基于Speedgoat实时仿真平台的风电变流器控制系统开发与测试

Development and Test of Wind Power Converter Control System based on Speedgoat Real-Time Simulation Platform

YISU熠速

www.yisuworld.com

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- **风电变流器控制系统开发的挑战**
  Challenges of Wind Power Converter Control System Development

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  Development of Wind Power Converter Core Control Algorithm

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风电变流器控制系统开发的挑战

Challenges of Wind Power Converter Control System Development


IEC

IEC 61400-21-1

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Wind energy generation systems –

IEC 61400-21-1:2019

Wind energy generation systems - Part 21-1: Measurement and assessment of electrical characteristics - Wind turbines

Table 1 – Overview of required test levels

Clause	Test	Component test	Sub-system Test	Field measurement – Wind turbine level	Field measurement – Wind power plant
Power Quality Aspects					
8.2.2	Flicker			S	O
8.2.3	Switching operations			S	O
8.2.4	Harmonics, interharmonics and higher frequency components		C	S	O
Steady-State Operation					
8.3.3	Maximum power			S	O
8.3.4	Reactive power characteristic (Q=0)		S	O	O
8.3.5	Reactive power capability		S	O	O
8.3.6	Voltage dependency of PQ diagram		S	O	O
8.3.7	Unbalance factor		S	O	O

S: Suggested minimum measurement / test level

C: Conditional measurement / test level, if certain conditions are fulfilled (details in corresponding clause)

O: Optional measurement / test level, if the function is available on other level than required as a minimum

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Challenges of Wind Power Converter Control System Development


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Clause	Test	Component test	Sub-system Test	Field measurement – Wind turbine level	Field measurement – Wind power plant
Control Performance					
8.4.2	Active power control		C	S	O
8.4.3	Active power ramp rate limitation		C	S	O
8.4.4	Frequency control		S	O	O
8.4.5	Synthetic inertia			S	O
8.4.6	Reactive power control		S	O	O
Dynamic Performance					
8.5.2	Fault ride-through capability		C	S	O
Grid Protection					
8.6.2	Grid protection	S	O	O	O
8.6.4	Reconnection time			S	O
8.6.3	Rate of change of frequency RoCoF (df/dt)	S	O	O	O

S: Suggested minimum measurement / test level

C: Conditional measurement / test level, if certain conditions are fulfilled (details in corresponding clause)

O: Optional measurement / test level, if the function is available on other level than required as a minimum

风电变流器控制系统开发的挑战
Challenges of Wind Power Converter Control System Development


IEC TR 61400-21-3

TECHNICAL REPORT

IEC 61400-21-3:2019

Wind energy generation systems – Part 21-3: Measurement and assessment of electrical characteristics – Wind turbine harmonic model and its application

The structure of the harmonic model presented in this document will find an application in the following potential areas:

- evaluation of the WT harmonic performance during the design of electrical infrastructure and grid-connection studies;
- harmonic studies/analysis of modern power systems incorporating a number of WTs with line side converters;
- active or passive harmonic filter design to optimize electrical infrastructure (e.g. resonance characteristic shaping) as well as meet requirements in various grid codes;
- sizing of electrical components (e.g. harmonic losses, static reactive power compensation, noise emission, harmonic compatibility levels, etc.) within WPP electrical infrastructure;
- evaluation of external network background distortion impact on WT harmonic assessment;
- standardised communication interfaces in relation to WT harmonic data exchange between different stakeholders (e.g. system operators, generators, developers, etc.);
- universal interface for harmonic studies for engineering software developers;
- possible benchmark of WT introduced to the academia and the industry.

The advantage of having standardized WT harmonic performance assessment by means of the harmonic model is getting more and more crucial in case of large systems with different types of WTs connected to them, e.g. multi-cluster wind power plants incorporating different types of WTs connected to the same offshore or onshore substation.

