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A DESIGN OF REAL-TIME SIMULATOR FOR PMSG BASED WIND FARMS USING PIPELINE TECHNIQUE

Hao Fu[1], Peng Li[1], Hao Yu[1*], Ligang Zhao[2], Zhiying Wang[1], Chengshan Wang[1]

1 Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin 300072, China

2 State Key Laboratory of HVDC, Electric Power Research Institute, CSG, Guangzhou 510663, China

ABSTRACT

Large-scale wind farm integration poses serious challenges to the operation and control of power systems. Real-time simulator is an effective tool to reproduce the dynamics within wind farms and the influence on the system. In this paper, a novel design of real-time simulator for permanent magnet synchronous generator (PMSG) based wind farms is proposed using pipeline technique, which can realize the high-efficiency simulation under limited hardware resources compared with traditional method. With the proposed design, a PMSG based wind farm is simulated, and the simulation results are compared with PSCAD/EMTDC to validate the correctness and effectiveness of the design.

Keywords: wind farm, pipeline technique, real-time simulation, permanent magnet synchronous generator (PMSG), field programmable gate array (FPGA)

NONMENCLATURE

Abbreviations	
WTG	wind turbine generator
PMSG	permanent magnet synchronous generator
FPGA	field programmable gate array
PCC	point of common coupling
MSC	machine-side converter
GSC	grid-side converter
ADC	associated discrete circuit

1. INTRODUCTION

The increasing penetration of wind power in the power system makes the interaction between wind farms and the grid to be effectively analyzed, from the voltage stability problem to the fault ride-through of wind turbines. Although off-line transient simulation can analyze the complex dynamic characteristics of these transient processes [1], rapid transient analysis of wind farms still needs real-time simulation, moreover, the real-time simulation is with the capabilities of hardware-in-the-loop.

Wind farms typically consist of tens to hundreds of wind turbine generator (WTG) units, along with varieties of controllers and high frequency power electronic devices, etc. The huge computation burden of wind farms poses challenges to real-time simulators, and researchers have been using the concept of processor-cluster to improve the performance of real-time simulators [2]. But the cost of more processors is relatively high, which is sometimes not suitable for the real-time simulation of large-scale wind farms.

The proposed design based on the pipeline technique is specified for real-time simulation of wind farms, in which large numbers of WTG units usually have the same structure. Especially for PMSG based wind farms whose model calculation can be divided into multi-level sub-processes, the efficient and accuracy simulation can be realized under limited hardware resources using the superscalar pipeline and module-level pipeline.

2. MODELLING OF PMSG WIND TURBINE

2.1 Topology

Due to the merits such as variable speed constant frequency operation, PMSG units occupy a major part of the newly installed wind farms [3]. A typical PMSG unit is shown in Fig. 1. Based on the decoupling relationship in solving, the PMSG unit can be divided into a control system and an electrical system. In the electrical system, a PMSG is connected to the point of common coupling (PCC) via a machine-side converter (MSC), a grid-side converter (GSC), a three-phase LC filter, a three-phase set-up transformer and a three-phase line. The control system mainly includes the controllers of MSC and GSC, the control modules of PMSG and so on.

