Research on AC/DC hybrid system real-time simulation progress improvement

Yang Li\textsuperscript{1}, Guoqing He and Xing Zhang

State Key Laboratory of Control and Operation of Renewable Energy and Storage Systems, China Electric Power Research Institute (CEPRI), Beijing, China

\textsuperscript{1}Email: liyang@epri.sgcc.com.cn

Abstract. In order to improve the accuracy of real-time simulation of power electronic transformers, all models are based on FPGA modeling, and a mathematical model of power electronic transformers suitable for FPGA operations has been established. Aiming at the simulation error caused by multi-rate simulation, this paper analyzes the source of simulation error, proposes a step wave average communication algorithm, which improves the oscillation and jitter of simulation results. The simulation platform is connected to the real controller of power electronics and the real controller of new energy generation unit. The real-time simulation verification is carried out for the dynamic characteristics, control performance and stability of AC / DC system. The simulation results verify the reliability and practicability of the simulation platform.

1. Introduction
In recent years, with the rapid growth of distributed renewable energy in China, large-scale distributed renewable energy has been connected to the grid, which poses new challenges to the flexible access and effective management of the system\cite{1-3}. The introduction of multi-port power electronic transformers makes the structure of AC / DC hybrid systems diversified, and also increases the number of couplings between AC / DC subsystems\cite{4-5}. The control-in-the-loop real-time simulation platform is used to analyze the power electronic transformer, which is an effective method based on the structure design, dynamic analysis and stability research of the multi-port power electronic transformer AC / DC hybrid system.

For large-scale power electronic systems, in order to improve the calculation accuracy, it is often necessary to decouple to form different modules according to the actual situation, and different modules are set to different simulation steps according to the simulation platform and calculation scale\cite{6-7}. Because of the different simulation rate, different sub-modules will produce large errors in data interaction, and even cause errors in simulation results\cite{8}. This error can be improved or even eliminated by optimizing the architecture of multi-rate systems. Literature \cite{9} realized that the whole photovoltaic power generation system is simulated in the FPGA with subtle simulation step size, and the data interaction between different subsystems is carried out at the common multiple of different simulation steps. Literature \cite{10} has optimized the data interaction mode in the literature \cite{9} and improved the efficiency and accuracy of real-time simulation by asynchronous communication. However, this method has FPGA problems of difficult simulation modeling and high hardware cost\cite{11}, so it has poor applicability to large-scale power systems. In order to improve the flexibility and effectiveness of large-scale power electronic system modeling, this paper adopts the
CPU+FPGA[12-13] model segmentation decoupling simulation method according to the actual topology, and carries out research from the system structure, mathematical modeling and information interaction of the simulation platform. Through technology upgrading and system optimization, the simulation accuracy can be comprehensively improved to meet the engineering requirements.

2. AC/DC hybrid system real time simulation model

2.1. AC/DC hybrid system model
Combined with the actual engineering requirements, the real-time simulation platform structure of AC-DC hybrid system is designed as shown in Figure 1. The mathematical model of AC / DC hybrid system is established in RT-Lab[14-15], and 0.5 us is taken as the fixed step of real-time simulation after weighing the simulation accuracy and simulation scale[16]. The real controller uses the same controller software and hardware as the real device in the field, and verifies the control strategy by controlling the mathematical model in the RT-Lab.

![Figure 1. Structure of real-time simulation platform for AC/DC hybrid system.](image1)

![Figure 2. Overall structure of power electronic transformer.](image2)

2.2. Power electronic transformer model
The power electronic transformer model consists of three parts: H-bridge + DAB power module, output DC / DC part and output DC / AC part.

The H-bridge cascade module is directly connected to the 10kV AC side. There are two bridge arms in each phase. Each bridge arm has six H-bridge modules cascaded. Six DABs are connected in parallel at the output side. The output side has two DC / DC and one DC / AC. The overall structure is shown in Figure 2.

The detailed structure and component parameters of single H-bridge module and DAB module are shown in Figure 3.

