The establishment of real time simulation platform of AC/ DC system based on power electronic transformer

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Abstract. This paper presents a real-time simulation platform of a AC/DC hybrid system using embedded simulators as kernel components, where the power electronic transformer (PET) is established by VHDL to break through the limitation of maximum emulatable switches in MATLAB/Simulink. Other components in the hybrid system including DC/DC converter, DC/AC converter and renewable generation units are simulated on CPU computing units. High-speed communication interface is used to ensure microsecond-level simulation step. Hardware-In-The-Loop (HIL) tests are taken to validate the proposed simulation platform.

1. Introduction
In recent years, with the rapid growth of distributed renewable energy in China, large-scale distributed renewable energy access to the power grid has raised new challenges and higher requirements for the flexible access and effective management of the system[1][2]. At present, there are many AC/ DC conversion applications in renewable energy access technology aiming to improve the efficiency and enhance the convenience of the access to energy [3-5]. However, the lack of interconnection and flexible regulation of distribution network limit the full consumption and efficient utilization of distributed renewable energy. With the use of bidirectional multi-port power electronic transformers (PET) in AC/ DC hybrid systems, many advantages can be achieved such as flexible networking, integration of distributed renewable energy at multiple AC and DC voltage levels, reduction in numbers of used conversion devices, improvement of energy efficiency and enhancement of system control capability [6].

Nevertheless, it has to be noticed that the introduction of PET adds diversity to the AC / DC hybrid system while increasing the coupling between microgrid and utility grid. To get a clear view of the complexity brought in by the PET, the control in the loop real-time simulation platform [7-15] is often used to analyze the dynamic complex behavior of the system caused by the diversity of operation forms and the strong coupling, which can provide basis for the structural design, dynamic analysis and stability qualitative research of the multi-port power electronic transformer AC/DC hybrid system. Therefore, it is of great practical significance to establish a real-time simulation platform of AC/DC hybrid system with small step size.

Many important research efforts have been done on the approaches to realize high-performance real time simulation [16-25]. For instance, the associated discrete circuit (ADC) method and its improvement [8-10] enable circuit parameters to keep constant by replacing each element with companion circuit, and thus alleviate computation burden; other researchers combine two-value resistor switch model with network-partitioning method [11][12] to make the strategy feasible for real-
time simulation. There are also some researches focusing on the hardware implementation to enhance simulation accuracy [13][14], concerning for example, floating-point representation of FPGA-based real time simulators. However, many of the aforementioned researches mainly pay attention to some converters with simple topologies, like Voltage Source Converer (VSC) and Modular Multilevel Converter (MMC), in small-scale microgrid, which may not fully excavate the hardware resources. Therefore, the modeling and real time simulation method of the relatively complicated converter (like PET) in a relatively large-scale is not fully explored. In this paper, a real time simulation method for a AC/DC hybrid system including PET is proposed. The AC and DC microgrids are decoupled and simulated on several CPUs while the model of PET is translated into VHDL for the simulation on FPGA.

The rest of the paper is organized as follows: Section 2 introduces the model of each part in hybrid system; the design of simulation platform is proposed Section 3; Section 4 gives the simulation results and analysis; Section 5 draws the conclusion.

2. Real time simulation model of AC/DC hybrid system

2.1. AC/DC hybrid system model

The structure of real-time simulation platform of AC-DC hybrid system is shown in Figure 1. Among them, the mathematical model of AC-DC hybrid system is established in RT-LAB and runs in fixed step (0.5us). The output of the simulation model are transmitted to the real controller through the simulation interface. The real controller uses the same software and hardware as the real equipment on site, and verifies the control strategy by controlling the mathematical model in RT lab.

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

2.2. Power electronic transformer model

The model of PET 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 cascaded H-bridge modules. 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.

The key technical parameters of H-bridge module and DAB module are shown in Table 1 and Table 2.
Table 1. List of power electronic equipment for AC / DC system.

| Serial number | Device name                      | Key Parameter                      |
|---------------|----------------------------------|------------------------------------|
| 1             | Power Electronic Transformer     | ±375V, 500kW; ±750V, 2MW; 380V, 500kW |
| 2             | Energy Storage DC / DC-1         | 750V, 500kW                        |
| 3             | Energy Storage DC / DC-2         | 375V, 100kW                        |
| 4             | Photovoltaic DC / DC-1           | 750V, 500kW                        |
| 5             | Photovoltaic DC / DC-2           | 375V, 100kW                        |
| 6             | Fan DC / DC-1                    | 750V, 500kW                        |
| 7             | Fan DC / DC-2                    | 375V, 100kW                        |
| 8             | Photovoltaic DC/AC               | 380V, 100kW                        |
| 9             | Fan DC/AC                        | 380V, 100kW                        |
| 10            | Energy storage DC/AC             | 380V, 100kW                        |

Figure 2. Overall structure of power electronic transformer.