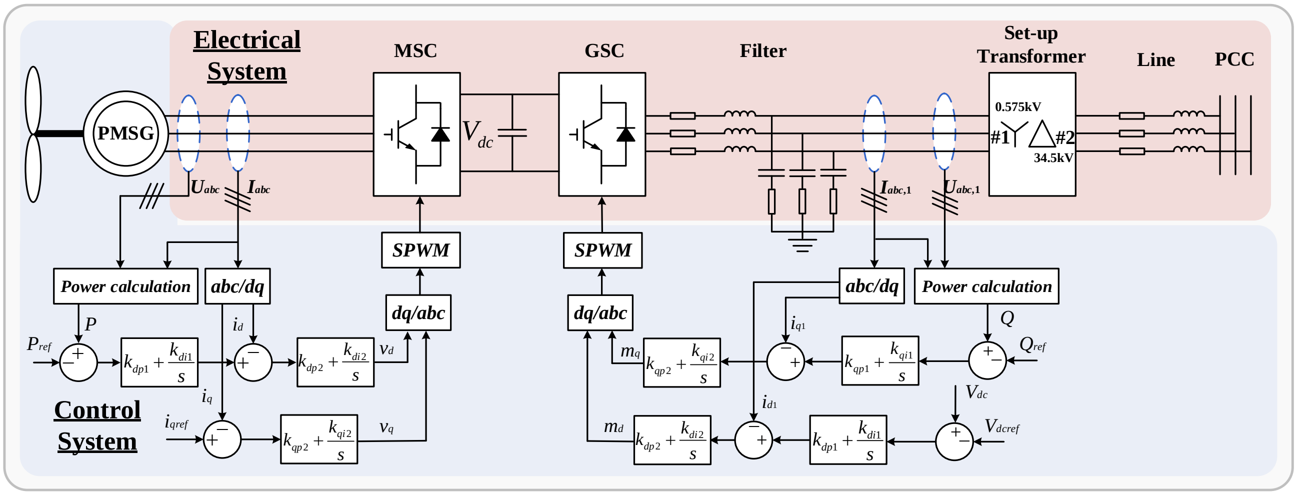

Fig 1 Configuration of the PMSG wind turbine

2.2 Modelling of electrical system

In the FPGA-based real-time simulator, the PMSG is equivalent to the controlled current source, realizing the connection between electrical and control system, and its complex mathematical model is calculated in the control system. To avoid matrix refactorization and reduce resources consumption, this paper adopts the associated discrete circuit (ADC) [4] to represent power electronic circuits in the converter.

Table 1 Four steps of the simulation of electrical system

Step 1	Calculating history current sources
Step 2	Forming the history current source vector
Step 3	Calculating node voltages
Step 4	Updating branch currents

The nodal analysis method is adopted to analyze the electrical system, and it includes four steps, listed in Table 1. Each step is realized by a basic solving unit, and each solving unit includes various component solving modules and functional modules, which is suitable for solving with the module-level pipeline.

2.3 Modelling of control system

The control elements are described in terms of I/O relation. The solving of control system is obtained according to the connection sequence of all elements. Feedback loops are decoupled by inserting a time step delay. This is appropriate since feedback loops are in small quantities in the control system of PMSG units and the real-time simulation step is usually in microsecond level. This method avoids the solving of nonlinear equations and enables parallel calculation, which is suitable for solving with superscalar pipeline.

In this paper, the q-axis model in the double-loop control of GSC is taken to illustrate the modeling of the control system, shown in Fig. 1. And the detailed hardware design of the q-axis model is shown in Fig. 2.

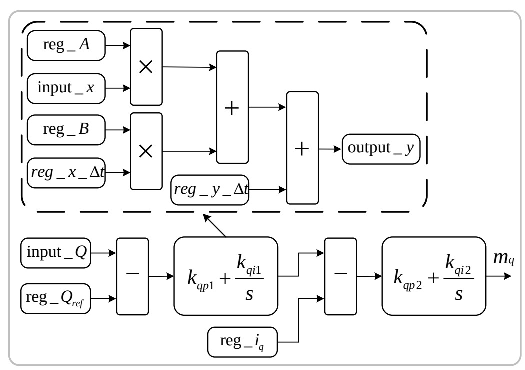

Fig 2 Hardware design of the q-axis model based on FPGA

3. PIPELINE TECHNIQUE

3.1 Superscalar pipeline

As an advanced data processing technology, the superscalar pipeline can effectively improve the computational efficiency of real-time simulators by solving two or more pipelines in parallel. Since the controllers in the PMSG unit and the structures inside the controller are mostly decoupled, there are multiple deep parallel pipelines in the control system of PMSG units, which is suitable for solving with superscalar pipeline technique.

In the proposed FPGA-based real-time simulator, each instruction in the pipeline consists of several stages, and the solution of each stage requires one clock cycle. Assuming that there are two deep pipelines in the control system, and the real-time simulator solves the stage 1 of instruction 1 in two pipelines of control system 1 in clock cycle 1. In clock cycle 2, stage 2 of instruction 1 in two pipelines of control system 1 are solved in parallel, and at the same time, stage 1 of instruction 2 in two parallel pipelines of control system 2 are solved. Different stages in two parallel pipelines of multiple control systems are simultaneously solved in each clock cycle until the last control system completes all instructions.