![Figure 3. H-bridge+DAB topology and parameters.](image3)

3. Traditional system structure and existing problems of real-time simulation
For systems containing large-scale power electronics, in order to achieve a microsecond level of high-precision real-time simulation, the simulation modeling and numerical calculation of nonlinear switching devices need to be solved. In order to improve the calculation progress of PWM wave in the model, the model division and decoupling simulation method of CPU + FPGA is usually used, which
has two characteristics. The first is that the switch circuit model with power electronic devices is simulated in FPGA with a small step size (1us). The accuracy of PWM waveform simulation is improved by the high-speed sampling and high-speed calculation function of FPGA. The second is that the mathematical model of the linear circuit adopts a large step (50us) simulation in the CPU, and uses Simulink's automatic code generation and numerical calculation functions to achieve real-time simulation; and the traditional composition structure of its simulation system is shown in Figure 4.

Using traditional multi-rate simulation system shown in Figure 4 will cause distortion of the PWM waveform transmission, distortion of the voltage and current sampling signal, and distortion of the display waveform. For example, the high-speed FPGA system outputs data to the CPU simulation system in 1us step, and the CPU collects the signal in 40us step, so that the signal is distorted. The distorted signal is used as the input voltage excitation source of the linear model, which causes the accuracy of the simulation result of the linear model to decrease, or even the wrong simulation result. At the same time, the voltage, current and other waveforms collected by the real controller from the CPU are not accurate simulation result, which leads to the decline of the control performance of the controller. In addition to the possibility that the steady-state results are not correct, it may also be that the voltage and current waveforms have no jitter phenomenon, and even more serious, it may even lead to the conclusion simulation error of unstable control.

Taking the semi-physical simulation of power electronic transformers as an example, Figure 5 is the semi-physical simulation results obtained using the traditional multi-rate simulation structure. By repeatedly adjusting the control parameters in the controller, the optimal simulation result still contains the chattering and waveform distortion that do not exist in the real system.

### 4. Multi-rate simulation system optimization

Through the analysis of the architecture and data transmission mode of the simulation system, it can be seen that the main factor affecting the simulation accuracy is the error caused by data transmission speed between different subsystems. By optimizing and improving the architecture of multi-rate system, such errors can be improved or even eliminated. One method is to use the whole FPGA simulation system architecture, build the whole mathematical model in the FPGA, and use the microsecond level simulation step to carry out real-time simulation, which eliminates the problem of multi-rate information transmission. However, this method has the problems of FPGA simulation modeling difficulty and high hardware cost, so it is very unlikely to be implemented at this stage.

In order to obtain higher-precision PET real-time simulation results and suppress simulation jitter and distortion, this project conducts research from the three aspects by the simulation of platform's system structure, mathematical modeling, and information interaction. With technical upgrades and
system optimization, the simulation accuracy is comprehensively improved to meet the needs of dynamic characteristic analysis, impedance stability analysis, and operation scenario analysis.

4.1. System structure optimization
The system structure optimization is mainly aimed at the overall structure construction and model segmentation of the real-time simulation platform. The schematic diagram is shown in Figure 6. The main optimization methods include the following:

- Simulate the switch circuit and high-frequency transformer in FPGA at the same time, write the underlying FPGA code to realize the numerical solution of the PET mathematical model, and achieve high-precision simulation within 1us.
- The AC / DC system model uses Simulink environment modeling, which is simulated in the CPU, with a simulation step size of 50us, which meets the needs of system simulation and simulation while reducing the difficulty of simulation modeling and system cost.
- The data transmitted by CPU and FPGA self-check each other, use the average compensation algorithm to improve the data progress, and overcome the error generated when the PWM waveform is output from the FPGA to the CPU.