Figure 3. H-Bridge+DAB topology and parameters.
Table 2. Key technical parameters of H-bridge+DAB module.

| Serial Number | Index                      | Parameter                   |
|---------------|----------------------------|-----------------------------|
| 1             | H-bridge Switching Frequency | 2-10kHz adjustable          |
| 2             | AC isolation inductance Larm | 10mH                        |
| 3             | DAB High Frequency Resonance | 4kHz-8kHz                   |

Control strategy: H-bridge+DAB module adopts outer voltage loop and inner resonant current loop, eliminating complex phase-locked links. The debugging algorithm adopts unipolar carrier phase-shifting debugging algorithm, as shown in the Figure 4.

![Double closed loop control algorithm of H-bridge + DAB module.](image)

The DC output link of the PET includes two step-down DC/DC modules, reducing 750V to 375V. The circuit topology and parameters are shown in the Figure 5.

![Power electronic transformer output DC/DC.](image)

![Power electronic transformer output DC/AC.](image)

The AC output port of PET is interfaced with AC microgrid whose circuit topology and parameters are shown in Figure 6.

2.3. New energy grid-connected converter model

Grid-connected converter refers to the grid-connected converter interacting with different voltage types, which is mainly divided into two types: DC/DC converter and DC/AC converter.

There are two sets of Photovoltaic DC grid-connected DC/DC modules both using the step-down buck circuit structure while connected to 375V and 750V DC buses respectively. The topology and parameters is shown in Figure 7.

![PV grid-connected DC/DC topology and parameters.](image)
The energy storage bidirectional DC/DC topology adopts a buck-boost circuit structure, connected to 375V and 750V respectively and having the same topology and parameters, as shown in Figure 8 and 9.

The AC/DC converter connects to photovoltaic devices, energy storage elements and wind farm through DC port when connects to the 380V AC bus through AC port. The topology and parameters are shown in Figure 8 and Figure 9.

Figure 8. Energy storage bidirectional DC/DC topology and parameters.  
Figure 9. Grid-connected DC/AC topology and parameters.

3. Real time simulation platform of AC/DC hybrid system

The real-time simulation system based on RT-LAB is mainly composed of OP5600 and OP5607. OP5600 uses Intel's CPU as the computing unit and is responsible for driving the real-time operating system as well as executing the linear system model calculation and simulation management functions. OP5607 takes FPGA as the core of operation; it converts Simulink model into HDL language for simulation, which is used for the simulation of high-speed power electronic switch model. The physical parameters of the two hosts are as follows:

**OPP5600 real-time simulation host**
1. X8/16/32/64 cores 3.46 GHz, Xilinx FPGA (Spartan 3 or virtex 6);
2. Real time operating system (Linux RedHat) and powerful I/O processing capability;
3. Up to 128 analog I/O or 256 digital I/O or both;
4. Connect with external equipment by DB37;
5. I/O monitoring on the front panel;
6. Up to 4 PCI slots;
7. Support the third-party I / O communication protocol IEC61850, UDP / IP, can, ARINC, Mil1553, IRIG-B, DNP3.0, c37.118, etc.
8. Parallel simulation by FPGA and CPU can be realized, and the simulation accuracy on FPGA can reach 0.25 microseconds (based on Virtex6FPGA). Power electronic system requires high simulation step size and model accuracy, which need to be in the step size of 20μs ~ 50μs In order to simulate high-speed transients.

**OP5607 real time simulation host**
1. Up to 128 analog I / O or 256 digital I / O or both;
2. 4U case, including a Virtex 7 FPGA card;
3. PCIe x 4 (20gbps) communication interface.

