Real-time simulation of PMSG based on FPGA

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***Abstract*—FPGA (Field Programmable Gate Array) has a high degree of parallelization and pipeline computing capabilities, and is widely used in real-time simulation. Based on FPGA, this paper studies PMSG (Permanent Magnetic Synchronous Machine). The real-time simulation modeling method of wind turbines was developed. The main work of the paper is as follows:**

Based on the closed-loop simulation model of the permanent magnet direct-drive wind turbine, the whole system is divided into an electrical system and a control system.

Based on the electromagnetic transient simulation framework, combined with the multi-zone Thevenin equivalent method, the data of each module in the electrical system is decoupled, which improves the FPGA solution speed and resource utilization.

Based on this real-time simulator, a real-time simulation example of the electromagnetic system of the wind turbine is realized, and the simulation results during the start-up process of the wind turbine are analyzed, and are compared with the simulation results of MATLAB; the simulation results show that this real-time simulator has high accuracy, and the real-time performance can be guaranteed under the simulation step size of 10 µs.

Keywords—FPGA; PMSG; Real-time Simulation, Electromagnetic Transient Simulation

I. Introduction

With the increasing complexity of the power system structure, it is a relatively reliable technical solution to build a "full electromagnetic" simulation model of the power system to ensure the simulation accuracy and simulation speed of the model [1]-[3]. Establishing an all-electromagnetic model for permanent magnet synchronous wind turbines and selecting appropriate hardware to realize its real-time simulation is a crucial part of realizing all-electromagnetic power grid simulation [4]-[5].

At present, the industry usually uses RTDS commercial real-time simulators for electromagnetic transient real-time simulation analysis. RTDS has high computing performance and can meet the needs of real-time simulation of electromagnetic transients of a certain scale. However, the use of RTDS for full electromagnetic transient modeling and simulation is prohibitively expensive [6][7]. At the same time, RTDS is a commercial simulator, and it is impossible to conduct more extended research on its basis, such as establishing a refined model of wind turbines and a real-time simulation platform [8].

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Existing real-time simulators have many shortcomings, and it is urgent to develop a set of real-time simulators for wind turbines with high real-time performance, flexible use and low cost.

FPGA (Field Programmable Gate Array) can meet the requirements of real-time simulation of electromagnetic transients. Compared with sequential hardware devices such as CPU and GPU, FPGA allows parallel processing and supports multiple concurrent execution threads. FPGAs are also fully configurable devices that can be configured to suit any specific application to maximize performance. In addition, FPGA also integrates abundant I/O devices to support high-speed signaling. With its highly parallel hardware structure, distributed memory blocks, deep pipeline structure, programmable features and abundant I/O resources, FPGA has laid the foundation for real-time simulated computing hardware. Reference [9] designed a real-time simulator based on FPGA for the simulation of traditional power system. Chen and Venkata in [10] presented a digital hardware design for detailed large-scale real-time electromagnetic transient simulation of power systems using a commercial circuit board containing multiple FPGAs. Due to its outstanding performance, FPGA has become the first choice for real-time simulation of permanent magnet synchronous wind turbines..

The internal logic of the FPGA can be changed according to the actual situation of the wind farm, which is more flexible and efficient than using commercial software RTDS.

II. Dynamic Model of PMSG Power System

The entire PMSG system includes an electrical system and a control system. The electrical system can be divided into three parts: induction motor module, converter module, and electrical network module. The modeling of the electrical system will be based on EMTP (Electromagnetic Transient Program) [11]; the modeling of the control system is different according to the choice of the control principle, this paper chooses the vector control strategy.

A. Passive Component Modeling

The basic passive components in a circuit are resistors, inductors, and capacitors. Inductance and capacitance components need to use differential equations to solve the system. The EMTP is used as the theoretical basis to model the components, and the components can be linearly processed by differential methods to solve the system. .

