Review of Real-time Simulation of Power Electronics

Fei Li, Yichao Wang, Fan Wu, Yao Huang, Yang Liu, Xing Zhang, and Mingyao Ma

Abstract—**Real-time simulation of power electronics has been recognized by the industry as an effective tool for developing power electronic devices and systems. Since there is no energy transfer during the course of the usage, real-time simulation has a lot of advantages in the process of development and experimentation. From the perspective of real-time simulation, this paper focuses on the main problems in modeling accuracy, system bandwidth and stability, limitations on communication interface and energy interface, and the cost of platform construction. Finally, we provide further research directions.**

Index Terms—**Hardware-in-the-loop simulation, modeling and simulation of power electronics, correction method, power interface algorithm, numerical method.**

I. Introduction

THE vigorous development of new energy power generation technology has alleviated the pressure of energy security and environmental protection. But the large-scale application of power electronic devices, which features the intermittency and unschedulability, has greatly affected the stable operation of the traditional power system. It is foreseeable that in the future, with the increase of rechargeable electric vehicles and distributed energy sources [1], the impact caused by power electronic devices on the power grid will become more and more conspicuous. At the same time, power electronic devices, as nonlinear time-varying systems, face many difficulties in the design and analysis, which require a lot of experimental researches and verification. The impact caused by the interaction between electromagnetic transient and electromechanical transient on the traditional power grid is more complicated.

Further development of the new energy industry has put forward a lot of requirements especially on optimal design of related devices [2] and stable operation of the increasingly complex control structures [3]. And real-time simulation technology, due to its extremely high security and repeatability, is a significant tool for solving these problems. Applying this technology to power electronic systems can facilitate designing controllers with good comprehensive performance, studying and developing new algorithms as well as new devices. Also, it can make experiments more secure, and in the meantime improve research and development (R&D) quality, save development costs, and shorten the development cycle [4]. Because of these merits, a large number of commercial simulation devices, auxiliary programs, and open source platforms customized based on different demands have been developed [5], [6]. This paper focuses on the accuracy of the modeling, the bandwidth and stability of the system, the limitation of communication interfaces and power interfaces, the economic efficiency of the platform establishment and other major problems encountered now. Besides, this paper presents a review of the existing researches on real-time simulation of power electronics and provides a reference for further researches.

II. Modeling Technology

The general process of a semi-physical real-time simulation is: building a model on the selected research object; choosing the corresponding simulation algorithm and step size; and establishing a complete simulation platform [7].

So the first step is modeling. The so-called modeling is a mathematical description of the physical phenomenon, while the simulation is the process of numerically solving the model on a computer or other tools [2]. As for device-level and system-level modeling, based on the consideration of computational complexity, some characteristics of devices are often ignored in system-level modeling, making it difficult to reflect the nonlinear characteristics of devices [8]. Reference [9] presents a more complex parameter identification method which can be used to establish models that can reflect their nonlinear characteristics. Reference [10] illustrates a classification of modeling methods that the device-level modeling can be divided into numerical modeling, physical modeling based on the analysis and functional modeling by characterizing device behavior. Reference [11] claims that the modeling can be divided into ideal-switch modeling, switch-function modeling and average modeling, while [8] proposes that modeling is primarily divided into the detail modeling and

Manuscript received: October 28, 2018; accepted: November 11, 2019. Date of CrossCheck: November 11, 2019. Date of online publication: January 23, 2020.

This work was supported by the National Natural Science Foundation of China (No. 51707053), the Anhui Provincial Natural Science Foundation (No. 1808085QE155) and the Fundamental Research Funds for the Central Universities (No. JZ2019HGTB0080).

F. Li (corresponding author), Y. Wang, F. Wu, Y. Huang, Y. Liu, X. Zhang, and M. Ma are with the School of Electrical Engineering and Automation, Hefei University of Technology, Hefei, China, and F. Li, X. Zhang, and M. Ma are also with National and Local Joint Engineering Laboratory for Renewable Energy Access to Grid Technology, Hefei, China (e-mail: sandflylf@qq.com; worldwyc@gmail. com; 476880379@qq. com; 949341675@qq. com; 278550286@qq. com; honglf@ustc.edu.cn; miyama@hfut.edu.cn).

DOI: 10.35833/MPCE.2018.000560

the behavior modeling. And the three types of modeling mentioned in [11] can be regarded as behavior modeling.

In this paper, the classification of the modeling methods is as follows. First, the model is divided into two types: a physical model and a mathematical model. The physical model describes the actual object which exists in the real world, while the mathematical model is the mathematical description of the physical model. The relationship between them is shown in Fig. 1. The methods to build mathematical model are divided into the analytical modeling and the black box modeling.

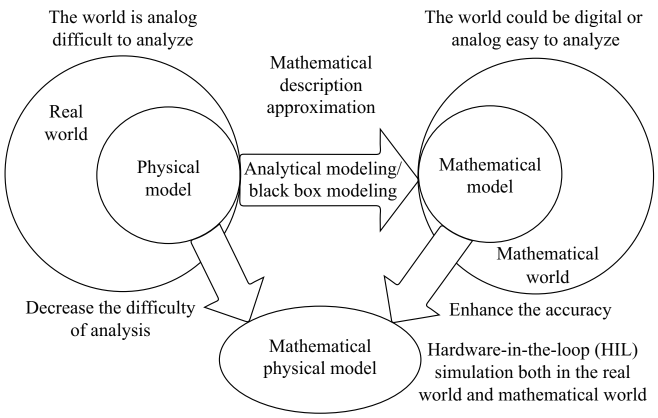

Fig. 1. Relationship between physical model and mathematical model.

Analytical modeling refers to the description of the basic physical laws by analyzing the physical mechanism of the object as well as establishing an appropriate mathematical model to deduce the theoretical relationship. In analytical modeling, there are no empirical and fitting constants. And each parameter has a clear physical meaning. In a power system which contains power electronic devices, the time scale spans microseconds of the switching devices to several seconds or even minutes of the synchronous machine. Detail modeling such as switching device model mentioned in [10], which contains numerous parameters, would make the simulation speed of the model extremely slow. However, many power electronic product suppliers will not provide the parameters. So this method is not appropriate in a real-time simulation. In this situation, we can consider the method of increasing the accuracy of the simulation model by adding some characteristic parameters proposed in [12] and [13], so that the requirements of modeling accuracy and computation capability can be both satisfied. For more complicated device-level modeling, some of the accuracy is sacrificed to increase the calculation speed. And the computation resources are primarily used to focus on output harmonics and other key problems to achieve a balance between the calculation and precision [14]. Many new modeling methods are based on this idea [15]-[17]. For power electronics, the switching function modeling is a better modeling method, but it is difficult to solve due to its segmented characteristics. Therefore, the state space average modeling described in [18] and [19] is used to further solve the problem. The field programmable gate array (FPGA) simulation model used by RT-LAB, a well-known power electronic real-time simulation platform, uses a method based on switching function modeling. The inductance/capacitance equivalent switching modeling designed according to [20] and [21] especially analyzes the application of the switch state model in real-time simulation. References [22] and [23] also make theoretical derivations of the nonlinear models of power electronic devices and propose quasi-linear and multi-model techniques based on analytical modeling, respectively.

The black box modeling refers to the modeling based on the information obtained from the input and output data by the application of identification techniques. For example, we generally use this method to get the key parameters of the system by measuring the input and output, and establish a model similar to the admittance matrix, namely the G-parameter model [24]. In the meantime, black box modeling can also reflect the nonlinear characteristics of the system. When the modeling needs to reflect the nonlinear characteristic relationship in steady state, Wiener and Hammerstein modeling strategies are used in [9]. Corresponding to the multi-model in the analytical modeling, the black box modeling can also establish different models according to different action status to reflect the steady-state and transient nonlinear characteristics of the system. This modeling method is also called polytopic modeling.

When the requirements of accuracy are too strict or some characteristic mechanism is not available, the mathematical model cannot be utilized. Then, the HIL model will be used. This mixed model is also called the mathematical physical model. And these modeling methods are simply listed in Table I to show their characteristics.

TABLE I
SIMPLE COMPARISON OF MODELING METHODS

Model type	Modeling method	Characteristic
Physical model	Null	This type of model exists in the real world
Mathematical model	Analytical modeling	It describes the basic physical laws by analyzing the physical mechanism of the object and reflects the theoretical relationship. It has both linear [11] and nonlinear [22], [23] modeling methods
	Black box modeling	It refers to the modeling based on the information obtained from the input and output data for lacking key parameters. It has both linear [24] and nonlinear [9] modeling methods
Mathematical physical model	HIL	According to the different objects of the simulation, it can be divided into controller HIL (CHIL) and power HIL (PHIL)

Real-time simulation, as an important tool for future grid research and planning, has the bottleneck that there is a contradiction between the accuracy of the modeling and computation capability. And the existing simulation tools cannot meet the increasing demand of the power electronic system simulation. Because the topology of the system model is highly complicated and contains tremendous computation nodes, like a simulation model of distributed generation system in a small-sized or medium-sized city. In addition, the actual PHIL real-time simulation technology based on the mathematical physical model is limited by the power interface characteristics and cannot be popularized. Therefore, how to improve the computational efficiency and realize the accurate real-time simulation of large-scale power electronic systems is still a problem that needs to be considered and solved in the future [19].