In order to meet the technical requirements of 1000 switching devices and 0.5us simulation step proposed in this project, this paper uses co-simulation system based on OP5600 and OP5607, and the hardware platform architecture is shown in Figure 10. The host computer communicates with OP5600, OP5607 and IPCs(Industrial Personal Computer) through a network switch, and performs data interaction through a network cable. OP5600, OP5607 and various IPCs are interconnected through Dolphin switches to synchronize data and improve simulation accuracy. Due to the characteristics of complex model and heavy computation burden when modeling electromagnetic transient simulation of AC/DC hybrid system, the model is decoupled into multiple subsystems and downloaded to different computing units to run, and thus increases the scale of system simulation. Through the host computer...
RT-LAB software and network cable, each subsystem could be downloaded to the core of each OP5600, OP5607 and IPC for calculation, so that the speed and accuracy of real-time simulation could be improved.

![Figure 10. OP5600 and OP5607 joint simulation system.](image)

In order to break through the limitation of EHS model on the numbers of power electronic switch devices for simulation, this paper uses underlying programming method in FPGA to build the mathematical model of power electronic transformer. Considering the voltage and current operation laws corresponding to the different switch states of power electronic transformer switch devices, VHDL language is used to build the modular cascade H-bridge model and the resonant converter model based on FPGA, which are packaged with Simulink library file as a callable mathematical model. The mathematical model of power electronic transformer built by this method could improve the efficiency of model operation and make full use of the digital logic operation ability of FPGA in OP5607, which greatly improves the simulation scale and efficiency. After being encapsulated as Simulink model, it could be used as standard module to facilitate the establishment of a mathematical model of an AC / DC hybrid system.

In the topology of multi-port PET, the total number of IGBTs and diodes is 884. Each of the three ports contains a certain number of renewable generation units and power electronic loads. The 380V port includes two back-to-back power generation units and one back-to-back power electronic load. The ±750V port consists of four power generating units and two power electronic loads. The ±375 port includes 4 power generating units and 2 power electronic loads. According to the simulation results of OP5607 simulation of power electronic devices, each OP5607 can simulate 500 switching devices, while ensuring that the simulation step of 0.5us with no time out. In this paper, five OP5607 are used for parallel simulation, with a total simulation capacity of 2500 switching devices and a simulation step of 0.5us. The specific statistical information is shown in the table below.

| Port Type   | Number of Generators | Number of Loads | Simulation Capacity | Simulation Step |
|-------------|----------------------|-----------------|---------------------|-----------------|
| 380V        | 2                    | 1               | 1000                | 0.5us           |
| ±750V       | 4                    | 2               | 2000                | 0.5us           |
| ±375V       | 4                    | 2               | 1000                | 0.5us           |
According to Table 3, in the AC/DC hybrid system, the number of switches for power electronic transformers of key equipment is 884, and the AC/DC system contains both renewable generation units and power electronic loads, and the total number of switches is 1004. In order to realize the simulation of the transient small step size of the AC and DC system, and to accurately simulate the high frequency harmonics and control characteristics of the system, the simulation step size of 0.5us could be used to meet the accuracy requirements. In the simulation platform established by this subject, a single high-performance FPGA simulator could simulate up to 500 switching devices at 0.5us steps, and the reason lies in that the model of PET is established by VHDL which can help realize more switches than MATLAB/Simulink model does. According to the configuration of 5 parallel operations, the final simulation capability could reach 2500 switching devices and 0.5us Simulation capability of simulation step size.

**Table 3.** Comparison of simulation requirements and simulation platform capacity of AC/DC system.

| Number of Switching Devices in Power Electronic Equipment | Simulation Platform Parameters |
|----------------------------------------------------------|--------------------------------|
| Power Electronic Transformer  | 884 | Number of Simulation Switches of single OP5607 | 500 |
| ±750V Line Power Electronic Equipment | 48 | Max Step Size | 0.5us |
| ± 375v Line Power Electronic Equipment | 48 | Number of OP5607 stations | 5 |
| 380V Line Power Electronic Equipment | 72 | Overall simulation capability of simulation platform | 2500 |
| Total | 1004 | Total | 2500A /0.5us |

**Figure 11.** Real time simulation platform to control hardware in the loop.

Through decoupling and multi-core parallel computation for AC and DC systems, the simulation efficiency can be greatly improved and the simulation step size can be reduced. As shown in Figure 11, the PET model and the renewable generation units are built in OP5607, the simulation step size of the FPGA simulator can reach 100ns-1us, and functions like data collection, calculation, processing, storage, transmission and so on are integrated in the CPU simulator OP5600, with the CPU simulation step size being able to reach 10-50us. Different simulation conditions can be set in OP5600, such as normal conditions, short circuit conditions, sudden load change conditions, system oscillation conditions, etc. The actual controller evaluates and controls the hybrid system according to the collected values of voltage, current and other physical quantities from the converter models, and sends the trigger signals of corresponding circuit breakers, contactors and IGBT. According to the received signals the AC/DC hybrid system model controls the closing and opening of corresponding circuit breaker, contactor and IGBT to simulate the actual operation of AC-DC system. Thus, the transient and steady-state characteristics of the AC/DC hybrid system under different operating conditions can be obtained.