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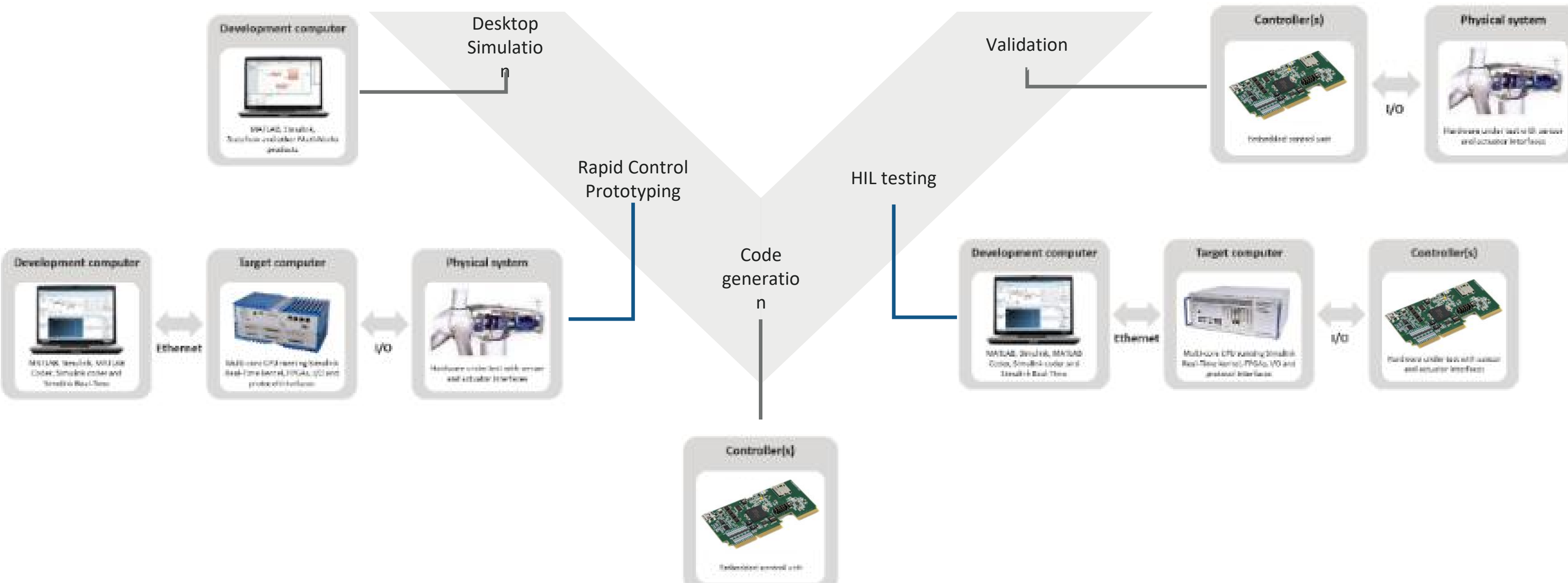
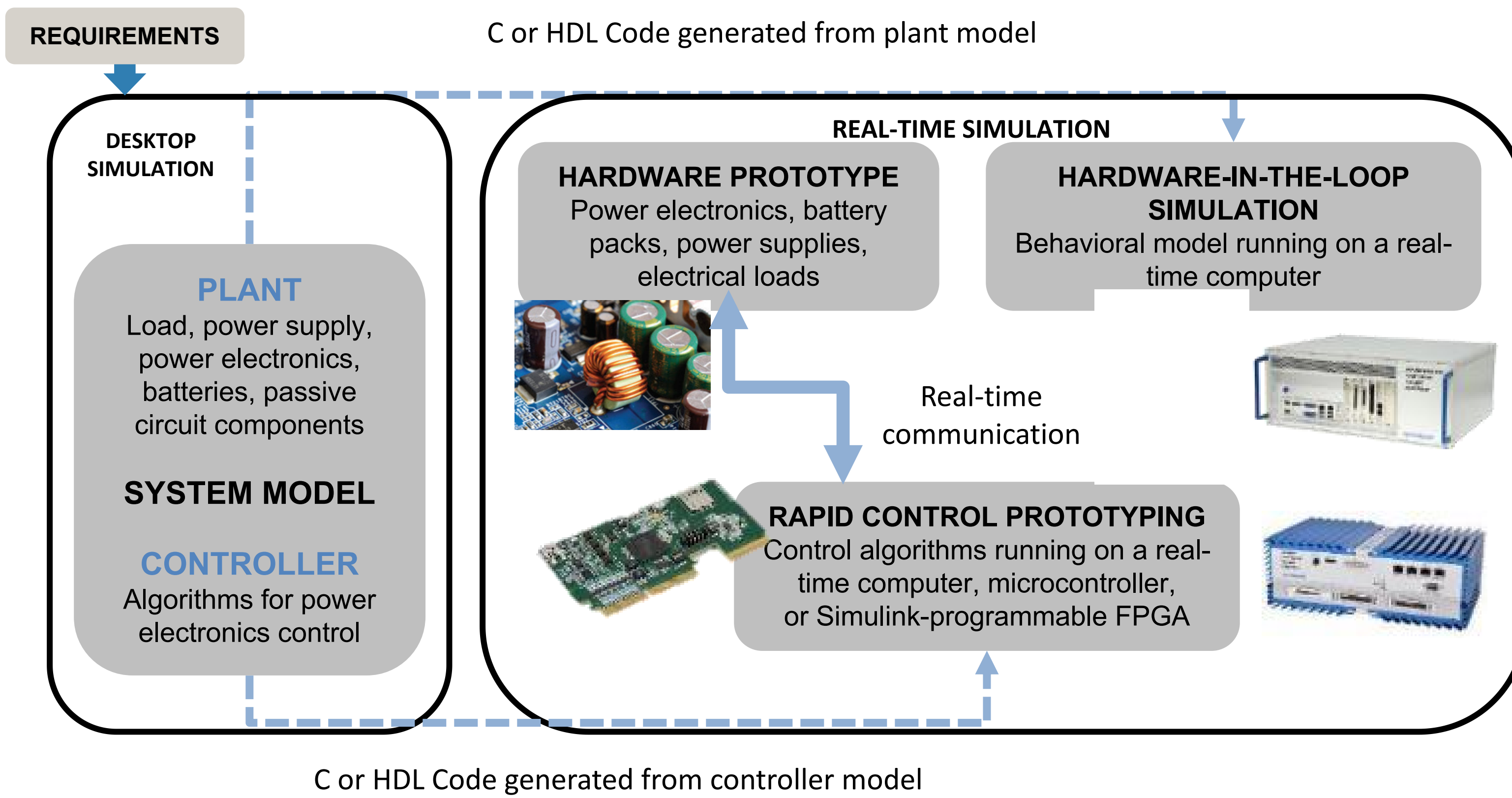
风电变流器核心控制算法的开发