III. Sampling and Compensation Strategy

In HIL, there are three kinds of factors resulting in low simulation accuracy. The first one is the low precision of the model itself. The second one is CHIL, when pulse width modulation (PWM) signals of the controller are delivered to the virtual controlled object, it might cause switching delay and multiple switching events. This is influenced by the asynchronous operations between the simulation step size and the action of switching [25]-[27], primarily concentrated on numerical sampling and numerical calculations [19]. The third one is in PHIL, the power interface also causes accuracy problems and stability problems. The accuracy problem [28] is caused by non-ideal power interface and noise perturbation from the real environment and the stability problem can be analyzed by the interface transfer function [29]. The two problems can be solved by the interface algorithms.

A. Sampling Method

The switching frequency of the power electronic device is related to its corresponding control mode. System consisting of power electronic devices has different switching frequencies. However, the real-time simulation can only execute digital step-sized sampling when the switching frequency of the power electronic device is not synchronized. It will lead to a Δt switching delay time between sampling and the actual switching. This phenomenon is shown in Fig. 2. The parameter T_{sw} means the switching time and T_s means the sampling time of its system.

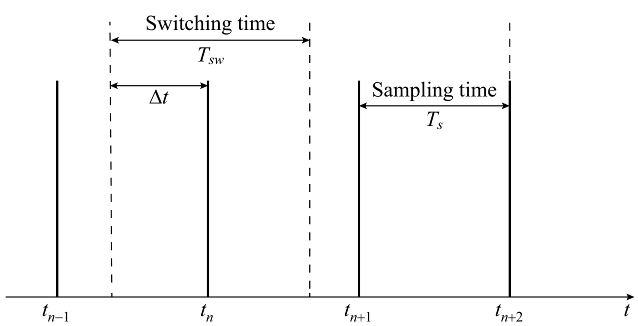

Fig. 2. Switching delay of real-time simulation.

For electromagnetic transient simulations, any switching action may cause numerical oscillation, because the changeover of the energy storage component caused by the switching process will lead to a sudden change of system state. And if the switching action does not coincide with the simulation step, non-characteristic harmonics may appear, causing the distortion of the result. For different circuit topologies, the switching delay phenomenon will generate voltage and current non-characteristic harmonics in different levels [30], and in some cases, may even lead to numerical oscillations.

Multiple switching events refer to the fact that the switch acts multiple times in one step while the simulator has only received one switching action due to excessive switching frequency, which will cause serious errors, greatly reducing the confidence level of the simulation results.

To avoid the phenomenon of switching delay and multiple switching events, it is necessary to pay attention to selecting the appropriate simulation step size and sampling strategy. It is useful to choose a step size less than 5% to 10% of the minimum time constant of the system in the project [31]. The sampling strategy is defined in [19], especially referring to the relationship between the simulation step size of the simulator and the frequency of PWM switching signals generated by the controller in the HIL simulation. There are two sampling strategies: synchronous low-speed sampling and asynchronous oversampling. The former drives the model at the same sampling frequency of the control loop and needs to be executed synchronously with the control algorithm or PWM cycle. But its realization needs a synchronization signal from the controller or a self-synchronization mechanism based on a phase-locked loop [32]. By using low-rate synchronous sampling, the output value is usually provided to the control loop with a delay of at least one sampling step, thus resulting in poor accuracy and stability. And when the switching frequency changes, the phase lock control may become unstable. So the main advantages of the synchronous low-speed sampling strategy are short execution time and low computation cost.

The latter takes a simulation step that is much shorter than the switching period. If the sampling ratio is 10 or higher, the simulation can be approximately regarded as quasi-continuous. The delay of output value provided to the control loop is quite small, significantly improving the accuracy and stability of the real-time simulation.

In general, using a high sampling ratio is a good way to avoid numerical oscillation in discrete models. However, the computation cost of this approach is quite high compared to low-rate simultaneous sampling. Assuming a switching frequency at 20 kHz, the sampling time of the model should be less than 5 μs. However, the sampling method based on the Nyquist-Shannon sampling theorem has a natural disadvantage. That is, the sampling signal is not fully involved in the signal reconstruction process, causing bandwidth waste. To solve this problem, there is a new algorithm called compressed sensing which processes the sampled signal according to the sparse theory. The data obtained during the sampling can be completely used in signal restoration [33]. But the specific application of this method still needs further research.

B. Correction Method

The high switching frequency will cause small sampling step size, raising higher requirements on the hardware of the simulation system. Applying the correction compensation method can lower the requirements [30]. At present, researches which focus on the correction method taking efficiency and precision into account can be classified into three categories: interpolation method, correction method and averaging method [27], [30], [34]-[41].

1) Double Interpolation Method (DIM)

Figure 3 shows the principle of the DIM [34], [35]. The switching event occurs at time t_e. But it is only sampled by the system at the specified sampling time. Therefore, the algorithm is implemented by the following steps: obtain the X_e by linear interpolation of the two sampling results X_1 and X_2, then get X_{e+T_s} by solving X_e with the original simulation step T_s. Finally, X_2' can be obtained by linear interpolation of X_e and X_{e+T_s}.

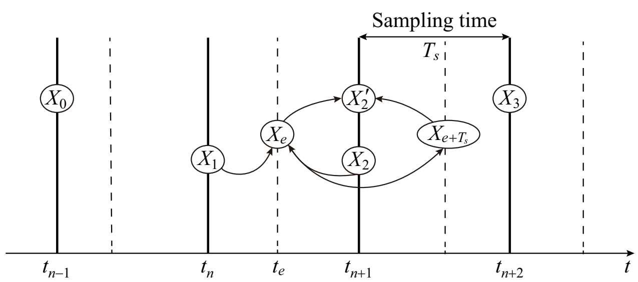

Fig. 3. Principle diagram of DIM.

The DIM is implemented by using double interpolation calculations and two normal calculations. The simulation results are quite accurate but the simulation requires a large amount of calculation, which drags down the simulation speed of the system. If multiple switching states occur within one step, it is necessary to use the DIM to solve the value many times, which will affect the real-time performance of the simulation.

2) Interpolation Extrapolation Method (IEM)

Similar to the DIM, the principle of the IEM is shown in [36], [37]. After getting X_{e+T_s} by solving X_e with the original simulation step T_s, the IEM calculates the next step state X_3' by an extrapolation process.

Because an interpolation calculation is omitted, the calculation amount and the accuracy of the simulation results are reduced.

3) Interpolation Variable Time Step Method (IVTS)

After obtaining X_e by the interpolation, the IVTS changes the simulation step to $T_s+\Delta t$ in order to directly solve X_3. The IVTS reduces once interpolation calculation based on the IEM. However, changes of the calculation step may lead to changes in the state matrix and require additional computation need. The principle is shown in [38]. Based on the algorithms above, [39] puts forward a self-correcting interpolation compensation algorithm at switching time, which only needs one interpolation calculation and parameter adjustment. Under the condition of maintaining stability, the amount of calculations will be significantly reduced.

4) Post Correction Method (PCM)

The common occurrences between these methods mentioned above is they all change the state variables and make the algorithm complex. Unlike interpolation compensation, correction compensation directly modifies the switching function without calculating the switching state at t_e [40]. The switching time will still be recorded, and then be used to offset any errors next time after the switching operation. This principle is shown in [41]. The accuracy of the PCM is also poor, and it is difficult to correct a complex structure because of the problem of matching models and algorithms.

5) Time Average Method (TAM)

The TAM is based on the idea of average value like the PCM, but it is achieved by using duty cycle to represent the switching function in a simulation step. The principle is shown in [42].

The TAM does not focus on specific switching time, but the length of time the switching signal occupies in a sampling period. However, the switch function variables are still contained within the state matrix. So the state matrix needs to be re-calculated when the switch state changes. How to make better use of this method remains to be studied. And it is important to point out that the TAM can handle the "multiple switching" problem without causing delays [40].

And these correction methods are listed in Table II to show their advantages and disadvantages.

TABLE II
SIMPLE COMPARISON OF CORRECTION METHODS

Correction method	Advantage	Disadvantage
DIM	Because of double interpolation procedures, DIM is the most accurate method [35]	Double interpolation procedures slow down the speed of calculation [30]
IEM	More efficient than DIM [36], [37] because an interpolation calculation is omitted	It generates undesired harmonics when a discrete event occurs between simulation steps because the state X_2 has been ignored [42]
IVTS	After interpolation, use variable step-size to resolve next step. Because an extrapolation process is omitted, it is efficient [38]	The admittance matrix needs to be reformulated and it generates undesired harmonics like EIM [38]
PCM	It corrects errors in the next step by adds or subtracts extra normalized gating area [40]	It generates undesired harmonics. The error will accumulate because it will be added to initial value at the next step [41]
TAM	TAM can solve the multiple switching problems within one step without introducing extra delays [42]	Averaging a high switching frequency model may result in mistakes because average process can filter the high frequency information [42]

C. Interface Algorithms

In PHIL simulation, due to the use of power amplifiers and different types of sensors [28], time delay and distortion will be brought into the system. And the accuracy of PHIL is severely affected by the time delay which primarily arises from the computation time of the simulation and the delay caused by analog to digital converters (ADC) and digital to analog converters (DAC). Once the interface circuit is unstable due to environmental noise, equipment zero drift, delay, etc., the error will increase with the iteration of each step until the linear area of the power amplifier or the limit of other hardwares is exceeded, which makes the simulation fail, and even damages the power hardware devices. Therefore, the impact of interface algorithms on system accuracy and stability should be analyzed.