4. Simulation and results
The developed real time simulation platform is tested in the following scenarios:
- (1) PET operates at 2MW in steady state;
- (2) Active power of PET has a step change;
(3) Reactive power of PET has a step change;
(4) Output power from AC 380V port of PET has positive and negative step changes;
(5) Active power from 10kV AC side of AC/DC hybrid system has a sudden change.

4.1. Power electronic transformer 2MW steady state operation simulation

The ± 750V DC bus of the power electronic transformer is connected to a power load of 2MW. During steady-state, the simulation waveform of the power electronic transformer in the loop is shown Figure 12, Figure 13, Figure 14, Figure 15 and Figure 16. It could be seen that ± 750V voltage and current are stable, and the control target with a power factor of 1 could be achieved on the 10kV AC side.

![Figure 12 DC bus voltage (+ 750V) and DC current waveform.](image)

![Figure 13. DC bus voltage (- 750V) and DC current waveform.](image)

![Figure 14. Waveform of AC 10KV voltage and current (60 times of current amplification).](image)

![Figure 15. The output of a 11 step line voltage waveform of power electronic transformer in steady state.](image)

![Figure 16. Primary voltage and current waveforms of the resonant converter at steady state.](image)
4.2. Active power step change of power electronic transformer

The electrical load on the ± 750V side is stepped from 1MW to 2MW, and the real-time simulation waveform is shown in Figure 17, Figure 18, Figure 19 and Figure 20. It can be seen from the waveform that the DC bus voltage drops 50V in the instant of the step, and then returns to stable state under the control. The dynamic process lasts for about 5 seconds, and the DC current can quickly follow the load change. The control performance of \( i_d \) and \( i_q \) on AC side is good, and the dynamic process lasts for 4 sine cycles.

![Figure 17. Voltage and current waveform of ± 750V DC bus.](image)

![Figure 18. AC three-phase voltage and current waveforms.](image)

![Figure 19. AC side ID, IQ setting and feedback current waveform.](image)

![Figure 20. Resonance voltage and current waveform.](image)

4.3. Reactive power step change of power electronic transformer

When the AC output active power of power electronic transformer is 1MW, the reactive power \( Q \) changes as follows: 0-200kvar-500kvar-200kvar-0. The real-time simulation waveform is shown in Figure 21, Figure 22, Figure 23 and Figure 24. When the reactive power suddenly changes, the voltage and current at ± 750V side are stable. The dynamic process of AC side lasts about 400ms.
**Figure 21.** Voltage and current waveform of ± 750V DC bus

**Figure 22.** AC three-phase voltage and current waveforms.

**Figure 23.** AC side ID, IQ setting and feedback current waveform.

**Figure 24.** Resonant voltage and current waveforms.
5. Summary
In order to meet the actual needs of structural analysis, dynamic characteristics and stability research of the AC/DC hybrid system based on the power electronic transformer, this paper establishes control-in-the-loop real-time simulation system with microsecond-level simulation step size, which provides a powerful tool for the simulation research of the AC-DC hybrid system.

First, the real-time simulation platform is established with the main structure of several pieces of OP5600 communicating with OP5607 through the high-speed interface PCIe, so the hardware resources are fully used and microsecond-level simulation step is obtained. In addition, the model of PET is constructed by VHDL which has the ability to realize more power electronic switches than the counterpart of Matlab/Simulink does.

Second, The 4GHz high-speed serial communication interface technology is designed to realize the signal interface between the PET controller and the real-time simulation system. A single optical fiber is used to transmit the switching signal and analog signal of power electronic transformer. Under the premise of ensuring the simulation step of 0.5us, the input cost of the simulation platform is greatly reduced.

The simulation platform is connected to the real controller of utility grid, the real controller of renewable generation units, etc., to carry out real-time simulation of the semi-physical and real-time simulation verification of the dynamic characteristics, control performance, stability, etc. of the AC and DC systems. The simulation results verify the reliability and practicability of the simulation platform.

Acknowledgements
This work is supported by Research on control performance improvement technology of new energy generation based on hardware in the loop simulation platform and National Key R&D Program of China, 2017YFB0903300.

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