Development of Wind Power Converter Core Control Algorithm

Model Based Design for Power Electronics Control Design

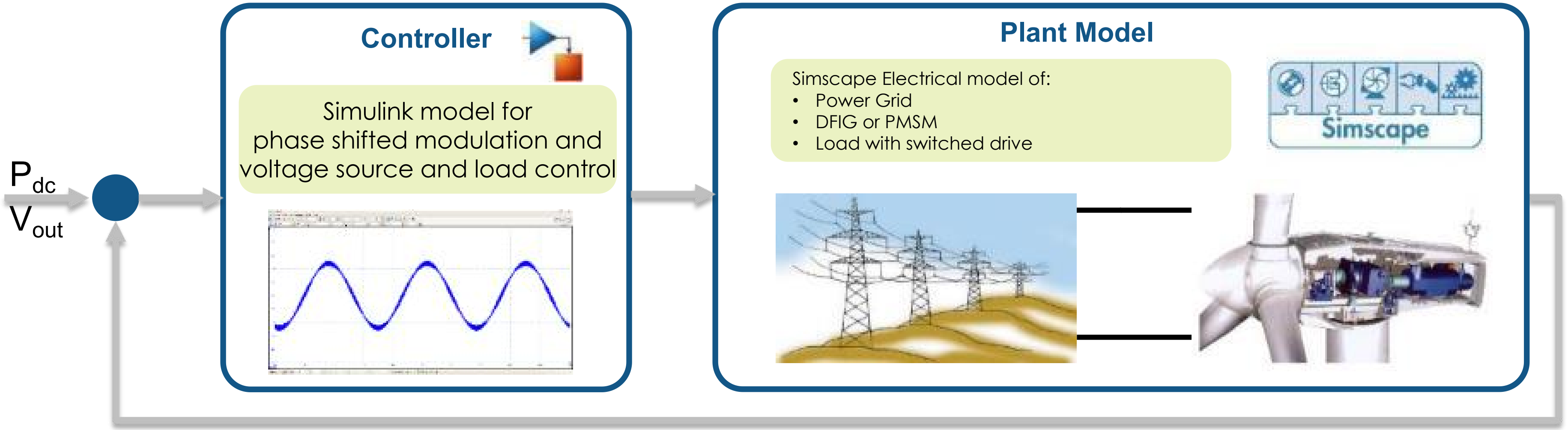


风电变流器核心控制算法的开发
Development of Wind Power Converter Core Control Algorithm



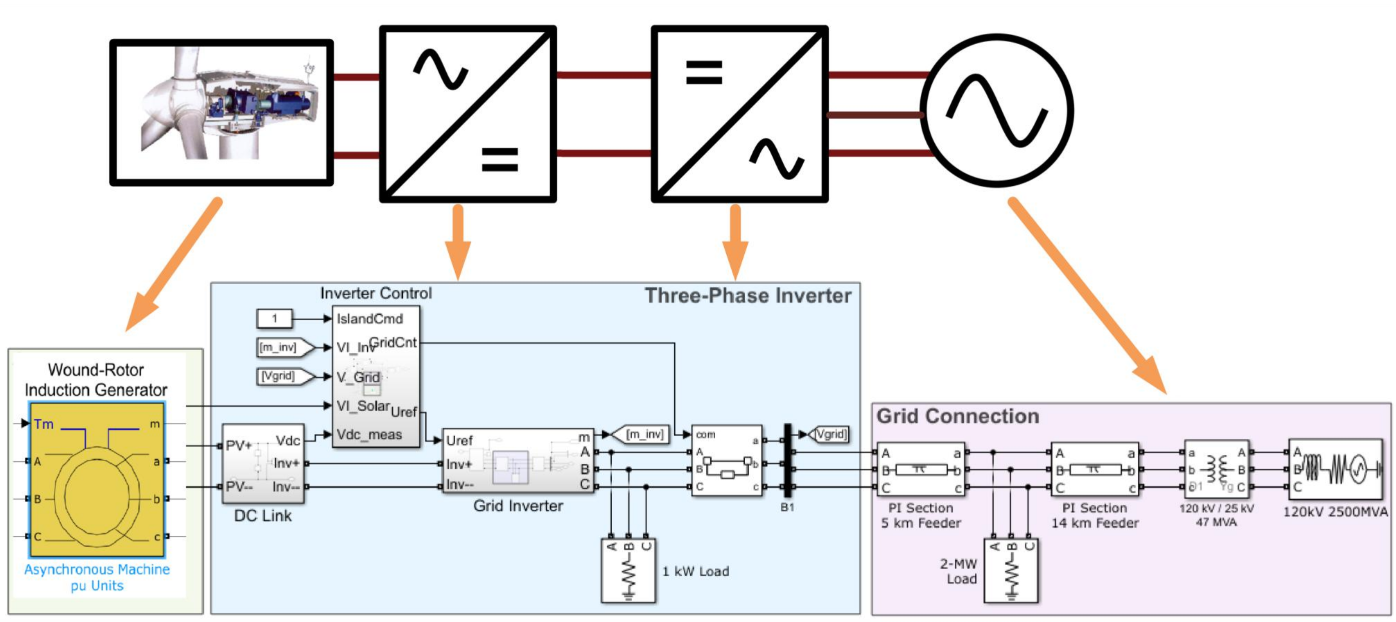
风电变流器核心控制算法的开发
Development of Wind Power Converter Core Control Algorithm

- Desktop Simulation
  - Used Simulink for control design
  - Simscape Electrical is used to simulate the converter topology



风电变流器核心控制算法的开发
Development of Wind Power Converter Core Control Algorithm

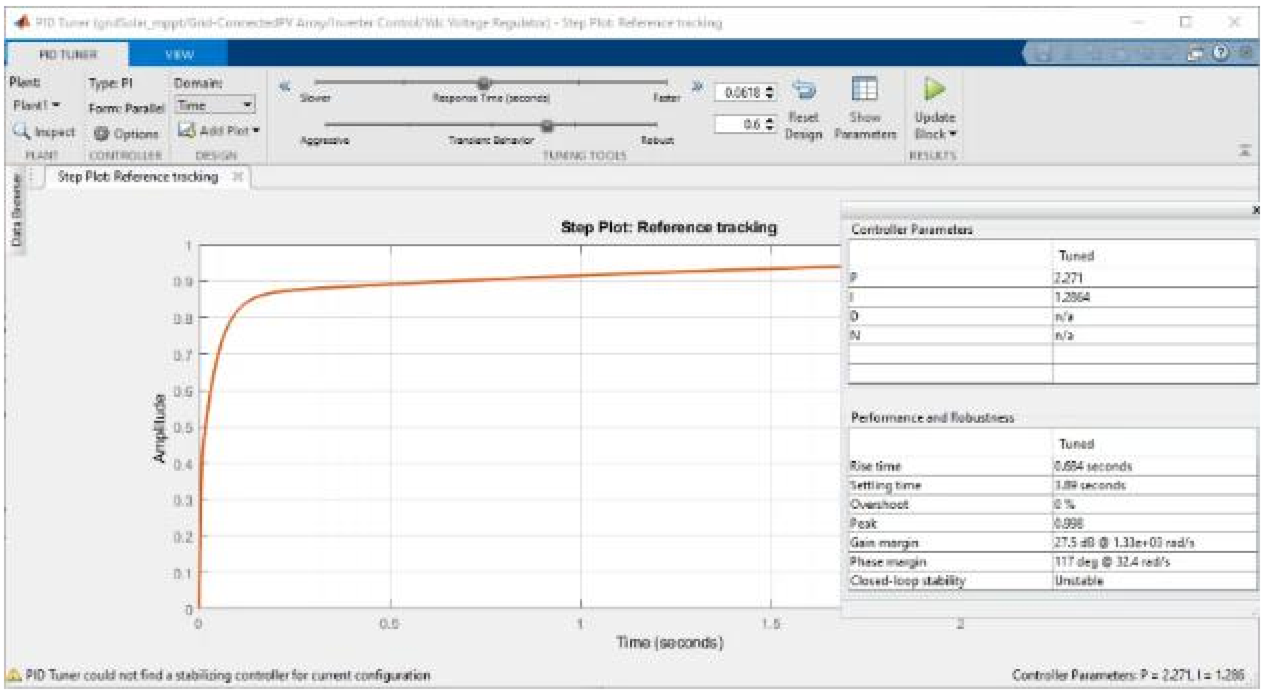
- Graphical modeling of power electronics topology
  - Power Grid
  - Wind Power Converter
  - DFIG or PMSM