The interface algorithm is a method representing how power and control signals are transmitted between the digital and physical parts in the PHIL. When the topology of the interface algorithm changes, its stability and precision characteristics change as well. Figure 4 is a comparison between the CHIL and PHIL. The AMP of this figure is an abbreviation of the amplifier.

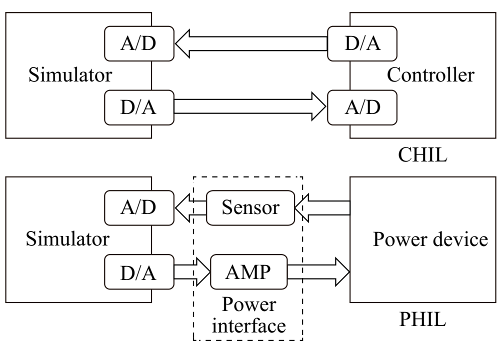

Fig. 4. Comparison between CHIL and PHIL.

1) Ideal Transformer Model (ITM) Interface Algorithm

This is the simplest interface algorithm as shown in Fig. 5, a voltage source V_a and its impedance Z_a are simulated by a simulator and the power hardware's impedance is Z_b.

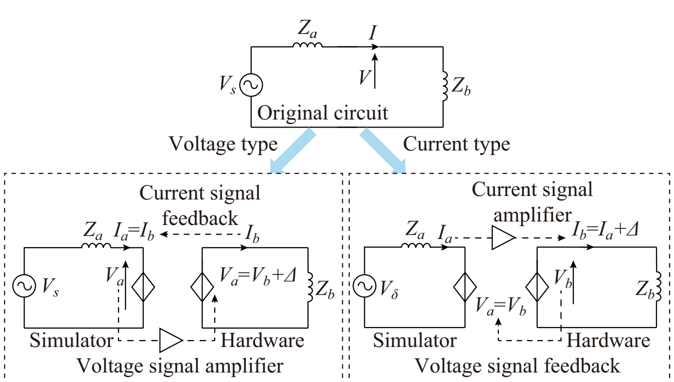

Fig. 5. Topology of ITM interface algorithm.

If the voltage is the amplified output signal and the current is the feedback signal, the algorithm is called voltage-type algorithm. And if the current is the output signal and the voltage is the feedback signal, the algorithm is called current-type algorithm. The transfer function of each interface algorithm is given as follows:

$$G_{\mathrm{ITM,V}} = -Z_a / Z_b \tag{1}$$

$$G_{\mathrm{ITM,I}} = -Z_b / Z_a \tag{2}$$

where $G_{\mathrm{ITM,V}}$ is the transfer function of voltage-type algorithm; and $G_{\mathrm{ITM,I}}$ is the transfer function of current-type algorithm. Note that the transfer functions deduced in this section are all in s-domain. Adding a small time delay $\mathrm{e}^{-s\Delta t}$ into the system such as $G_{\mathrm{ITM}}\mathrm{e}^{-s\Delta t}$, the characteristics of accuracy and stability will be weakened. So the system needs to be verified before being used. However, this method is widely used in PHIL due to its high accuracy [43].

2) Time-variant First-order Approximation (TFA) Interface Algorithm

Reference [44] proposes the TFA. It makes the hardware tested in the PHIL simulation equivalent to a first-order linear system (RL or RC circuit topology). Then, by using a large amount of historical simulation data, it solves and updates the online coefficients of the tested hardware model during the experiment, and corrects the error introduced from the interface by compensating in the simulator. The schematic diagram is shown in Fig. 6. In Fig. 6, I_{eq} and G_{eq} are a Norton equivalent of R_b and L_b.

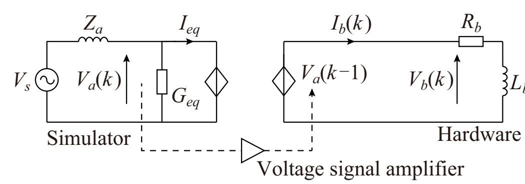

Fig. 6. Topology of TFA interface algorithm using a linear RL circuit.

The transfer function can be expressed as:

$$G_{\mathrm{TFA}} = -\frac{Z_a}{R_b + sL_b}\left(1 - \frac{sT}{2}\right) \tag{3}$$

where T is the time delay; and Z_b has been equivalent to a RL circuit topology as $R_b + sL_b$.

However, due to the prediction compensation through a large amount of historical and experimental data, the algorithm will fail when the system changes rapidly or changes from the RL circuit topology to the RC topology. At the same time, it can be observed in the transfer function that the accuracy of the system will decrease and become more unstable at high frequencies. Reference [45] shows that the TFA has high precision but poor stability, and [46] shows the TFA can be applied to a limited circuit configuration.

3) Transmission Line Model (TLM) Interface Algorithm

Since the TLM is established directly in a discrete domain rather than transforming from a continuous domain, the error impact caused by time delay can be ignored [47]. The algorithm assumes the interface as an inductor or a capacitor connecting the simulator's impedance and the power hardware's impedance [48]. If the algorithm is realized by regarding the interface link as L, the schematic diagram is shown in Fig. 7 and the transfer function can be expressed as:

$$G_{\mathrm{TLM}} = \frac{1-\alpha Z_a \mathrm{e}^{-2s\Delta t}}{1+\alpha Z_a \mathrm{e}^{-2s\Delta t}} \frac{Z_a}{Z_L} \tag{4}$$

where the intermediate variable $\alpha = (Z_b - Z_L)/(Z_b + Z_L)$, $Z_L = L/T$; and Δt is the propagation time of the transmission line.

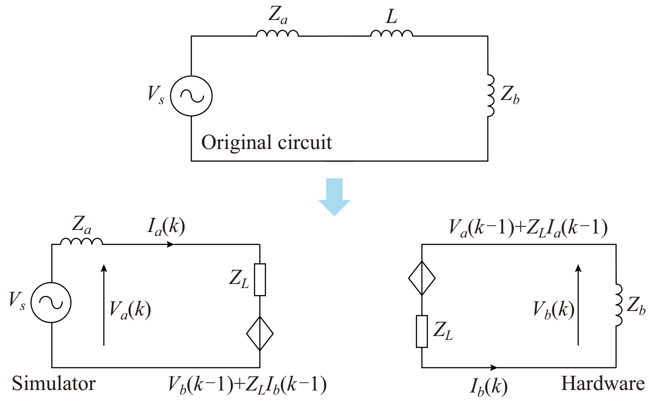

Fig. 7. Topology of TLM interface algorithm when the interface link is L.

If the algorithm is realized by regarding the interface link as C, Z_L is just changed as $Z_L = T/C$.

It can be seen from the transfer function that the main disadvantage of this method is that the value of the simulation step length T is related to the state of the power devices and the frequency of the transmitted data. If the system state changes greatly while the T remains unchanged, the accuracy will decrease. If T changes while the system state changes, the model will change as well. So, it is not easy to use.

4) Partial Circuit Duplication (PCD) Interface Algorithm

The PCD is a method based on the convergence of relaxation iterations, which decomposes the original circuit into multiple sub-circuits, as shown in Fig. 8. Z_{ab} is the impedance of the link component. And an iterative method to improve the accuracy of the calculation and the system stability is used during the simulation [49].

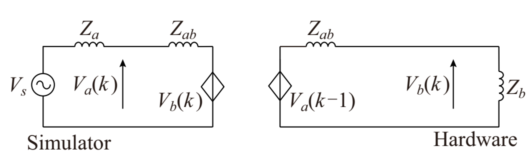

Fig. 8. Topology of PCD interface algorithm.

Its transfer function can be expressed as:

$$G_{\mathrm{PCD}} = \frac{Z_a Z_b}{(Z_a + Z_{ab})(Z_{ab} + Z_b)} \mathrm{e}^{-s\Delta t} \tag{5}$$

From the transfer function, Z_{ab} should be large enough to improve the accuracy, which is difficult to meet in the actual situation [50]. At the same time, since the PCD requires multiple iterations to reduce the errors, there is no way to realize the advantages of the iteration in the simulation with small simulation steps. Therefore, the PCD is difficult to be implemented in the simulation.

5) Damping Impedance Method (DIM) Interface Algorithm

The DIM is equivalent to the voltage-source-type ITM and the PCD method combining by a damping impedance Z^* [27]. As shown in Fig. 9, the transfer function can be expressed as:

$$G_{\mathrm{DIM}} = \frac{Z_a (Z_b - Z^*)}{(Z_a + Z_{ab} + Z^*)(Z_{ab} + Z_b)} \mathrm{e}^{-s\Delta t} \tag{6}$$

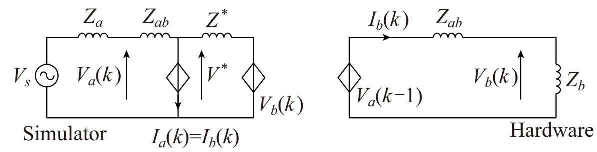

Fig. 9. Topology of DIM interface algorithm.