![Figure 6. PET real-time simulation platform proposed in this paper.](image)

4.2. Mathematical models suitable for FPGA real-time simulation
The model of power electronic transformer is completely simulated in FPGA, and FPGA operation code is needed. The FPGA code of the model is the mathematical analysis of the operation principle of the power electronic transformer. Therefore, the mathematical analysis method of the power electronic transformer determines the efficiency and accuracy of the code. To establish a mathematical model of electronic and electronic equipment, two types of modeling methods can be used. One is based on a general IGBT modeling method and uses a general modeling theory to complete the modeling of power electronic transformers. The second is to build a model of power electronic transformers in a targeted manner, and build a model with the help of working principles. The choice between the two methods is mainly in the calculation efficiency of the simulation model. Under the premise of the same simulation accuracy, which method is more efficient, which method is preferred. In this paper, the number of power electronic transformer switching devices is large and the structure is complex. The general node voltage method and other modeling methods are difficult to compare with the targeted modeling method in terms of operation efficiency. Therefore, based on the operation principle of PET, this paper establishes a PET mathematical model suitable for FPGA programming, uses a controlled voltage source and a controlled current source to replace the original circuit switching device, the simulation system judges the output of the controlled power supply through the switch state of the collected IGBT, and realizes the PET mathematical model which can be used for FPGA programming.

For the AC / DC converter model on the 10kV side, the circuit topology of each H-bridge module is transformed into an equivalent circuit composed of controlled sources, as shown in Figure 7. The voltage values of the first controlled voltage source Uchb1 and the second controlled voltage source
Uchb2 are determined by the switching states of the capacitance voltage $U_{pc}$ of the primary capacitor $C_p$, and the switch state of the first switch $S_1$, the second switch $S_2$, the third switch $S_3$ and the fourth switch $S_4$, as shown in Table 1.

**Table 1.** The output logic diagram of the equivalent controlled source.

| State | 1 | 2 | 3 | 4 | 5 |
|-------|---|---|---|---|---|
| S1    | Off | On | Off | On | Off |
| S2    | Off | Off | On | Off | On |
| S3    | Off | On | Off | Off | On |
| S4    | Off | Off | On | On | Off |
| Uchb1 | $U_{cp}$ | 0 | 0 | $U_{cp}$ | $-U_{cp}$ |
| Uchb2 | $-U_{cp}$ | 0 | 0 | $U_{cp}$ | $-U_{cp}$ |
| $I_{hc}$ | $|larm|$, | 0 | 0 | $larm$, | $-larm$ |

In Figure 7, regardless of the simultaneous opening and dead band effects of any two switches of the same bridge arm, when the first switch $S_1$, the second switch $S_2$, the third switch $S_3$, and the fourth switch $S_4$ are off, the first voltage value of the controlled voltage source $U_{chb1}$ is the capacitance voltage $U_{pc}$ of the primary capacitor $C_p$, and the voltage value of the second controlled voltage source $U_{chb2}$ is the negative value of the capacitance voltage $U_{pc}$ of the primary capacitor $C_p$; when the first switch $S_1$ is in the on state, the second switch $S_2$ is in an off state, the third switch $S_3$ is in an on state, and the fourth switch $S_4$ is in an off state. The voltage value of the first controlled voltage source $U_{chb1}$ is zero, and the voltage value of the second controlled voltage source $U_{chb2}$ is zero; When the first switch $S_1$ is off, the second switch $S_2$ is on, the third switch $S_3$ is on, and the fourth switch $S_4$ is off, the voltage value of the first controlled voltage source $U_{chb1}$ is a negative number of the voltage $U_{pc}$ value of the original capacitance $C_p$, and the voltage value of the second controlled voltage source $U_{chb2}$ is a negative number of the voltage $U_{pc}$ value of the original capacitance $C_p$.

The above method is used to perform an equivalent of the LC resonance circuit, and the equivalent circuit of the Module shown in Figure 8 could be obtained. Among them, the IGBT switch circuit is replaced by a controlled voltage source and a controlled current source, and the secondary side of the high-frequency transformer is converted to the original side, thereby forming a new controlled source equivalent model. The voltage value of the third controlled voltage source $U_{pr}$ is determined by the voltage value $U_{pc}$ of the primary capacitor $C_p$ and the switching states of the fifth switch $S_5$, the sixth switch $S_6$, the seventh switch $S_7$ and the eighth switch $S_8$. The logic table is shown in Table 2.
Table 2. The output logic diagram of equivalent controlled source.

| Status 1 | Status 2 | Status 3 | Status 4 |
|----------|----------|----------|----------|
| S5       | On       | Off      | On       |
| S6       | Off      | On       | Off      |
| S7       | On       | Off      | Off      |
| S8       | Off      | On       | On       |
| Upr      | 0        | 0        | Ucp - Ucp |

Figure 8. The equivalent model of the single H-bridge module in the backward stage.