风电变流器核心控制算法的开发

Development of Wind Power Converter Core Control Algorithm

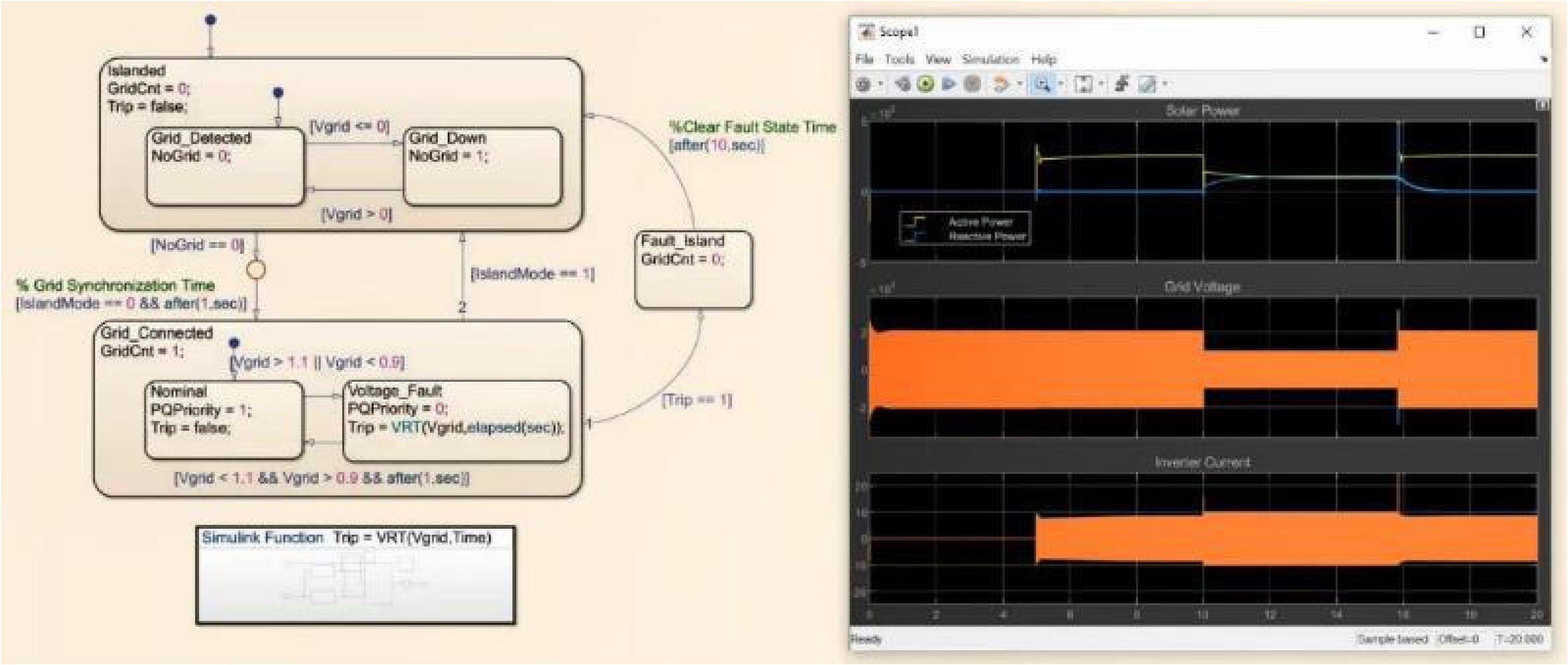
- Controller Design



风电变流器核心控制算法的开发

Development of Wind Power Converter Core Control Algorithm

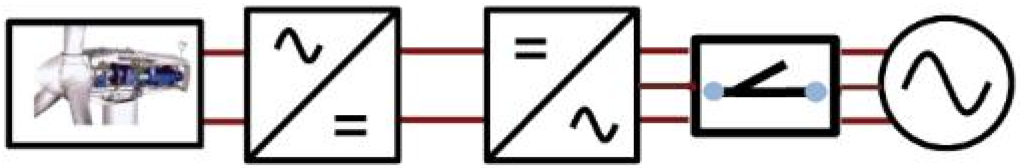
- Desktop Simulation Test

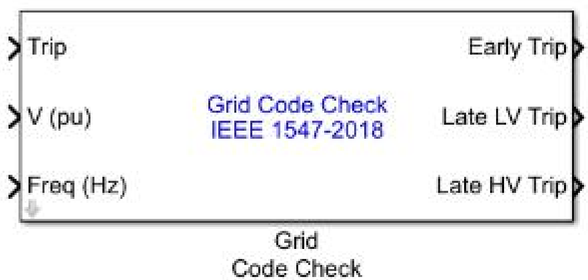


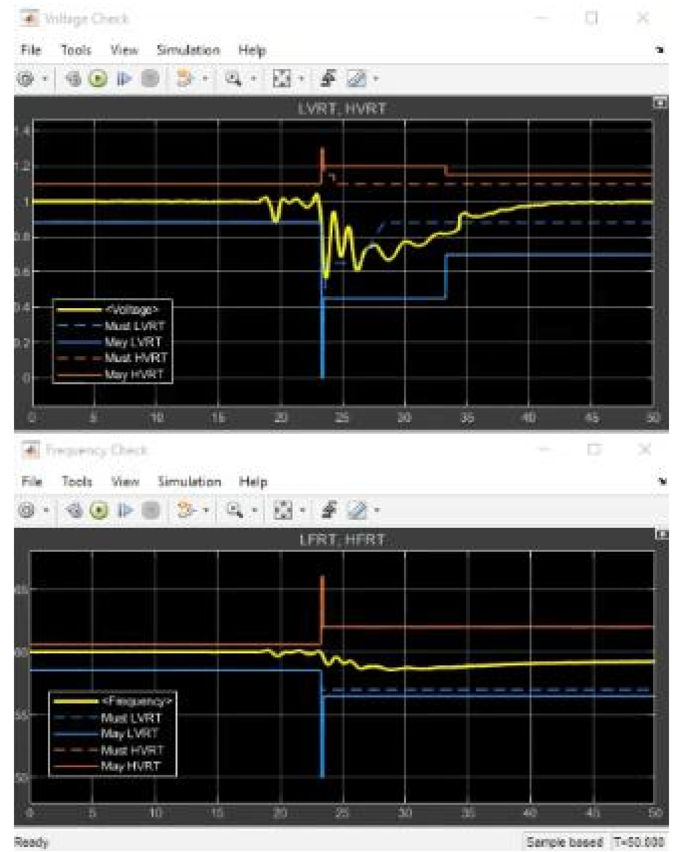
风电变流器核心控制算法的开发

Development of Wind Power Converter Core Control Algorithm

- 故障穿越判据 - IEEE 1547-2018



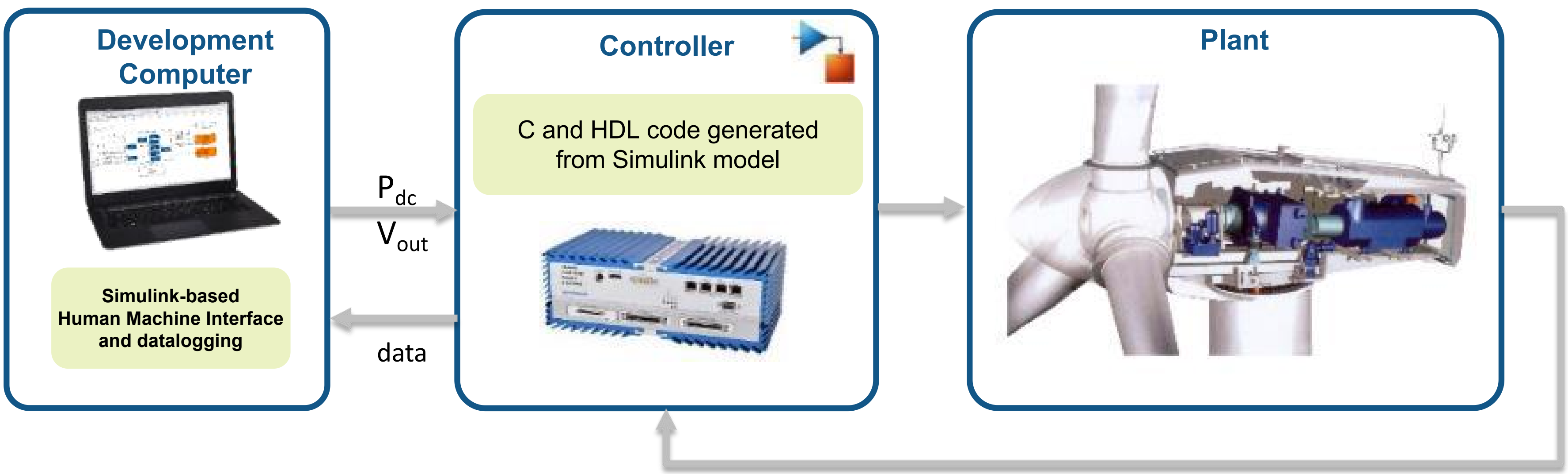




- Grid Code Compliance for Renewable Resource Integration

风电变流器核心控制算法的开发
Development of Wind Power Converter Core Control Algorithm

- Tested and tuned controller algorithm with Speedgoat hardware prototype
- Controller code generated using Simulink Real-Time and HDL Coder



User Stories: Wind Technologies, UK

New drivetrain for wind turbines dramatically decreases lifetime capital costs

Controlling 250 kW Brushless DFIG using an Education Real-Time Target Machine

Cabinet with control system

Control strategy

Brushless DFIG is inherently an unstable machine in open-loop operation and requires a robust controller to manage the speed and power of the generator. This is critical for extracting maximum power from the wind.