From the transfer function, it can be seen that when $Z^* \to \infty$, the model degenerates into the ITM form. And when $Z^* \to 0$, the model degenerates into the PCD form. Therefore, the main difficulty of the DIM method is how to determine the value of Z^* [51]. It is worth mentioning that when Z^* is strictly equal to Z_b, the transfer function is 0 and then the system is stable and the error will not accumulate. When the established model can ensure $Z_b = Z^*$, PHIL loses its advantage. At the same time, [46] points out that due to the existence of Z^*, the speed of the iterative convergence will decrease. Therefore, when selecting the interface algorithm, further analysis and verification are required to ensure that it can be used in the simulation.

However, algorithms except the TIM interface algorithms such as TLM, PCD and DIM interface algorithms, only theoretically provide high stability but are difficult to be implemented with higher accuracy than ITM [29]. These interface algorithms are listed in Table III to show their advantages and disadvantages.

Reference [29] even introduces the idea of impedance reshaping into the design of PHIL, and proposes a method to adjust the stability of the system by changing the proportion of impedance of the simulation system and the actual impedance. Since the main sources of stability accuracy problems are the actual power interfaces, the literature also points out that the impedance adjustment methods for solving the stability problem can also improve the simulation accuracy. In general, the PHIL interface algorithm is yet to be further studied compared to other more mature correction methods.

IV. Numerical Methods

Whether the numerical oscillation will occur depends on the numerical calculation algorithm. Generally, the model consists of a set of ordinary differential equations that represent the physical characteristics of the research object. The complexity of the model and the amount of computation required are determined according to the order of the corresponding differential equations. It is very important to select a proper numerical integration method to obtain the approximate solution that meets the accuracy requirements when conducting the power electronic system simulation [2].

TABLE III
SIMPLE COMPARISON OF INTERFACE ALGORITHMS

Interface algorithm	Advantage	Disadvantage
ITM	It is simplest interface algorithm with high accuracy	It is difficult to be stable [28]
TFA	It uses recorded historical data to compensate the time delay errors and has been more accurate in some situations [44]	It would generate more errors and even be unstable in high frequencies [45]. It is sensitive to noise. Therefore, its accuracy would be reduced [28]. This method can be only used in limited circuit configuration [46]
TLM	It can deal with circuit coupling problems and treatment non-linearities [48] and it can ignore errors caused by the time delay [47]	Its accuracy is lower than TFA because Z_L cannot be flexibly adjusted when the circuit configuration is changed [45]
PCD	It uses iterative methods and divides the original simulation into 2 subsystems to obtain a solution that can save resources [49]	It is difficult to adjust Z_{ab} large enough to satisfy accuracy needs. Therefore, it has poor accuracy [50]
DIM	It has advantages of ITM and PCD, high accuracy and good stability [49]	The accuracy and stability are all based on the chosen Z^*. It is difficult for implementation [51]

The numerical integration method has been developed rapidly since it can be conveniently calculated. According to different classification, it can be roughly divided into single-step or multi-step methods and explicit or implicit algorithms [4]. The selection of the numerical integration method to some extent affects the stability of the system and the accuracy of the simulation results. To meet the requirements of high speed, high precision and strong stability, it is necessary to improve the simulation process. Real-time simulation technology is based on the fixed-step sampling of digital system, so the fixed-step method can be applied.

Compared with the explicit algorithm, the implicit algorithm has stronger stability but more iterations. Since it will increase the computational burden, it is less likely to be applied in a real-time simulation. Therefore, most of the real-time simulations use the explicit algorithm with a fixed step size. However, considering that the internal switching process of power electronic systems is quite different and the model belongs to the rigid equation, which is prone to numerical oscillation problems, a developing trend is to adopt an implicit algorithm with stronger stability.

It is worth figuring out that for the objective of constant active and reactive power control, the parallel connection to the grid is equivalent to add a differential negative impedance term in the node admittance matrix at the point of common coupling (PCC), which can easily cause the numerical oscillation and simulation errors. A solution to modify the input conductance matrix is given in [25].

A. Numerical Integration Methods

1) Euler Method

The Euler method is a first-order method, which stipulates that the local error is proportional to the square of the step size, and the cumulative error is proportional to the step size. The Euler method is often used as a basis of more complex methods.

The formula of the Euler method is:

$$y_{n+1} = y_n + hF(t_n, y_n) + O(h^2) \tag{7}$$

where y_n is a current value of the state function $F(t_n, y_n)$; y_{n+1} is the next-step value; h is the step size; and $O(h^2)$ implies that this method has the first-order accuracy.

Based on this, there are a modified Euler method and a backward Euler method. For example, the standard solver of RT-LAB is the backward Euler method, which can quickly solve the model at the step of 2.0×10^{-5} s.

And the trapezoidal method is also based on the Euler method, its formula is:

$$y_{n+1} = y_n + \frac{h}{2}\left(F(t_n, y_n) + F(t_{n+1}, y_{n+1})\right) + O(h^3) \tag{8}$$

Since the trapezoidal method uses $F(t_{n+1}, y_{n+1})$, it is an implicit method. Compared with the modified Euler method, every time before the calculation, the initial value needs to be provided by the Euler method which increases the amount of computation. But more accurate results can be obtained.

2) Runge-Kutta Method

Strictly, the Runge-Kutta method includes a series of algorithms [52]-[54]. In the first-order case, it is called the Euler method. The Runge-Kutta method can also be divided into an explicit type and implicit type in order to cope with different problems. Its different orders correspond to different truncation errors.

The commonly used fourth-order formula is:

$$y_{n+1} = y_n + \frac{h}{6}(k_1 + k_2 + k_3 + k_4) + O(h^5) \tag{9}$$

where k_1, k_2, k_3, k_4 represent different statuses such as $F(t_n, y_n)$ in the Euler method. The explicit and implicit algorithms are both generalized by this fourth-order formula.

3) Linear Multi-step Method

Compared with the Runge-Kutta method, the linear multi-step method is simple in form and easy to be calculated [55]. It primarily includes three types of algorithms: the explicit Adams-Bashforth method, the implicit Adams-Moulton method, and the backward differentiation formula (BDF) method, in which the BDF method is widely used for solving rigid problems [56].

BDF is a linear multi-step formula with the k-step k-order form constructed as:

$$y_{n+k} = \sum_{i=0}^{k-1} \alpha_i y_{n+i} + h\beta_k f_{n+k} \tag{10}$$

The coefficients α_i and β_k are chosen to achieve the order

k. The $f_{n+k}=f(t_{n+k},y_{n+k})$ is used to evaluated the unknown y_{n+k} like the $F(t_{n+1},y_{n+1})$ used in trapezoidal method. The difference between $f(t_{n+k},y_{n+k})$ and $F(t_{n+1},y_{n+1})$ reflects the difference between multi-step method and single-step method.

It is also known as the Gear method. The disadvantage is that the stability of the oscillation equation is very poor in the 5th and 6th orders, and it is difficult to guarantee the stability requirements when exceeding the 6th order. But the Gear method is still widely recognized as one of the effective methods for solving stiff problems, especially for a system with low accuracy requirements [57].

It should be noted that the accuracy of high-order algorithms that can meet the stability requirements is generally better, but the implicit algorithms are more likely to avoid numerical oscillations. This paper summarizes the comparisons in Table IV.

TABLE IV
COMPARISON OF COMMON NUMERICAL INTEGRATION ALGORITHMS

Algorithm	Characteristic
Explicit Euler method	It is generally used to provide initial values, but both accuracy and numerical stability are poor
Implicit Euler method	Compared to the explicit Euler method, its stability has been improved
Trapezoidal method	It has the minimum errors among 2nd-order implicit methods [53]
Explicit Runge-Kutta method	Its accuracy is poor and cannot be used in stiff problem [54]
Implicit Runge-Kutta method	Its accuracy is higher than the explicit Runge-Kutta method and it is suitable for stiff problems. It is also better to avoid the numerical oscillations [54]
Adams-Bashforth method	It has more efficiency than the Runge-Kutta method with the same order, but it has to use other methods to get the initial value. It is also suitable for stiff problems [55] but has less efficiency than the Runge-Kutta method in variable step-size situations [52]
Adams-Morton method	It can be used in high precision conditions. It is preferably used to solve oscillatory problems compared to the Gear method [58]
Gear method	When its order is higher than 2, it would not satisfy the need for stability. And its accuracy is not high but its calculation efficiency is pretty good [57]
BDF method	It is more stable in conditions of rapidly varying step size than the Gear method, when the method order is higher than 6, it would be unstable [56]

Different numerical integration methods have different convergences and stabilities. If the error expansion phenomenon occurs, the step size can be correspondingly reduced. Numerical precision, computation time and computation resources are the key factors to consider when choosing the most appropriate integration method, we should choose a suitable simulation time step and numerical integration method based on the actual situation to ensure that the simulation is stable, real-time and accurate.

B. Iterative Method

When describing the action state of a switching element such as an inverter, a switching function model of the system is usually established. But since the switching function model includes a set of piecewise functions, it is usually simplified to be a switching state model [21]. Iterative methods are often used to solve these problems. The commonly used iterative methods are the Jacobi method and the Gauss-Seidel method.