3.2 Module-level pipeline

As mentioned in Section 2.2, the simulation of the electrical system consists of four steps. Taking each step as a section of the pipeline, the simulation of wind farms can be realized using module-level pipeline technique. Based on the decoupling methods, wind farms can be divided into several subsystems. Assuming that the electrical system of subsystem i needs $\Delta s(i, j)$ to complete the solution of step j, $\forall\ i = 1, 2, ..., N$, $j= 1, 2, 3, 4$. To avoid running halts in the pipeline, the solution time of each step should be guaranteed equal. Generally, the maximum value of $\Delta s(i, j)$ is taken as a simulation period. It is worth noting that only when the number of simulation periods under each simulation step is not less than the number of subsystems plus three, the real-time performance of the simulation can be ensured, otherwise the simulation step needs to be readjusted.

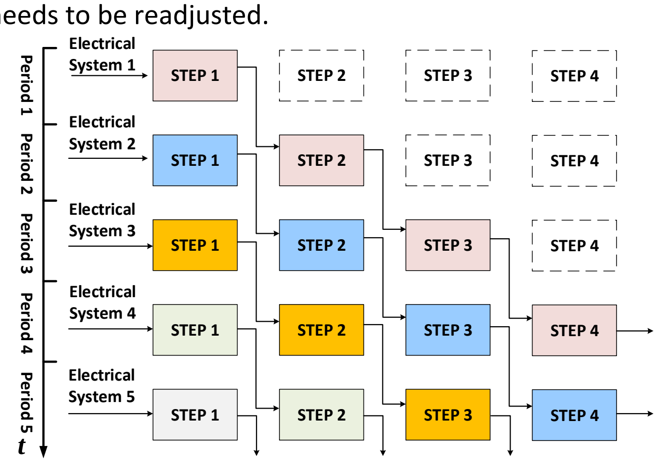

Fig 3 Space-time diagram of the simulation for electrical system

The space-time diagram of the simulation for electrical systems based on the module-level pipeline is shown in Fig. 3. In simulation period n, the real-time simulator simultaneously solves the fourth step of electrical system (n-3), the third step of electrical system (n-2), the second step of electrical system (n-1), and the first step of electrical system n. In this way, different steps of multiple electrical systems are simultaneously solved in each simulation period until the last electrical system completes the calculation of the fourth step.

4. CASE STUDY

4.1 Test case

In this section, a PMSG based wind farm equivalent to four 1.5 MW PMSG units with the same structure is simulated on the FPGA-based real-time simulator. As is shown in Fig. 4, the tested wind farm is decomposed into five subsystems with the Bergeron line model [5], including an electrical network, PMSG unit 1, PMSG unit 2, PMSG unit 3 and PMSG unit 4.

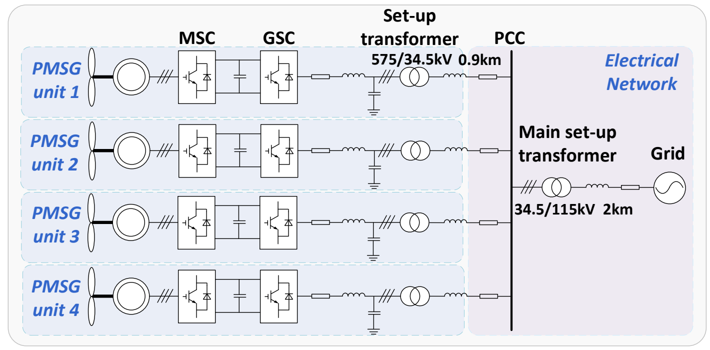

Fig 4 Configuration of the tested wind farm

Considering the computing speed and simulation accuracy, the time-step for the tested wind farm is set to 3μs. In order to solve the electrical system with module-level pipeline, a time-step is divided into 8 simulation periods. A transient event, the wind speed of PMSG unit 1 and 3 decreasing from 12m/s to 10m/s and that of PMSG unit 2 and PMSG 4 decreasing from 12.5m/s to 10.5m/s at 2.0s, is simulated to validate the correctness of the proposed design.

4.2 Resource Performance

Table 2 lists the main computational resources utilized by the tested case based on the proposed design. As can be seen, the percentage of logical resources consumed is more than twice that of DSP blocks. Considering that the logic resources and DSP resources of FPGA are interconvertible, adjusting the proportion properly is a feasible way to further expand simulation scale.