"We wanted to find a solution which allowed the design team to rapidly prototype and modify control loops in real-time based on models developed in Simulink", says Dr. Abdi, CEO of Wind Technologies.

To develop a control strategy efficiently, within the shortest possible time frame, it is important to have the ability to easily test and modify coding algorithms. Before the Speedgoat solution, the Wind Technologies team had to hard code every change in the microcontroller. This resulted in significant time delays and reduced quality.

Benefits

Brushless DFIG offers significant cost reductions and reliability improvements when compared with conventional DFIG's. It does not require slip-rings or carbon extraction equipment, and as the machine operates at a slower speed than conventional DFIG, the failure-prone high-speed stage of the gearbox can be eliminated.

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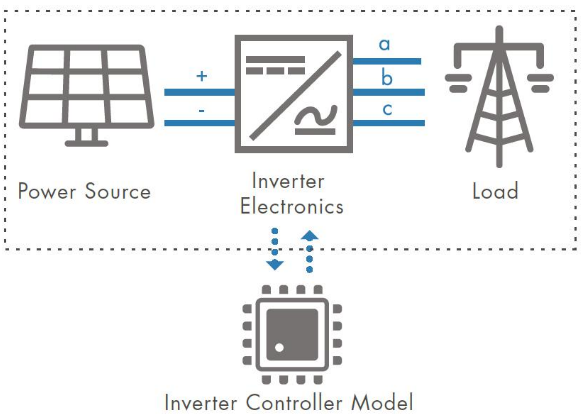
风电变流器核心控制算法的测试与验证

Test and Verification of Wind Power Converter Core Control Algorithm

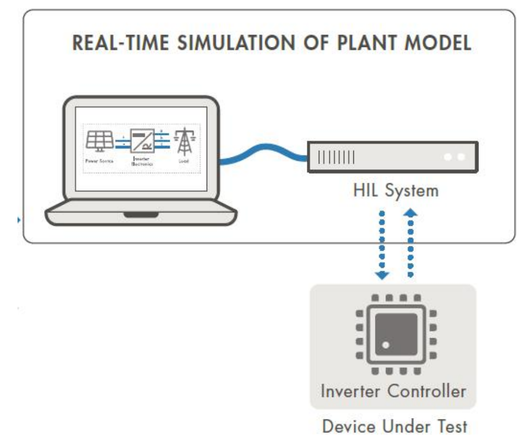
Design and optimize controls using electrical systems simulation