1) Jacobi Method

For the general linear equations $\boldsymbol{Ax}=\boldsymbol{b}$, we can change the state matrix $\boldsymbol{A}$ as $\boldsymbol{A}=\boldsymbol{L}+\boldsymbol{U}+\boldsymbol{D}$, where $\boldsymbol{L}$ is a lower triangular matrix, $\boldsymbol{U}$ is an upper triangular matrix, and $\boldsymbol{D}$ is a diagonal matrix. The general form of the Jacobi method can be expressed as:

$$\boldsymbol{x}^{(k+1)}=-\boldsymbol{D}^{-1}(\boldsymbol{L}+\boldsymbol{U})\boldsymbol{x}^{(k)}+\boldsymbol{D}^{-1}\boldsymbol{b} \tag{11}$$

If we define $\boldsymbol{B}_J=-\boldsymbol{D}^{-1}(\boldsymbol{L}+\boldsymbol{U})$, $\boldsymbol{d}_J=\boldsymbol{D}^{-1}\boldsymbol{b}$, we can get the simplified formula:

$$\boldsymbol{x}^{(k+1)}=\boldsymbol{B}_J\boldsymbol{x}^{(k)}+\boldsymbol{d}_J \quad k=0,1,\ldots \tag{12}$$

2) Gauss-Seidel Method

The general form of the Gauss-Seidel method is:

$$\boldsymbol{x}^{(k+1)}=-(\boldsymbol{D}+\boldsymbol{L})^{-1}\boldsymbol{U}\boldsymbol{x}^{k}+(\boldsymbol{D}+\boldsymbol{L})^{-1}\boldsymbol{b} \tag{13}$$

If we define $\boldsymbol{B}_G=-(\boldsymbol{D}+\boldsymbol{L})^{-1}\boldsymbol{U}$, $\boldsymbol{d}_G=(\boldsymbol{D}+\boldsymbol{L})^{-1}\boldsymbol{b}$, we can get the simplified formula:

$$\boldsymbol{x}^{(k+1)}=\boldsymbol{B}_G\boldsymbol{x}^{k}+\boldsymbol{d}_G \quad k=0,1,\ldots \tag{14}$$

The Jacobi method and Gauss-Seidel method are extremely suitable for solving linear problems [59], especially for FPGA applications. Discretization is performed by the CPU through the backward Euler method, and then iterated by the FPGA, which can fully utilize the high-speed performance of the FPGA. Taking RT-LAB as an example, the selected FPGA chip can achieve a simulation step size of less than 1 μs using this method.

V. PLATFORMS

After establishing the model and selecting the corresponding numerical method, correction method and interface algorithm, the appropriate hardware platform should be selected to complete the simulation. For power electronic devices, the real-time simulation model features high parallelism and complex processes due to the fixed step-size and linearization simulation, so new requirements are put forward for the simulation platform [60].

With the advent of chip multiprocessors, graphics processing units and FPGAs, choices of hardware for real-time simulation have increased a lot. Especially the development of parallel computation technology has greatly improved the speed of simulation and reduced the computation time.

Although we can satisfy the demand of computation capability and small-step simulation by parallel computation technology, it is necessary to take into consideration the delay time in parallel computation. Using graphics processing units (GPUs) and personal computer-clusters (PC-clusters) may cause severe delay in the data transmission process. Generally, increasing the simulation step will save adequate time for data transmission. The hardware platforms are listed as follows.

A. Chip Multiprocessor (CMP)

CMP is a universal CPU with multiple processing cores and generally supports the Hyper-Threading technology. Although the core frequency is around 3 GHz, even less than that of a single core processor which was created many years ago, its computation ability is still extremely strongly depending on the excellent transistor technology and Hyper-Threading technology. And the communication time within the cores are very short, because the cores share multi-level caches. So CMPs are more suitable for small-scale simulations.

B. PC-cluster

PC-cluster is the most classic simulation configuration, it is a large-scale data processing hardware composed of multiple computers based on general-purpose processors through communication cables, local area networks and other devices.

It is commonly used to deal with more complex models that cannot be processed by CMPs, and has good performance in a small-scale simulation at microsecond level. Since it is composed of multiple general-purpose computers, it is highly scalable and can be expanded or upgraded as needed. But it will also be affected by transmission delays.

The representative platform is advanced digital power system simulator (ADPSS), which was developed by China Electric Power Research Institute (CEPRI) for hybrid simulation including both electromechanical and electromagnetic transient processes. It can also be used in quite large-scale grid containing new energy resources [61], [62]. But its weakness is in solving the problem of small-step simulations, which means it cannot adequately conduct high-frequency power electronic simulations.

C. FPGA

FPGAs have become function modules of mainstream real-time simulation systems with their powerful parallel processing capabilities and multiple-input multiple-output (MIMO) characteristics [63]. The extremely fast running speed makes the simulation step size reach the nanosecond level, which is very suitable for the simulation of power electronic devices. Limited by computation resources, high costs and communication bandwidth, it is difficult to form a large-scale computer cluster. At the same time, the relevant code is written in the languages such as hardware description language (HDL) and high-level synthesis (HLS), making it difficult to model and set. The FPGA is usually used as a hardware interface for controlling signal transmission [64]. In addition, FPGA can cooperate with the CPU to conduct the simulations [26]. That is, the models with high precision are assigned to the FPGA processor, while other models with lower requirements are distributed to the CPUs for calculation. Based on the characteristics of simulations themselves and the computation capability of the FPGA processor, an economical high-speed real-time simulation platform is being developed [19].

Most of the common platforms are developed based on FPGAs and CPUs. But they are applied for different purposes. For example, dSPACE is used for development and testing of control system, and can meet most requirements of engineering design [65], [66]. RT-LAB [67]-[70] and Typhoon HIL [71] are the only two platforms with rich FPGA resources. RTDS is a real-time simulation device for studying electromagnetic transient phenomena in power systems [72]-[74]. Although RTDS could test the controllers [75], it is generally used to test the performance of protection devices [76]. There are also two other platforms called RT-BOX and MT, respectively [77], [78].

D. GPU

GPUs have a large number of stream processors on a single chip which can achieve a large amount of data throughput and operations [79]. Compared with general-purpose processors, they are more suitable for data processing and have excellent performance for floating-point operations.

Unfortunately, for each model, the kernel should be written separately and there is a large delay. Therefore, compared to PC-cluster simulations, the GPUs are more suitable for solving a large-scale high-order model. If the scale is small, the data transmission delay of GPUs will cause a worse performance. The hardware structures above, except for FPGA, are sensitive to the influence of data transmission delays. Their characteristics are summarized in Table V [60], [63], [79]-[81].

In general, the best comprehensive performance equipment is based on the combination of CMP and FPGA. PC-cluster is restricted by the simulation step size, and GPU is limited by the transmission delay. The specific platform selection needs to be determined based on the application requirements.

VI. Problems and Challenges

Real-time simulation is an effective and important approach to validate new ideas and techniques of control and protection systems. Traditional power grid shows low frequencies and continuous characteristics. However, a large number of power electronic devices connected to the power grid will have a deep impact on it. The switching processes seriously influence the stability and reliability of power grid [82], [83]. Thus the new energy power plants should be evaluated by simulation before they are put into operation. Nevertheless, the electromagnetic transient process and the switching processes of power electronic devices are always neglected in the existing grid-level simulation tools.

Therefore, there are new demands on existing traditional simulation methods while the power electronic simulation platform lacks the capability of large-scale and multi-time simulations.

TABLE V
SIMPLE COMPARISONS OF HARDWARE PLATFORMS USED IN REAL-TIME SIMULATION

Hardware platform	Characteristic	Minimum step size
CMP	It is cheap but difficult to enlarge computation scale and can only deal with the data with low sampling rates [60]. The communication delay between cores is low, but the complex model will reduce the computation efficiency	μs
PC-cluster	It consists of a host PC with clusters, and the number of clusters can be freely configured. It can process large-scale simulations. However, the simulations scale is limited by the communication delay between host and clusters. It is not suitable for power electronic devices simulations with a high sampling rate [80]. And as the simulation scale expands, the model becomes even more complicated	μs
FPGA	Its costs are high, but due to parallel computation, the complexity of the model does not affect the efficiency of the computation. It is suitable for simulating power electronics with high switching frequency and large-scale simulations [63]	ns
GPU	It is suitable for large-scale parallel computation and its cost is lower than FPGA [79]. But the communication delay between GPUs is larger than FPGAs, which is unsuitable for small-step simulations [81]	μs

A. Key Technologies

The impedance network is a more effective method to model and design control processes [84]. Using the impedance analysis method is the mainstream approach in the power electronic field. However, it still does not completely solve the system oscillation problem in theory [82]. Reference [15] puts forward the ADC modeling method based on the integrated consideration in the switching state and the snubber circuit. This method can reflect not only the actions of converters and high frequency switching characteristics, but also the snubber circuit characteristics. References [16] and [17] give a better modeling method with FPGAs depending on the thermal characteristics of the subjects. But the modeling method based on the thermal characteristics is rare in the actual simulation. The modeling of the electrical and thermal characteristics of photovoltaic cells has been conducted in [85]. Although its performance is excellent, the applicability in other fields is yet to be tested. References [34] and [86] give new averaging modeling and a principle to achieve a faster adaptive interpolation algorithm. Although there are many modeling methods mentioned above, there is not yet a modeling method that is widely recognized and has a wide range of applicability. In [87], the HLS method for real-time simulation of FPGA-based sub-microsecond converters is evaluated. The Vivado HLS method is an improved HLS method for FPGA related programming and setting, which can make FPGAs reach the balance between performance and computation time with extremely limited resources. However, due to the different developing habits, the application is not popular and the problem of FPGA modeling is not solved. Currently, only RT-LAB and Typhoon HIL have systematic solutions to FPGA modeling.