This paper chooses to model the components with the implicit trapezoidal method. Taking the inductive element and the resistor series circuit as an example, assuming that the integral step size is Δt, the differential model of the inductive element can be obtained by the implicit trapezoidal method.

$$i_L(t)=\frac{\Delta t}{2L}u_L(t)+\frac{\Delta t}{2L}u_L(t-\Delta t)+i_L(t-\Delta t) \quad (1)$$

The inductive element can be equivalent to the parallel connection of the conductance and the current source.

$$\begin{aligned} G_L &= \frac{\Delta t}{2L} \\ I_{his} &= \frac{\Delta t}{2L}u_L(t-\Delta t)+i_L(t-\Delta t) \end{aligned} \quad (2)$$

The current source is a historically controlled current source. Other components can be differentially modeled to obtain the following table:

TABLE I. DIFFERENTIATED MODELING PARAMETERS

	I_{his}	G_{eq}
R	0	$\frac{1}{R}$
L	$\frac{\Delta t}{2L}u_L(t-\Delta t)+i_L(t-\Delta t)$	$\frac{\Delta t}{2L}$
C	$-\frac{2C}{\Delta t}u_C(t-\Delta t)-i_C(t-\Delta t)$	$\frac{2C}{\Delta t}$
RL	$\frac{2L-\Delta tR}{2L+\Delta tR}i_L(t-\Delta t)+\frac{\Delta t}{2L+\Delta tR}u_L(t-\Delta t)$	$\frac{\Delta t}{2L+\Delta tR}$
RC	$\frac{RC}{RC+\Delta t}i_C(t-\Delta t)-\frac{C}{RC+\Delta t}u_C(t-\Delta t)$	$\frac{C}{RC+\Delta t}$

B. Power Electronic Converter Modeling

The converter in PMSG system is a three-phase six-arm back-to-back converter, and the common modeling methods are: detailed model, switching function model, and average model [12].

In this paper, the detailed model is used for modeling, and the switch is equivalent to two parallel resistors with greatly different resistance values. When the switch is off, a large resistor is connected, and when the switch is closed, a small resistor is connected. Simulation tools such as PSCAD/EMTDC also adopt this model [13]-[14].

When using the detailed model to simulate the back-to-back converter, the frequent switching action will lead to the generation of numerical oscillation during the simulation process. In [15]-[17], a power electronic switch numerical value based on interpolation method to reduce numerical oscillation and simulation error is proposed. However, these algorithms need to be calculated back in the time domain, and can only be used in offline electromagnetic transient simulation. The real-time simulation cannot use this algorithm; in the reference [18], the parallel RC circuit is used to reduces the generation of numerical oscillation. The parallel RC branch is also called Snubber circuit. This method has two advantages: it does not need to change the integration method, and it can also be applied to suppress the generation of oscillation in real-time simulation. The key of this method is how to choose R_{snu} and C_{snu} , while a reasonable set of data is provided in reference [19], which can be applied to the model in this paper. At the same time, in order to reduce the generation of numerical oscillation more significantly, the Snubber circuit adopts the backward Euler method modeling with high numerical stability.

C. Permanent Magnetic Synchronous Machine Modeling

This modeling adopts the conventional PMSG model. Three stator windings are included, with two additional short-circuit windings to simulate the effects of electromagnetic damping. The following equations describe the model:

$$\begin{aligned} v_d &= r_s i_d + \frac{d\lambda_d}{dt} - \lambda_q \frac{d\theta_r}{dt} \\ v_q &= r_s i_q + \frac{d\lambda_q}{dt} + \lambda_d \frac{d\theta_r}{dt} \\ v_0 &= r_s i_0 + \frac{d\lambda_0}{dt} \end{aligned} \quad (3)$$

The above formula is the voltage equations for the main stator windings in the dq0 reference frame.

$$\begin{aligned} 0 &= r'_{kd} i'_{kd} + \frac{d\lambda'_{kd}}{dt} \\ 0 &= r'_{kq} i'_{kq} + \frac{d\lambda'_{kq}}{dt} \end{aligned} \quad (4)$$

The above formula is the voltage equations for the short-circuited windings in the dq0 reference frame.