Generate embedded code for the plant

and the controller

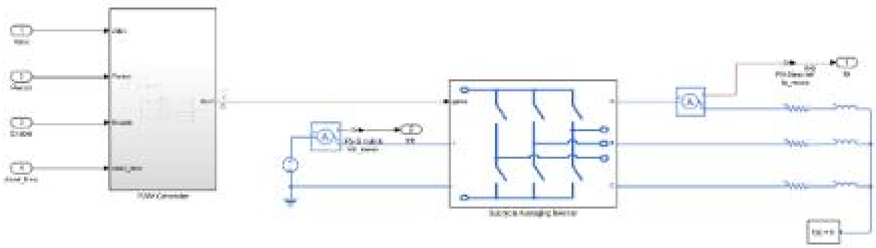
Test the control hardware using HIL simulation



风电变流器核心控制算法的测试与验证

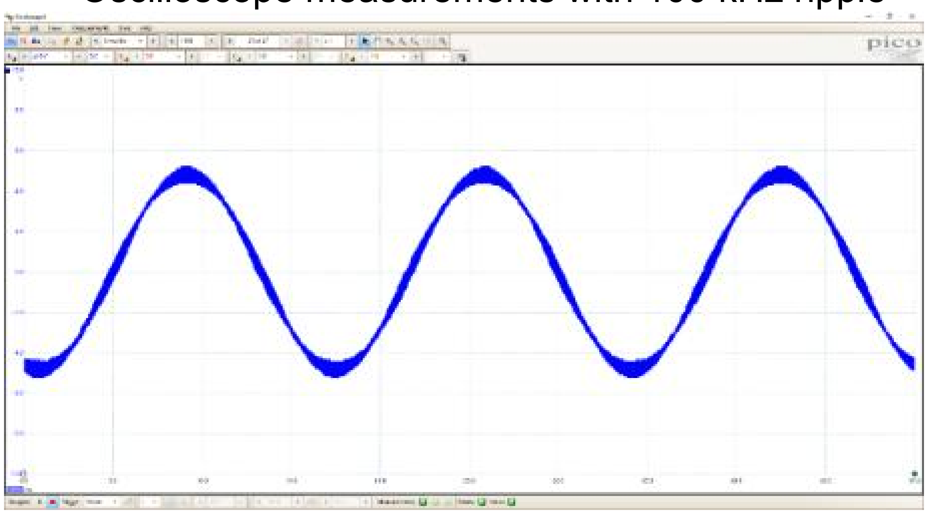
Test and Verification of Wind Power Converter Core Control Algorithm

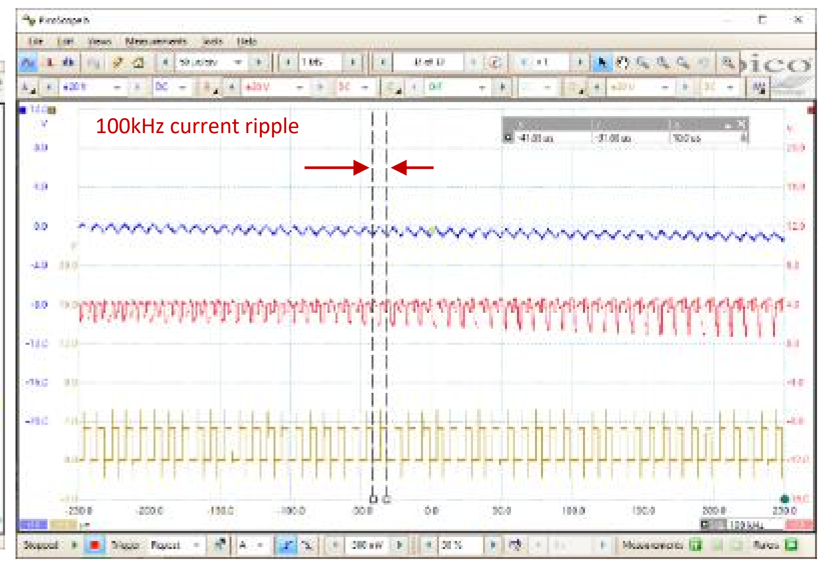
Simulink combined with Simscape to HDL



- Three phase-two level inverter
- Fsw = 20kHz
- Ts = 1μs
- PWM resolution: 5ns!