The application of the compressed sensing theory in real-time simulation applications has yet to be completed. Relevant commercial companies use FPGA hardware platforms with related algorithms to solve the problem of switching delay. It is important to match the correction method with numerical method. In this way, there are a time compensation algorithm in [27] and an adaptive interpolation algorithm in [34]. About interface algorithms, for PHIL, most of the experiments are now based on the simplest TIM method with obvious weakness. Except for TIM, other methods are not suitable to be widely used. It is necessary to find new theoretical tools.

As for numerical methods and simulator solvers, there are no new theories or methods. But wavelet analysis might be a promising approach. So, how to popularize it in the field of power electronics based on Fourier transform requires more effort and commitment. Finally, promoting a pure FPGA simulation platform is also extremely important [88].

B. Further Research Contents

Based on the analysis above, the main points for further research are as follows.

1) Deeply research the model equivalent substitution technique such as the method of parameter identification and black box modeling. Modeling methods should satisfy more actual needs such as multi-device parallel operations [89] and work mode transition of devices in the power grid [25].

2) Search a correction method which has a synergistic effect on the modeling method [86], or set up a high matching modeling based on the correction method algorithm such as that one in [27]. Look for better interface algorithms to promote the universal use of PHIL and to reduce the need for real experimentation. For example, [29] improves the stability and accuracy of PHIL by adjusting physical and virtual loop impedance.

3) Study the real-time simulation model of new energy generation based on FPGAs or other hardware platforms such as GPUs. For example, [83] studies the modeling of doublely-fed induction generators and permanent magnet synchronous motors based on FPGA.

4) Develop the model separation technology. For example, [69] points out that the RT-LAB's electric hardware solver (eHS) which can simplify the complex model for calculation. Search new algorithms and develop parallel computation technologies to reduce the nodes increased by complex topologies and decrease the computation time to meet the needs of a large number of switching processes.

5) Study the specification and modeling of large-scale grid-connected power electric devices, improve the classification of related structures, and develop a typical structure for following studies [90]. For example, [82] proposes the dynamic model of multi-scale layered control after enumerating the development of the synchronous motor theory, which

is designed to simplify the complex converter into a generic model.

6) Find a more reliable real-time communication technology and reduce communication delays on the real-time simulation. For example, [15] adopts fixed-point computation and carries data in synchronous transmissions between FPGA and the host computer with unified clock frequency to reduce delay time. Reference [6] shows that the delay can be minimized by sharing common memories or buses of CPUs.

VII. Conclusion

Currently, there are more and more power electronics emerging in power systems. As systems and relevant standards continue to evolve, higher requirements are needed for real-time simulation of power electronics. The scale of the simulation is larger, the parameters are more complex and the interaction among parameters becomes more obvious. The bandwidth and stability of the system, the accuracy of the modeling, the limitations of communication interfaces and energy interfaces, and the cost of platform construction still require extensive research.

The problems encountered in the field of power electronic simulation also hinder the development of actual production. Only when these problems are solved, can the new power generation replace the traditional power generation more quickly.

References

[1] M. Mao, Y. Wang, Y. Yue *et al*., "Multi-time scale forecast for schedulable capacity of EVs based on big data and machine learning," in *Proceedings of IEEE Energy Conversion Congress and Exposition*, Cincinnati, USA, Oct. 2017, pp. 1425-1431.

[2] S. Mojlish, N. Erdogan, D. Levine *et al*., "Review of hardware platforms for real-time simulation of electric machines," *IEEE Transactions on Transportation Electrification*, vol. 3, no. 1, pp. 130-146, Mar. 2017.

[3] A. S. Vijay, S. Doolla, and M. C. Chandorkar, "Real-time testing approaches for microgrids," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 5, no. 3, pp. 1356-1376, Sept. 2017.

[4] J. Wang, "Discussion on hardware-in-loop simulation technology of power electronic system," *High Power Converter Technology*, vol. 2, pp. 1-5, Feb. 2011.

[5] J. Belanger, P. Venne, and J. Paquin, "The what where and why of real-time simulation," *Planet RT*, vol. 1, no. 1, pp. 25-29, Jan. 2010.

[6] M. D. O. Faruque, T. Strasser, G. Lauss *et al*., "Real-time simulation technologies for power systems design, testing, and analysis," *IEEE Power and Energy Technology Systems Journal*, vol. 2, no. 2, pp. 63-73, Jun. 2015.

[7] M. Schlager, *Hardware-in-the-loop Simulation*. Saarbrucken, Germany: VDM Verlag, 2008.

[8] G. G. Parma and V. Dinavahi, "Real-time digital hardware simulation of power electronics and drives," *IEEE Transactions on Power Delivery*, vol. 22, no. 2, pp. 1235-1246, Apr. 2007.

[9] A. Francés, R. Asensi, Ó. García *et al*., "Modeling electronic power converters in smart DC microgrids – an overview," *IEEE Transactions on Smart Grid*, vol. 9, no. 6, pp. 6274-6287, Nov. 2018.

[10] W. Wang, Z. Shen, and V. Dinavahi, "Physics-based device-level power electronic circuit hardware emulation on FPGA," *IEEE Transactions on Industrial Informatics*, vol. 10, no. 4, pp. 2166-2179, Nov. 2014.

[11] H. Jin, "Behavior-mode simulation of power electronic circuits," *IEEE Transactions on Power Electronics*, vol. 12, no. 3, pp. 443-452, May 1997.

[12] X. H. Mai, S. Kwak, J. Jung *et al*., "Comprehensive electric-thermal photovoltaic modeling for power-hardware-in-the-loop simulation (PHILS) applications," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 8, pp. 6255-6264, Aug. 2017.

[13] C. H. Broeck, L. A. Ruppert, A. Hinz *et al*., "Spatial electro-thermal modeling and simulation of power electronic modules," *IEEE Transactions on Industry Applications*, vol. 54, no. 1, pp. 404-415, Jan. 2018.

[14] X. Ma, Z. Yang, C. Liu *et al*., "Real-time simulation of power electronic devices," *Automation of Electric Power Systems*, vol. 37, no. 18, pp. 108-112, Sept. 2013.

[15] M. Matar and R. Iravani, "FPGA implementation of the power electronic converter model for real-time simulation of electromagnetic transients," *IEEE Transactions on Power Delivery*, vol. 25, no. 2, pp. 852-860, Apr. 2010.

[16] L. Herrera and J. Wang, "FPGA based detailed real-time simulation of power converters and electric machines for EV HIL applications," in *Proceedings of IEEE Energy Conversion Congress and Exposition*, Denver, USA, Sept. 2013, pp. 1759-1764.

[17] L. Herrera, C. Li, X. Yao *et al*., "FPGA-based detailed real-time simulation of power converters and electric machines for EV HIL applications," *IEEE Transactions on Industry Applications*, vol. 51, no. 2, pp. 1702-1712, Mar. 2015.

[18] J. Chen, *The Application of Computer Simulation in Power Electronics*. Beijing, China: Tsinghua University Press, 2008.

[19] C. Graf, J. Maas, T. Schulte *et al*., "Real-time HIL-simulation of power electronics," in *Proceedings of Annual Conference of IEEE Industrial Electronics*, Orlando, USA, Nov. 2008, pp. 2829-2834.

[20] P. Pejovic and D. Maksimovic, "A new algorithm for simulation of power electronic systems using piecewise-linear device models," *IEEE Transactions on Power Electronics*, vol. 10, no. 3, pp. 340-348, May 1995.

[21] H. F. Blanchette, T. Ould-Bachir, and J. P. David, "A state-space modeling approach for the FPGA-based real-time simulation of high switching frequency power converters," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 12, pp. 4555-4567, Dec. 2012.

[22] P. G. Maranesi, V. Tavazzi, and V. Varoli, "Two-part characterization of PWM voltage regulators at low frequencies," *IEEE Transactions on Industrial Electronics*, vol. 35, no. 3, pp. 444-450, Aug. 1988.

[23] W. E. V. Velde, *Multiple-input Describing Functions and Nonlinear System Design*. New York, USA: McGraw-Hill, 1968.

[24] L. Arnedo, D. Boroyevich, R. Burgos *et al*., "Un-terminated frequency response measurements and model order reduction for black-box terminal characterization models," in *Proceedings of Annual IEEE Applied Power Electronics Conference and Exposition*, Austin, USA, Feb. 2008, pp. 1054-1060.

[25] L. Harnefors, M. Bongiorno, and S. Lundberg, "Input-admittance calculation and shaping for controlled voltage-source converters," *IEEE Transactions on Industrial Electronics*, vol. 54, no. 6, pp. 3323-3334, Dec. 2007.