Using the modeling method described in this article, a mathematical model suitable for FPGA programming can be obtained, which mainly has the following characteristics:

- The IGBT circuit is converted with a controlled voltage source and a controlled current source, which can be handled as a linear circuit, and it has the foundation to establish a real-time simulation model;
- The output of the controlled power supply is determined by the logical combination of the original IGBT switching signals, which is suitable for FPGA to perform high-speed logic calculation;
- The high-frequency transformer is converted into a non-coupled passive circuit through winding conversion, which is convenient for establishing linear differential equations and developing numerical solutions;
- The establishment and calculation of the model are all implemented in FPGA, the simulation step is within 1us, and the simulation accuracy meets the needs of the project.

4.3. Multi-rate simulation communication quick compensation algorithm

Different rate simulation sub-modules realize parallel synchronous calculation by exchanging simulation results with each other. In general, the FPGA simulation model with small step size usually needs to output the three-phase AC ladder wave output by PET to the CPU. The voltage and current from CPU simulation are output to FPGA. The error source of multi-rate simulation communication is mainly the staircase wave output from the FPGA to the CPU, as the sampling interval is very long in the CPU, the staircase wave is distorted, which affects the simulation results. In this project, the step size of FPGA is generally 0.5us, which can ensure that the output ladder wave is close to the precise at the rising and falling edges of each waveform transition. The CPU step size is about 50us, and the step wave acquired by the 50us interval will lead to a large difference between the step wave obtained by the CPU and the step wave actually output by the FPGA, which is the source of the error, as shown in Figure 9. The influence of this error on the simulation results of 10kV AC side is especially obvious.

Figure 9. Sources of multi-rate parallel communication errors

Figure 10. Communication algorithms to calculate the average.
In response to the source of this error, this project proposes a communication algorithm based on the average output of the staircase wave, with its basic principle is shown in Figure 10. The staircase wave simulated in the FPGA calculates the average value of the waveform according to the simulation step size of the CPU, that is, the area of the waveform is divided by 50us, and the average value is output to the large-step model through the communication system. In the CPU, the step wave is often used as the input excitation power supply as the system equation. The power supply generally performs the integral operation in the system model solution. The average value communication algorithm in this paper can ensure the accuracy of the long stride integral in the CPU, and then ensure the accuracy of the integral result of the CPU. Using this method is equivalent to adding a 5kHz low-pass filter link to the simulation system, but it still has sufficient bandwidth and accuracy for power system dynamic characteristics and oscillation analysis.

5. Simulation verification

With the improvement scheme of real-time simulation technology described in this section to carry out simulation verification on the AC / DC hybrid system based on power electronic transformer, and under the premise that the control strategy does not change, the resulting waveform jitter and waveform distortion have been greatly improved, and the simulation results are shown in Figure 11.

![Figure 11. Comparison of real-time simulation results before and after improvement.](image)

Carry out real-time power step simulation on the DC750V port: the power electronic transformer absorbs the power electronic transformer changes from 1MW absorbed grid power to 1MW feedback grid power, and the simulation results show that the controller can realize dynamic and steady-state characteristics simulation. Compared with the previous simulation results, it can be seen from the simulation results in figures 9 to 11 that the waveform jitter of DC bus voltage and AC current has been obviously suppressed, and the resonance effect of high-frequency resonance transformer fully meets the theoretical requirements, while the high-frequency current waveform has no waveform distortion.

6. Summary

This paper establishes the control loop real-time simulation system of microsecond stage simulation step size, establishes the mathematical model of power electronic transformer of core equipment, solves the FPGA modeling of resonant DC/DC converter, and realizes the microsecond stage high precision simulation of high frequency transformer. The staircase average communication algorithm is used to improve the oscillation and jitter of the simulation results. Mathematical model of AC / DC hybrid system with full FPGA is established. Through the above measures, high-precision real-time simulation is realized, which lays the foundation for real-time simulation verification of the dynamic characteristics, control performance and stability of the AC and DC systems.
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