- Oscilloscope measurements with 100 kHz ripple





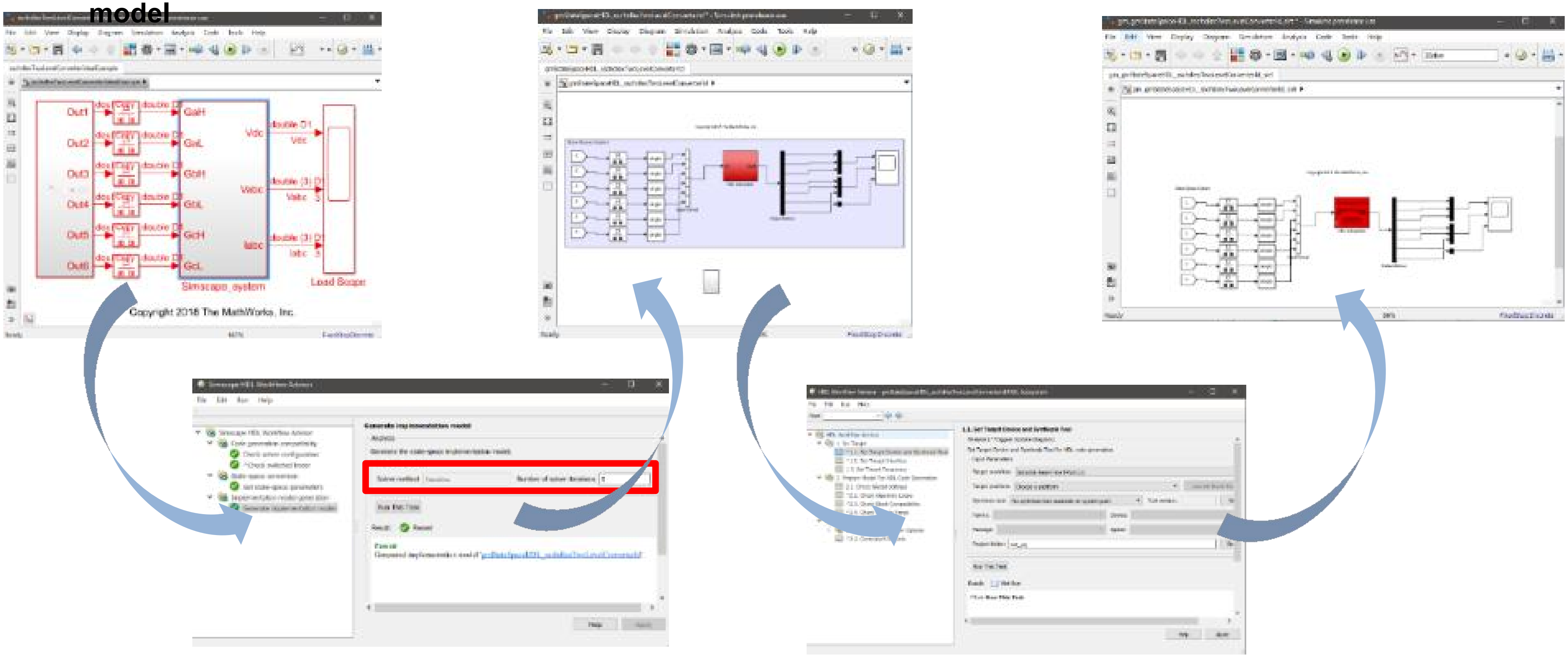
Simscape to HDL to FPGA

R2018b

Simscape model

Simulink state-space model

Generated model



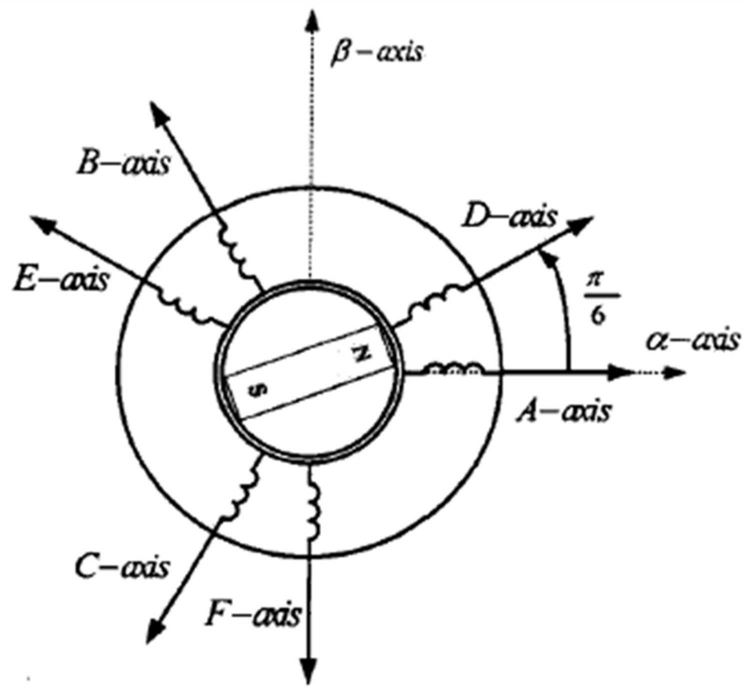
Simscape HDL Workflow Advisor

HDL Workflow Advisor

风电变流器核心控制算法的测试与验证

Test and Verification of Wind Power Converter Core Control Algorithm

- **Double winding permanent magnet synchronous motor**



风电变流器核心控制算法的测试与验证
Test and Verification of Wind Power Converter Core Control Algorithm

- **Motor Parameters**

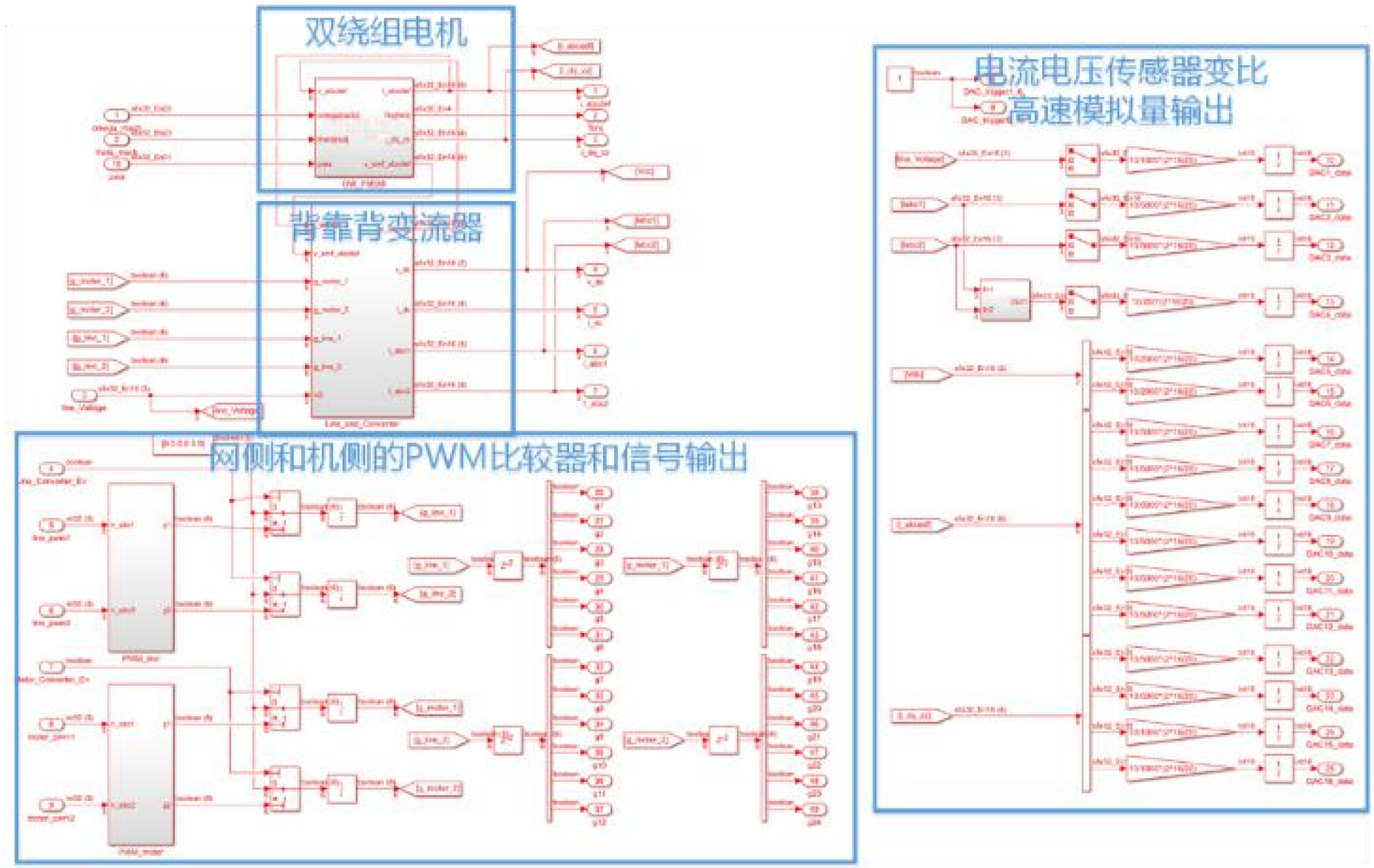
名称	数值	单位	名称	数值	单位
定子电阻Rs	8.912	mOhm			
d轴电感Ld	3.4105	mH	q轴电感Lq	3.4105	mH
转子磁通Psi	12.727	Wb	极对数PP	40	Pairs
z1z2坐标系定子电阻	8.912	Ohm	z1z2坐标系定子漏感	0.5	mH
额定电压	690	V	额定电流	——	A
额定功率	4500	kW	额定转速	——	rpm
额定转矩	——	Nm			