[26] A. Ingalalli, H. Satheesh, and M. Kande, "Platform for hardware in loop simulation," in *Proceedings of International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, Anacapri, Italy, Jun. 2016, pp. 41-46.

[27] T. Charles, S. K. Sahoo, M. Balamurugan *et al*., "Time compensated models of switching elements for hardware in loop simulation," in *Proceedings of IEEE Region 10 Conference*, Singapore, Nov. 2016, pp. 831-836.

[28] W. Ren, M. Steurer, and T. L. Baldwin, "Improve the stability and the accuracy of power hardware-in-the-loop simulation by selecting appropriate interface algorithms," *IEEE Transactions on Industry Applications*, vol. 44, no. 4, pp. 1286-1294, Jul. 2008.

[29] H. Miao, "Modeling, stability and accuracy of power hardware-in-the-loop simulation of power electronic systems," Ph.D. dissertation, Osaka University, Osaka, Japan, 2010.

[30] M. O. Faruque, V. Dinavahi, and W. Xu, "Algorithms for the accounting of multiple switching events in digital simulation of power-electronic systems," *IEEE Transactions on Power Delivery*, vol. 20, no. 2, pp. 1157-1167, Apr. 2005.

[31] M. Zou, J. Mahseredjian, G. Joos *et al*., "Interpolation and reinitialization in time-domain simulation of power electronic circuits," *Electric Power Systems Research*, vol. 76, no. 8, pp. 688-694, May 2006.

[32] A. Wagener, T. Schulte, P. Waeltermann *et al*., "Hardware-in-the-loop test systems for electric motors in advanced power train applications," in *Proceedings of SAE World Congress*, Detroit, USA, Apr. 2007, pp. 1-16.

[33] T. T. Do, L. Gan, N. Nguyen *et al*., "Sparsity adaptive matching pursuit algorithm for practical compressed sensing," in *Proceedings of Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, USA, Oct. 2008, pp. 581-587.

[34] B. D. Kelper, L. A. Dessaint, K. Al-Haddad *et al*., "A comprehensive approach to fixed-step simulation of switched circuits," *IEEE Transac-*

tions on Power Electronics, vol. 17, no. 2, pp. 216-224, Mar. 2002.

[35] B. D. Kelper, L. A. Dessaint, V. Q. Do *et al*., "An algorithm for accurate switching representation in fixed-step simulation of power electronics," in *Proceedings of IEEE PES Winter Meeting*, Singapore, Jan. 2000, pp. 762-767.

[36] K. Strunz, L. Linares, J. R. Marti *et al*., "Efficient and accurate representation of asynchronous network structure changing phenomena in digital real time simulators," *IEEE Transactions on Power Systems*, vol. 15, no. 2, pp. 586-592, May 2000.

[37] K. Strunz, "Real time nodal-analysis-based solution techniques for simulations of electromagnetic transients in power electronic systems," in *Proceedings of Power Systems Computation Conference*, Trondheim, Norway, Jul. 1999, pp. 1047-1053.

[38] V. R. Dinavahi, M. R. Iravani, and R. Bonert, "Real-time digital simulation of power electronic apparatus interfaced with digital controllers," *IEEE Transactions on Power Delivery*, vol. 16, no. 4, pp. 775-781, Oct. 2001.

[39] D. Shu, C. Zhang, Q. Jiang *et al*., "A switching point self-correction interpolation algorithm for power electronic simulations," *Power System Technology*, vol. 40, no. 5, pp. 1455-1461, May 2016.

[40] Q. Song, Z. Liu, H. Zhang *et al*., "Advance of real time digital simulation for high-power electronics," *Journal of System Simulation*, vol. 18, no. 12, pp. 3329-3333, Dec. 2006.

[41] K. Lian, "Real time simulation of a VSC," M.S. thesis, University of Toronto, Toronto, Canada, 2003.

[42] K. Lian and P. W. Lehn, "Real-time simulation of voltage source converters based on time average method," *IEEE Transactions on Power Systems*, vol. 20, no. 1, pp. 110-118, Feb. 2005.

[43] A. Aguirre, M. Davila, P. Zuniga *et al*., "Improvement of damping impedance method for power hardware in the loop simulations," in *Proceedings of IEEE International Autumn Meeting on Power, Electronics and Computing*, Ixtapa, Mexico, Nov. 2016, pp. 1-6.

[44] X. Wu, S. Lentijo, and A. Monti, "A novel interface for power-hardware-in-the-loop simulation," in *Proceedings of IEEE Workshop on Computers in Power Electronics*, Urbana, USA, Aug. 2004, pp. 178-182.

[45] X. Wu, S. Lentijo, A. Deshmuk *et al*., "Design and implementation of a power-hardware-in-the-loop interface: a nonlinear load case study," in *Proceedings of Annual IEEE Applied Power Electronics Conference and Exposition*, Austin, USA, Mar. 2005, pp. 1332-1338.

[46] I. Yoo, "A study on the improvement of simulation accuracy in power hardware in the loop simulation," Ph. D. dissertation, The University of Manitoba, Manitoba, Canada, 2013.

[47] S. Y. R. Hui and C. Christopoulos, "Numerical simulation of power circuits using transmission-line modelling," *IEE Proceedings A – Physical Science, Measurement and Instrumentation, Management and Education*, vol. 137, no. 6, pp. 379-384, Nov. 1990.

[48] S. Y. R. Hui, K. K. Fung, and C. Christopoulos, "Decoupled simulation of DC-linked power electronic systems using transmission-line links," *IEEE Transactions on Power Electronics*, vol. 9, no. 1, pp. 85-91, Jan. 1994.

[49] V. B. Dmitriev-Zdorov, "Generalized coupling as a way to improve the convergence in relaxation-based solvers," in *Proceedings of European Design Automation Conference with EURO-VHDL' 96 and Exhibition*, Geneva, Switzerland, Sept. 1996, pp. 15-20.

[50] R. Kuffel, R. P. Wierckx, H. Duchen *et al*., "Expanding an analogue HVDC simulator's modelling capability using a real-time digital simulator (RTDS)," in *Proceedings of International Conference on Digital Power System Simulators*, Texas, USA, Apr. 1995, pp. 199-204.

[51] W. Ren, "Accuracy evalaution of power hardware-in-the-loop (PHIL) smulation," Ph. D. dissertation, Florida State University, Tallahassee, USA, 2007.

[52] J. R. Cash and A. H. Karp, "A variable order Runge-Kutta method for initial value problems with rapidly varying right-hand sides," *ACM Transactions on Mathematical Software*, vol. 16, no. 3, pp. 201-222, Sept. 1990.

[53] J. D. Lambert, *Numerical Methods for Ordinary Differential Systems: the Initial Value Problem*. London, UK: John Wiley & Sons, Inc., 1991.

[54] P. J. Davis and P. Rabinowitz, *Methods of Numerical Integration*. North Chelmsford: Courier Corporation, 2007.

[55] D. F. Griffiths and D. J. Higham, "Linear multistep methods II: convergence and zero-stability," in *Numerical Methods for Ordinary Differential Equations.* London, UK: Springer, 2010.

[56] R. K. Brayton, F. G. Gustavson, and G. D. Hachtel, "A new efficient algorithm for solving differential-algebraic systems using implicit backward differentiation formulas," *Proceedings of the IEEE*, vol. 60, no. 1, pp. 98-108, Jan. 1972.

[57] X. Song, Y. Tang, W. Liu *et al*., "Mixed numerical integral algorithm for full dynamic simulation of the power system," *Proceedings of the CSEE*, no. 28, pp. 23-29, 2009.

[58] J. Y. Astic, A. Bihain, and M. Jerosolimski, "The mixed Adams-BDF variable step size algorithm to simulate transient and long term phenomena in power systems," *IEEE Transactions on Power Systems*, vol. 9, no. 2, pp. 929-935, May 1994.

[59] Y. Saad, *Iterative Methods for Sparse Linear Systems*, 2nd ed. Philadelphia: SIAM, 2003.

[60] Z. Fu, J. Ma, and R. Sun, "Real-time simulation based on high-speed signal processing system," *Journal of System Simulation*, vol. 19, no. 16, pp. 3680-3683, Aug. 2007.

[61] W. Lin, X. Zhang, G. Li *et al*., "A novel platform for experimenting and testing FACTS controllers," *Transactions of China Electrotechnical Society*, vol. 27, no. 3, pp. 227-232, Mar. 2012.

[62] Z. Liu, Y. Wang, J. Chen *et al*., "Modeling and simulation research of large-scale AC/DC hybrid power grid based on ADPSS," in *Proceedings of IEEE PES Asia-Pacific Power and Energy Engineering Conference*, Hong Kong, China, Dec. 2014, pp. 1-6.

[63] A. Myaing and V. Dinavahi, "FPGA-based real-time emulation of power electronic systems with detailed representation of device characteristics," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 358-368, Jan. 2011.

[64] K. Sharma and L. M. Saini, "Performance analysis of smart metering for smart grid: an overview," *Renewable and Sustainable Energy Reviews*, vol. 49, pp. 720-735, 2015.