$$\begin{aligned}\lambda_d &= L_d i_d + L_{md} i'_{kd} + \lambda'_m \\ \lambda_q &= L_q i_q + L_{mq} i'_{kq} \\ \lambda_0 &= L_{ls} i_0 \\ \lambda'_{kd} &= L_{md} i_d + L'_{kd} i'_{kd} + \lambda'_m \\ \lambda'_{kq} &= L_{mq} i_q + L'_{kq} i'_{kq}\end{aligned} \tag{5}$$

The above formula is the flux linkage equations of the windings. $\lambda'_{kq}, \lambda'_{kd}$ is Flux linkage of the shorted damper windings.

III. Simulation System Solution

This chapter focuses on the solution algorithms for electrical systems and control systems and their implementation on FPGAs.

There are many nodes in the electrical system. If the algorithm is directly used to solve the problem, the calculation result cannot be obtained within one simulation step due to the large amount of calculation, so optimization is required.

Wind turbines can be roughly divided into three modules: induction motor, converter, and electrical network. These three modules are interdependent but relatively independent. The three modules are interdependent, only serial calculations can be performed. When one module is solved, the other two modules can only be in a waiting state, resulting in a waste of time. Therefore, cut off the data dependencies of the three modules and converting serial computing to parallel computing can greatly optimize the timing of this model.

A. Multi-Area Thevenin Equivalent

MATE, also known as multi-area Thevenin equivalent, is originally intended to be applied in large-scale interconnected power systems, decomposing a large power grid into several small-scale power grids, solving each small power grid in blocks, and then merging into a large power grid [20]. Applying this algorithm to solve is roughly divided into two steps: first select some branches in the network, cut these branches and replace them with current sources; then solve each module independently, and secondly perform Thevenin equivalent at each disconnected node, the entire network can be solved [21] [22]. Assuming that the induction motor module is module A, the converter module and the electrical network module are B and C, respectively, the solution matrix of the network can be obtained.

$$\begin{bmatrix} Y_A & 0 & 0 & P_1^T \\ 0 & Y_B & 0 & P_2^T \\ 0 & 0 & Y_C & P_3^T \\ P_1 & P_2 & P_3 & -Z_\alpha \end{bmatrix}\begin{bmatrix} U_A \\ U_B \\ U_C \\ i_\alpha \end{bmatrix} = \begin{bmatrix} I_{Asou} \\ I_{Bsou} \\ I_{Csou} \\ 0 \end{bmatrix} \tag{6}$$

Among them, P_1, P_2, P_3 are the matrix of the node connection relationship between the ABC networks. When the two nodes are connected, and the current is the reference direction, the corresponding position value is 1. I_{sou} is the current of the network in the case of partitions without connection lines. Z_α, I_α are the connection line impedance and current.

After the voltage value of each node is solved according to the formula, the branch current of the network still needs to be solved. Assuming that the branch current value is I_b, then:

$$I_b = I_{sou} + Y\left(U_{n1} - U_{n2}\right) \tag{7}$$

The solution process of the electrical system network requires the participation of four matrices, namely I_{sou} ($I_{Asou}, I_{Bsou}, I_{Csou}$), Y(Y_A, Y_B, Y_C), P(P_1, P_2, P_3 P_1^T, P_2^T, P_3^T), Z_α.

B. Wind Turbine Control System

Classical VOC (Vector Oriented Control) can be divided into two parts, RSC (Rotor Side Converter) control and GSC (Grid Side Converter) control. Among them, the input of RSC is active power and reactive power, so it controls the power; the input of GSC is the voltage value of the DC bus, so it controls the voltage, and the signal acts on the power electronic switch of the converter, So as to realize the control of power and voltage. The VOC control flow is shown in the figure.