Table 2 Computational resource utilization

Hardware design	Logic resources (172,600)	DSP blocks (1590)	Memory bits (41,246,720)
Proposed design	82%	35%	17%

4.3 Accuracy Performance

To illustrate the correctness and effectiveness of the proposed design, simulation results are compared with the commercial simulation tool PSCAD/EMTDC. The total simulation time is 4s and time step for PSCAD/EMTDC is also 3μs. The results of the simulation in comparison with PSCAD/EMTDC are shown in Fig. 5 to Fig. 7, and Fig. 8 shows the relative error of the Phase-A voltage of PMSG unit 3 using the result of PSCAD as a reference.

It can be seen from the figures, the results of FPGA-based real-time simulator are very close to that of PSCAD/EMTDC, which well verifies the accuracy and correctness of the proposed design.

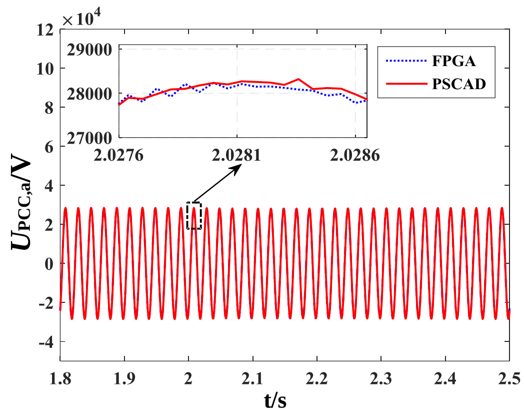

Fig 5 Phase-A voltage of PCC

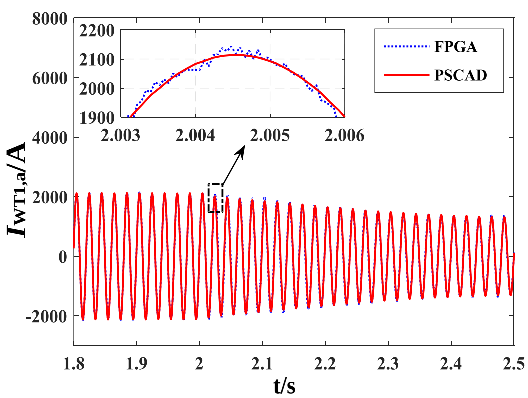

Fig 6 Phase-A current of PMSG unit 1

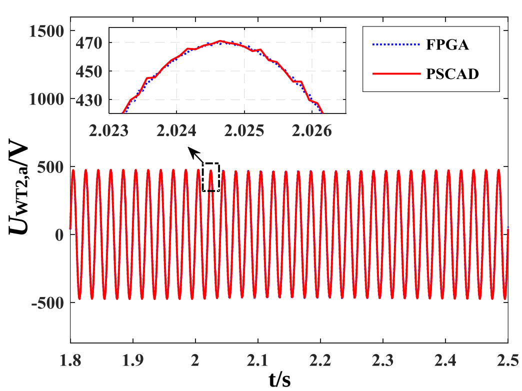

Fig 7 Phase-A voltage of PMSG unit 2

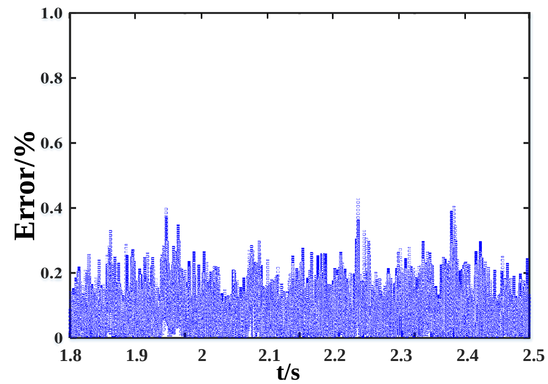

Fig 8 Relative error curve

5. CONCLUSION

In this paper, we presented a highly efficient design of real-time simulator based on pipeline technique for PMSG based wind farms, which has been proved to have high accuracy and obvious advantage in computing speed through case studies. In addition, the proposed design gives full play to the advantages of pipeline technique, greatly saving the hardware resources of FPGA. As a conclusion, the proposed design is an effective and promising design, and the work in this paper lays a foundation for the real-time transient simulation of larger wind farms.

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