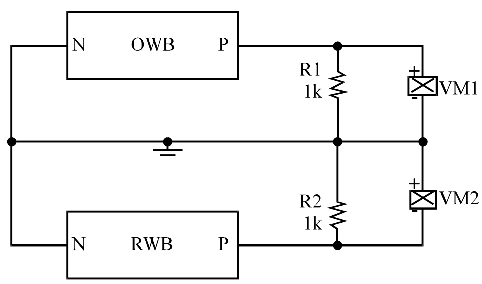

Fig. 11: Simulation circuit for comparing OWBM with RWBM

Table 1: Effectiveness of model optimization for OWBM on different target waveform (model error δ = 1.2 e-2, simulation duration is 60 s)

	ECG		EEG		SINE	
	No. of sampling points Z	Total simulation time sec	No. of sampling points Z	Total simulation time sec	No. of sampling points Z	Total simulation time sec
Before optimization	300	15	420	21	70	8
After optimization	98	5	213	11	22	31

RESULTS

According the construction and optimization methods discussed above, A program has been developed to create the SPICE model file automatically, which can be used directly in an EDA software (e.g. PSPICE, TINA, PROTEL, MULTISIM etc.). Here TINA was chosen as our circuit simulation environment, because it is very easy to use and distinctive in waveform plotting. So long as a model file with the extension ".cir" that describe the SPICE model is in hand, a circuit module of the complex-waveform can be created very easily by "new macro wizard" in TINA. Fig. 11 is the schematic for simulating the proposed OWBM and the RWBM. "VM1" and "VM2" are virtual voltage meters, with which the output voltage can be displayed in a virtual oscilloscope or drawn on a chart.

Figure 12 shows the simulation results for different target waveforms. It is obvious that waveform generated by RWBM is more smooth and accurate than that generated by OWBM. OWBM can generate all kinds of periodical waveform(ECG, EEG, SINE, etc) with the same accuracy as PLW.

Figure 13 gives the compare result of three models in total time consumed in the whole simulation process (including the time it takes to generate the required simulation duration of the target waveform, model compilation time, simulation calculation time) for outputing ECG signal as shown in Fig. 12.

Figure 13, it is seen that with the increase of the simulation duration, the total time consumed by PLM increase more rapidly than OWBM and RWBM. This is because, for PLM, more sample points are required for longer simulation duration to construct the model, while

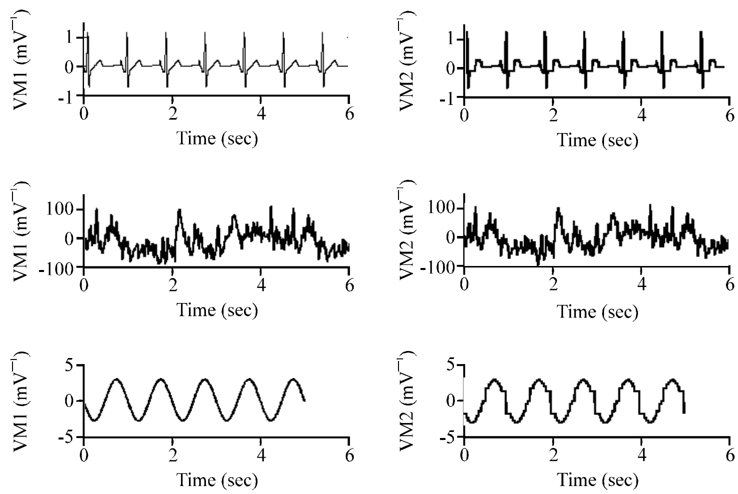

Fig. 12: Simulation results of different target waveforms

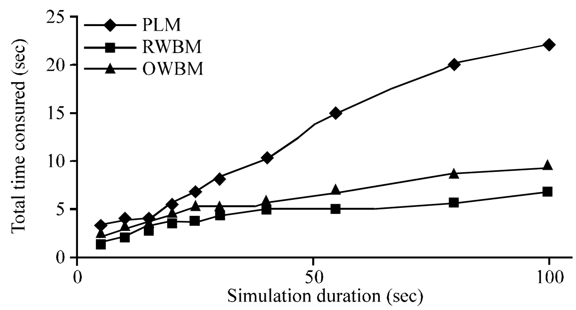

Fig. 13: Comparison of three models in total time consumed in simulation

RWBM and OWBM need only one period of sampling points of the target periodical waveform.

Table 1 shows the effectiveness of model optimization when using OWBM to generate three different waveform. It is seen that at the same model error, the proposed optimization algorithm can decrease the total simulation time to different degrees, which is determined by the shape of the target waveform.

DISCUSSION

It is a usual step that using a sine source as the input of circuits to be simulated. However, for the circuit that is designed to amplify complex periodical or approximatively periodical signal such as ECG, EEG, etc., a complex periodical waveform generator may be more preferable for circuit simulation, because the effectiveness of the circuit can be seen visually from the output of the circuit.

OWBM is a new SPICE model for generating genuine periodical waveform. Results indicate the availability and wide versatility of the model. When it is difficult to decompose the target waveform accurately into summation of a limited number of sine wave by using Fourier transform, OWBM may be more suitable.

Compared with traditional RWBM, OWBM is more accurate, it is actually the same accurate as PLM, while PLM can not generate genuine periodical waveform.

It should be noted that more basic elements for OWBM are required compared with RWBM, so more total time is used in simulation. However, the shortcoming can be overcome to some extend by using the proposed optimization algorithm based on nonuniform sampling.

CONCLUSION

OWBM of generating arbitrary periodical waveform for circuit simulation has been proposed together with the corresponding optimization method based on a nonuniform algorithm. The SPICE statement of the model can be automatically produced by a computer program. Simulation results show that the accuracy of the new model is higher than RWBM and the total time consumed by using OWBM is less than that by using PLM when the required simulation duration comes to a certain value. By using the proposed optimization algorithm, the shortcoming of OWBM can be overcome to some extend. So OWBM is a more suitable SPICE model for generating complex periodical waveform when relatively long simulation duration of the target waveform is required.

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