[65] Y. Wang, X. Wang, F. Blaabjerg *et al*., "Frequency scanning-based stability analysis method for grid-connected inverter system," in *Proceedings of IEEE International Future Energy Electronics Conference and ECCE Asia*, Kaohsiung, China, Jun. 2017, pp. 1575-1580.

[66] X. Lin, K. Xiahou, Y. Liu *et al*., "Design and hardware-in-the-loop experiment of multiloop adaptive control for DFIG-WT," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 9, pp. 7049-7059, Sept. 2018.

[67] OPAL-RT Inc., RT-LAB v7.0 user's manual. Montréal, Canada: OPAL-RT Inc., 2004. [Online]. Available: https://manualzz. com/doc/7216224/7.0-user-s-manual---opal-rt

[68] C. Dufour, J. Belanger, and V. Lapointe, "FPGA-based ultra-low latency HIL fault testing of a permanent magnet motor drive using RT-LAB-XSG," in *Proceedings of Joint International Conference on Power System Technology and IEEE Power India Conference*, New Delhi, India, Oct. 2008, pp. 1-7.

[69] O. Crăciun, A. Florescu, S. Bacha *et al*., "Hardware-in-the-loop testing of PV control systems using RT-LAB simulator," in *Proceedings of International Power Electronics and Motion Control Conference*, Ohrid, Macedonia, Sept. 2010, pp. 1-6.

[70] J. Bélanger, A. Yamane, A. Yen *et al*., "Validation of eHS FPGA reconfigurable low-latency electric and power electronic circuit solver," in *Proceedings of 39th Annual Conference of the IEEE Industrial Electronics Society*, Vienna, Austria, Nov. 2013, pp. 5418-5423.

[71] A. J. Jones, "State of charge based droop surface for optimal control of dc microgrids," Ph.D. dissertation, Michigan Technological University, Houghton, USA, 2014.

[72] J. Xu, T. Lan, S. Liao *et al*., "An on-line power/voltage stability index for multi-infeed HVDC systems," *Journal of Modern Power Systems and Clean Energy*, vol. 7, no. 5, pp. 1094-1104, Sept. 2019.

[73] T. B. Rasmussen, G. Yang, A. H. Nielsen *et al*., "Effects of centralized and local PV plant control for voltage regulation in LV feeder based on cyber-physical simulations," *Journal of Modern Power Systems and Clean Energy*, vol. 6, no. 5, pp. 979-991, Sept. 2018.

[74] H. Chang, M. Zhang, and W. Ma, "Real time digital simulator (RTDS) and its applications," *Electric Power*, vol. 39, no. 7, pp. 56-60, Jul. 2006.

[75] X. Wang, D. Yu, S. L. Blond *et al*., "A novel controller of a battery-supercapacitor hybrid energy storage system for domestic applications," *Energy and Buildings*, vol. 141, pp. 167-174, Apr. 2017.

[76] B. Wang, X. Dong, Z. Bo *et al*., "RTDS environment development of ultra-high-voltage power system and relay protection test," in *Proceedings of IEEE PES General Meeting*, Tampa, USA, Jun. 2007, pp. 1-7.

[77] M. Ciobotaru, T. Kerekes, R. Teodorescu *et al*., "PV inverter simulation using MATLAB/Simulink graphical environment and PLECS blockset," in *Proceedings of 32nd Annual Conference on IEEE Industrial Electronics*, Paris, France, Nov. 2006, pp. 5313-5318.

[78] J. A. Dias, E. V. Liberado, P. J. A. Serni *et al*., "Simulation of a distributed generator with wireless communication using TrueTime and PLECS," in *Proceedings of IEEE PES Innovative Smart Grid Technol-*

ogies Latin America, Montevideo, Uruguay, Oct. 2015, pp. 624-628.

[79] A. J. Adzima, P. T. Krein, and T. C. O'Connell, "Investigation of accelerating numerical-field analysis methods for electric machines with the incorporation of graphic-processor based parallel processing techniques," in *Proceedings of IEEE Electric Ship Technologies Symposium*, Baltimore, USA, Apr. 2009, pp. 59-64.

[80] M. O. Faruque and V. Dinavahi, "An advanced PC-cluster based real-time simulator for power electronics and drives," in *Proceedings of IEEE International Symposium on Industrial Electronics*, Montreal, Canada, Jul. 2006, pp. 2579-2584.

[81] M. Papadonikolakis, C. Bouganis, and G. Constantinides, "Performance comparison of GPU and FPGA architectures for the SVM training problem," in *Proceedings of International Conference on Field-Programmable Technology*, Sydney, Australia, Dec. 2009, pp. 388-391.

[82] X. Yuan, S. Cheng, and J. Hu, "Multi-time scale voltage and power angle dynamics in power electronics dominated large power systems," *Proceedings of the CSEE*, vol. 36, no. 19, pp. 5145-5154, Oct. 2016.

[83] F. Huerta, R. L. Tello, and M. Prodanovic, "Real-time power-hardware-in-the-loop implementation of variable-speed wind turbines," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 3, pp. 1893-1904, Mar. 2017.

[84] Y. P. Siwakoti, F. Z. Peng, F. Blaabjerg *et al*., "Impedance-source networks for electric power conversion Part II: review of control and modulation techniques," *IEEE Transactions on Power Electronics*, vol. 30, no. 4, pp. 1887-1906, Apr. 2015.

[85] X. H. Mai, S. Kwak, J. Jung *et al*., "Comprehensive electric-thermal photovoltaic modeling for power-hardware-in-the-loop simulation (PHILS) applications," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 8, pp. 6255-6264, Aug. 2017.

[86] D. Shu, Y. Li, C. Zhang *et al*., "Comverter averaged model based on amplitude distribution function and its application," *Automation of Electric Power Systems*, vol. 40, no. 15, pp. 73-78, Aug. 2016.

[87] F. Montano, T. Ould-Bachir, and J. P. David, "An evaluation of a high-level synthesis approach to the FPGA-based submicrosecond real-time simulation of power converters," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 1, pp. 636-644, Jan. 2018.

[88] C. Liu, R. Ma, H. Bai *et al*., "A new approach for FPGA-based real-time simulation of power electronic system with no simulation latency in subsystem partitioning," *International Journal of Electrical Power & Energy Systems*, vol. 99, pp. 650-658, Jul. 2018.

[89] X. Zhang, C. Yu, F. Liu *et al*., "Modeling and resonance analysis of multi-paralleled grid-tied inverters in PV systems," *Proceedings of the CSEE*, vol. 34, no. 3, pp. 336-345, Jan. 2014.

[90] M. Ding, W. Wang, X. Wang *et al*., "A review on the effect of large-scale PV generation on power systems," *Proceedings of the CSEE*, no. 1, pp. 1-14, Jan. 2014.

Fei Li received his Ph.D. degree from Hefei University of Technology, Hefei, China, in 2015. He is currently an Associate Professor with the School of Electrical Engineering and Automation, Hefei University of Technology, Hefei, China. His current research interests include resonance analysis and suppression of multi-inverter system, topology and parameter design of grid-connected inverter high-order filters and HIL simulation of new energy generation systems.

Yichao Wang received his B.S. degree in Hefei University of Technology, Hefei, China. Now he is pursuing the M.S. degree in Electric Engineering and Automation at the Hefei University of Technology, Hefei, China. His research interests include resonance analysis and suppression of multi-inverter systems.

Fan Wu is pursuing her M.S. degree in electric engineering and automation at the Hefei University of Technology, Hefei, China. Her research interests include HIL simulation of new energy generation system.

Yao Huang is pursuing his M.S. degree in electric engineering and automation at the Hefei University of Technology, Hefei, China. His research interests include HIL simulation of new energy generation system.

Yang Liu is pursuing his M.S. degree in electric engineering and automation at the Hefei University of Technology, Hefei, China. His research interests include resonance analysis and suppression of multi-inverter system and HIL simulation of new energy generation system.

Xing Zhang received his B.S., M.S., and Ph.D. degrees in electric engineering and automation from the Hefei University of Technology, Hefei, China, in 1984, 1990, and 2003, respectively. Since 1984, he has been a Faculty Member with the School of Electric Engineering and Automation, Hefei University of Technology, Hefei, China, where he is currently a Professor. He is also with the Photovoltaic Engineering Research Center, Ministry of Education, Beijing, China. His research interests include photovoltaic generation technologies, wind power generation technologies, and distributed generation systems.

Mingyao Ma received the B.Sc. and Ph.D. degrees in applied power electronics and electrical engineering from Zhejiang University, Hangzhou, China, in 2004 and 2010, respectively. From October 2008 to October 2009, she was a visiting Ph.D. postgraduate research student in the University of Strathclyde, Glasgow, UK, and in 2010, she joined Zhejiang University, Hangzhou, China, as a Post-Doctoral Research Fellow. In 2011, she worked for the University of Central Florida, Orlando, USA, as the visiting scholar. From April 2012 to April 2015, she joined the Newcastle University, Newcastle, UK, as the Research Associate. From 2015 she works in Hefei University of Technology, Hefei, China, as a Professor. Her research interests include multilevel converters, distributed control of power electronic building blocks (PEBB)-based converters, software design using FPGA and digital signal processor (DSP), switched reluctance (SR) motor control, and health monitoring of power electronics systems.