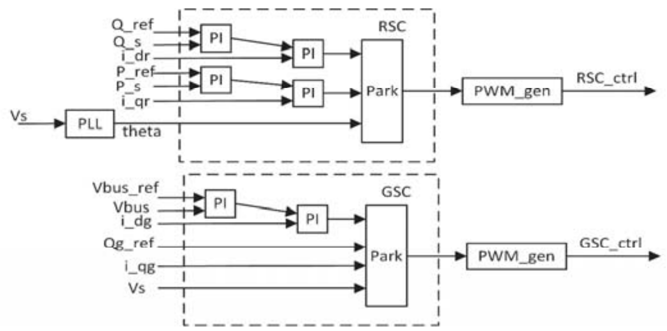

Fig. 1. VOC control flow

IV. Example Simulation and Verification

The parameters used in this experiment are as follows:

TABLE II. COMPONENT PARAMETERS

Component	Parameters	Value	Parameters	Value
Generator	Rated Capacity	2MW	Rated frequency	50Hz
	Rated line voltage	690V	Pole pairs	2
	Stator resistance	26mΩ	Stator leakage inductance	87μH
	Rotor resistance	29mΩ	Rotor leakage inductance	87μH
Converter	On resistance	1mΩ	Damping resistance	200Ω
	Off resistance	$1\times10^{10}\Omega$	Damping capacitor	$1\times10^{10}F$
	DC side capacitance	0.08F	Protection resistor	10Ω
Transformer 1	Winding 1 resistance	0.01 mΩ	Winding 2 resistance	0.01 mΩ
	Winding 1 Inductance	1μH	Winding 2 Inductance	0H
Transformer 2	Winding 1 resistance	0.01 mΩ	Winding 2 resistance	0.01 mΩ
	Winding 1 Inductance	1μH	Winding 2 Inductance	1μH
LCL filter	Inductance 1	800μH	Inductance 2	400μH
	Capacitance	60μF		

In this experiment, Xilinx Virtex®-7 FPGA VC707 was selected as shown in the figure below:

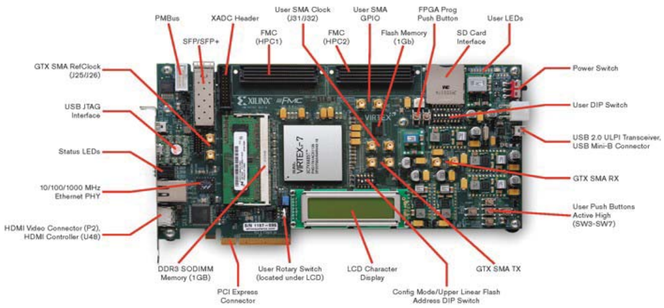

Fig. 2. Xilinx Virtex®-7 FPGA VC707

The Virtex®-7 FPGA VC707 Evaluation Kit is a full-featured, highly-flexible, high-speed serial base platform using the Virtex-7 XC7VX485T-2FFG1761C and includes basic components of hardware, design tools, IP, and pre-verified reference designs for system designs that demand high-performance, serial connectivity and advanced memory interfacing. It is equipped with up to 40Gb/s Connectivity platform for high-bandwidth and high-performance applications and Advanced memory interface with 1GB DDR3 SODIM Memory up to 800MHz / 1600Mbps.

In order to verify the correctness of the real-time simulation platform, the same electrical system and control system are built in MATLAB, and the simulation results of FPGA are compared with them. This experiment simulates the start-up process of the wind turbine. The initial speed of the wind turbine is 0m/s, and the controlled wind speed is stable at 10m/s. The entire simulation process lasted for 7s.

Pci is the active power of the rectifier side in the back-to-back converter during the start-up process of the wind turbine, and Pco is the active power of the inverter side of the converter. The simulated data in MATLAB and FPGA are compared respectively, and the results are shown in the following figure:

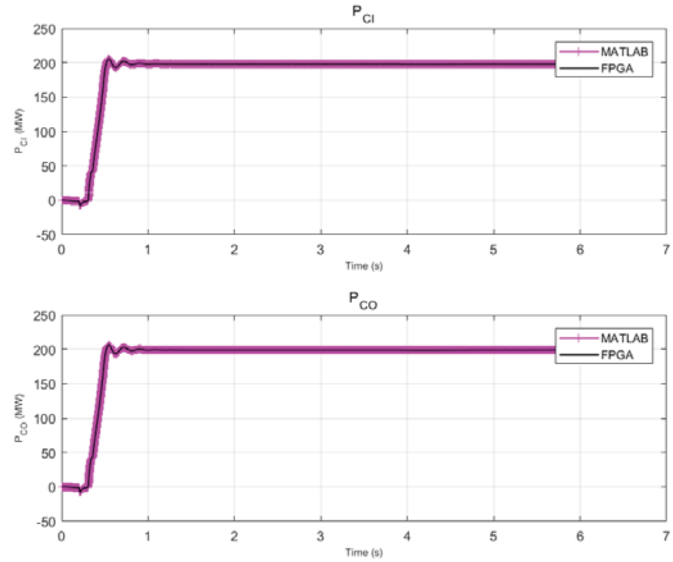

Fig. 3. Active power comparison 1

The figure below shows the comparison of active power between the rectifier side and the inverter sisde of the back-to-back converter.

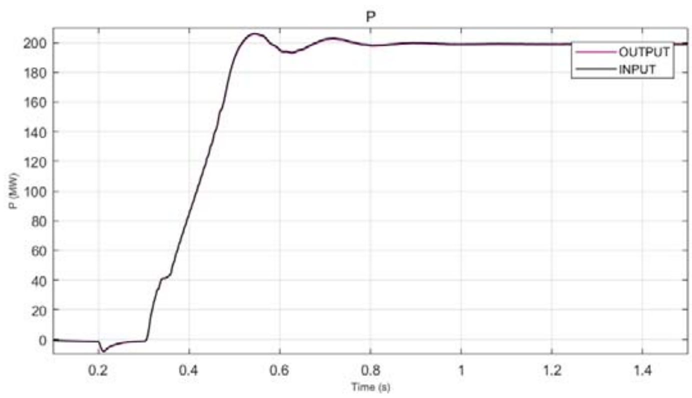

Fig. 4. Active power comparison 2

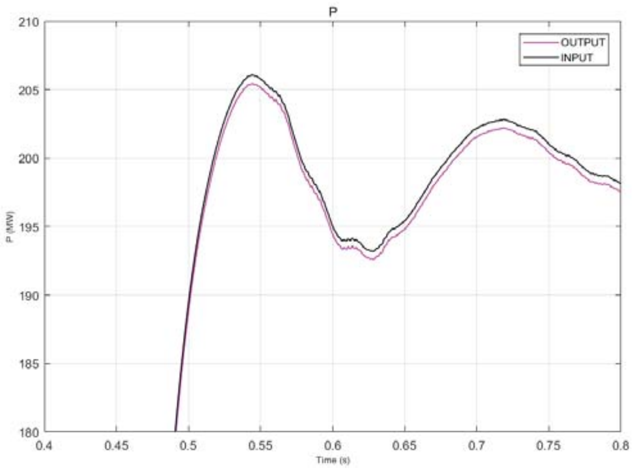

Fig. 5. Active power comparison 3

Qci is the active power of the rectifier side in the back-to-back converter during the start-up process of the wind turbine, and Qco is the active power of the inverter side of the converter. The simulated data in MATLAB and FPGA are compared respectively, and the results are shown in the following figure:

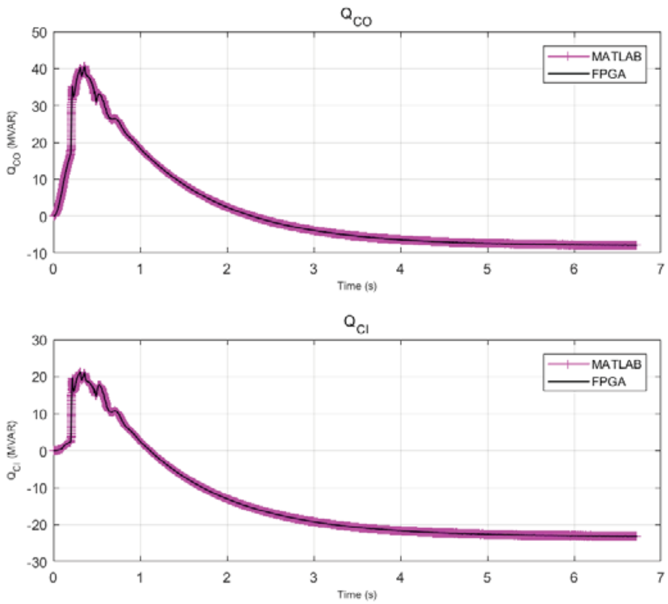

Fig. 6. Reactive power comparison

Vrms_CO is the voltage on the rectifier side, and Vrms_CI is the voltage on the inverter side. The comparison between the MATLAB and FPGA data of the voltage at both ends is as follows:

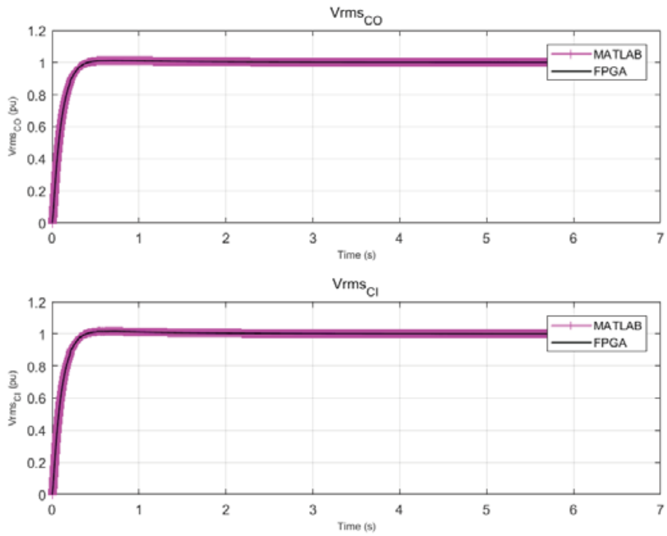

Fig. 7. Vrms comparison

The figure compares the voltage, active power, and reactive power output by the generator and back-to-back converter of the MATLAB and FPGA models. The data proves that when the simulation progresses to 0.4 seconds, the motor has entered a stable state, and the relative error at this time is within 1%. The data proves that the permanent magnet direct drive generator battery transient model based on FPGA has high accuracy. The reasons for the error are as follows:

The floating-point numbers used in FPGA simulation are 32-bit, and 64-bit floating-point numbers are used in MATLAB. The accuracy of the data involved in the calculation is different. In the end, errors will be caused by rounding, and the errors will continue to accumulate as the number of iterations increases.

In the remainder calculation, the conversion from floating-point numbers to fixed-point numbers will exchange bit width for precision, and then convert from fixed-point numbers to floating-point numbers. Errors are generated in the two conversion processes.

In order to simulate the PMSG in real time on the FPGA platform, this paper has done the following work:

1) For the electromagnetic model of the wind turbine, the simulation system is divided into two parts: the electrical system and the control system. Based on the parallelization characteristics of FPGA, a corresponding model is established.

2) Combined with the model characteristics of the electrical system, the idea of multi-area Thevenin equivalent is used to decouple the modules with data dependence, realize the parallelism at the module level, and improve the simulation speed and resource utilization in the FPGA.

3) The simulation platform is verified by applying the example of the 2MW wind turbine system. The simulation results are compared with the model in MATLAB, and the results are consistent, which proves that the simulation platform can realize the real-time simulation of the wind turbine system.

References

[1] Y. Tang, L. Wan, J. Hou,“ Full electromagnetic transient simulation for large power systems,” Global Energy Interconnection, vol 2, Issue 1, 2019, pp. 29-36.

[2] C. Warren, A. Giannopoulos, A. Gray, et al, “A CUDA-based GPU engine for gprMax: Open source FDTD electromagnetic simulation software,” Computer Physics Communications, vol 237, 2019, pp. 208-218.

[3] Y. Inoue, H. Asai, “Efficient electromagnetic simulation including thin structures by using multi-GPU HIE-FDTD method,” Applied Computational Electromagnetics Society Journal, 2018, 33(2).

[4] Z.D. Lu, Y.L. Huang, Z. Chen, Y.F. Wang, “Adaptive neural network tracking control for SbW system,” Control Engineering of China, pp. 1-6, August 2022.

[5] X.Y. Zhang, Z.Z. Zhu, Y. Fu, “Virtual synchronous stability analysis and optimized inertia control for wind power grid-connected system,” High Voltage Engineering, vol. 46, No.8, pp. 2922-2932, August 31 2020.

[6] M. Park, I.K. Yu. “A novel real-time simulation technique of photovoltaic generation systems using RTDS.” IEEE Transactions on Energy Conversion, pp. 164-169, 2004.

[7] B.L. Schenkman, D.G. Wilson, R.D. Robinett, et al, “Photovoltaic distributed generation for lanai power grid real-time simulation and control integration scenario,” SPEEDAM, 2010, pp. 154-157, 2010.

[8] V. Jalili-Marandi, L.F. Pak, V. Dinavahi, “Real-time simulation of grid-connected wind farms using physical aggregation,” IEEE Transactions on industrial electronics, 2009, pp. 3010-3021.

[9] Y. Chen, D. Venkata, “FPGA based real-time EMTP,” IEEE Transactions on Power Delivery, 2008, pp. 892-902.

[10] Y. Chen, D. Venkata, “Multi-FPGA digital hardware design for detailedlarge-scale real-time electromagnetic transient simulation of power systems,” IET Generation, Transmission & Distribution, 2013, pp. 451-463.

[11] A. Gonzalo, Rodriguez, et al, “Doubly fed induction machine : modeling and control for wind energy generation,” China Machine Press, 2014.

[12] Y. Xu, Y. Chen, L.J. Chen, Z.M. Ren, “Fast simulation method of PWM converter electromagnetic transient based on averaging theory (1): establishment of segment average model of PWM converter,” Automation of Electric Power Ststems, vol. 37 June 2013.

[13] C.S. Wang, F. Gao, P. Li, B.B. Huang, et al, “Adaptability analysis of typical models of power electronic devices,” Automation of Electric Power Ststems, vol. 36 Mar 2012.

[14] J.Xu, K.Y. Wang, G.J. Li, et al, “A general small time-step model based on the parameterized history current sources,” Proceedings of the CSEE, Vol.38, Mar. 20, 2018.

[15] Y.P. Huang, “Research on electromagnetic transient simulation algorithm of power system with power electronic apparatures,” Shanghai Jiao Tong University, 2015.

[16] C. Hong, B.R. Zhou, W.F. Yao, et al, “An interpolation method for electromagnetic transient simulation in a hybrid framework for state variable nodal analysis,” China Southern Power Grid Company Limited.

[17] K.Y. Wang, Y.P. Huang, et al, “Real-time simulation method of power electronic switch interpolation,” Shanghai Jiao Tong University.

[18] H.W. Dommel, “Digital computer solution of electromagnetic transients in single-and multiphase networks,” IEEE Transactions on Power Apparatus and Systems, 1969 pp. 388-399.

[19] Y.K. Ji, J.Z. Xu, et al, “Design method of damping circuit for suppressing numerical oscillation in simulation platform without interpolation,” Electric Power Automation Equipment, vol 36, Jul, 2016.

[20] A. Sangiovanni-Vincentelli, L.K. Chen, L.O. Chua, “A new tearing approach-node tearing nodal analysis,” IEEE International Symposium on Circuits and Systems, 1977 pp. 143-147.

[21] M.A. Tomim, J.R. Martí, et al, “MATE network tearing techniques for multiprocessor solution of large power system networks,” IEEE PES General Meeting, 2010 pp. 1-6.

[22] J.R. Martí, L.R. Linares, J.A. Hollman, et al, “OVNI: Integrated software/hardware solution for real-time simulation of large power systems,” Proceedings of the PSCC. 2002, 2.