风电变流器核心控制算法的测试与验证
Test and Verification of Wind Power Converter Core Control Algorithm

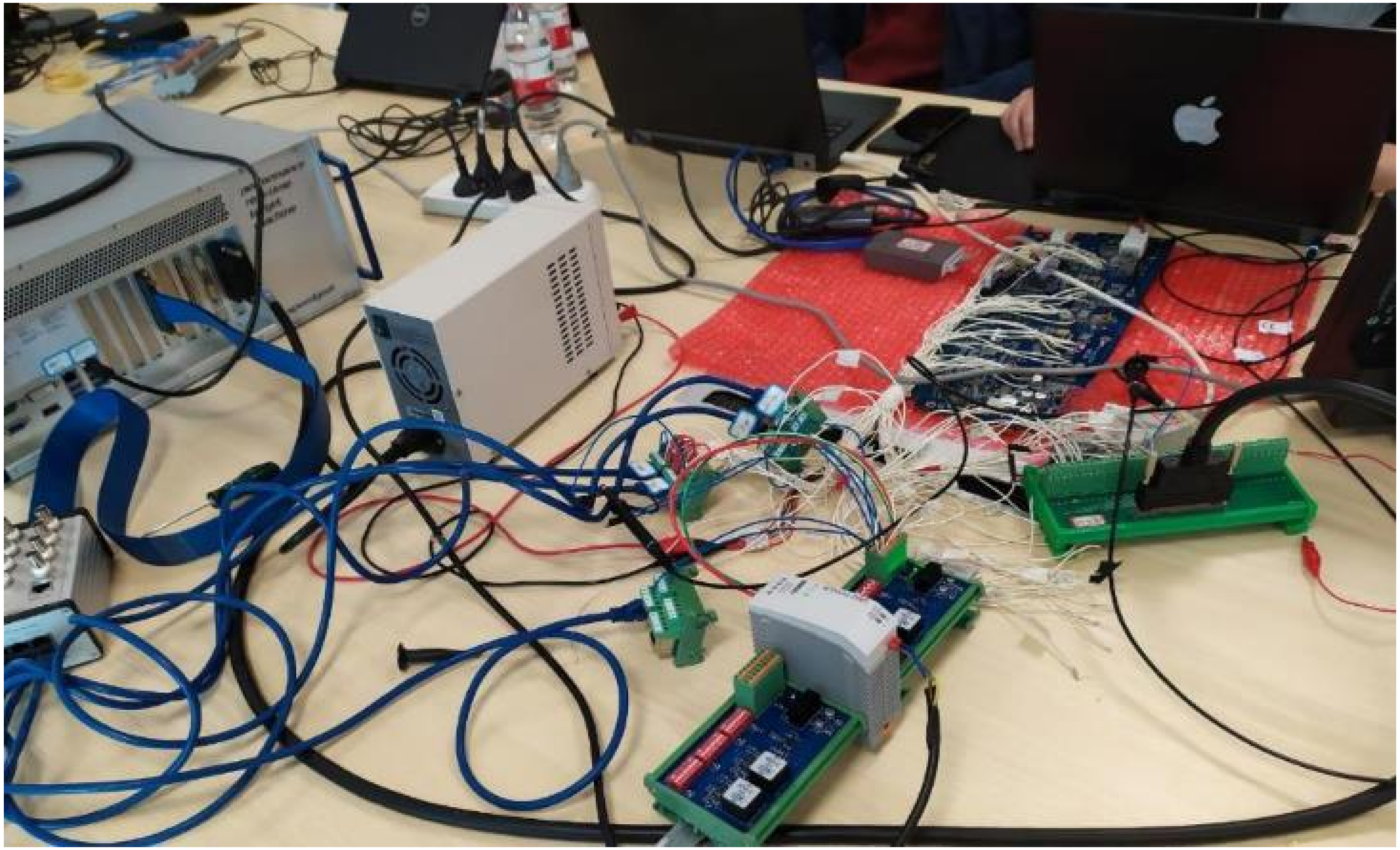
- **HIL Test Parameters**

名称	数值	单位	名称	数值	单位
电路拓扑模型仿真频率	50	MHz	控制器模型仿真频率	10	kHz
PWM输入更新频率	50	MHz	电流电压输出更新频率	2	MHz
电网输入电压	35	kV	直流电压设定值	1080	V
网侧开关频率	2700	Hz	网侧死区时间	5	µs
机侧开关频率	1500	Hz	机侧死区时间	5	µs
电机转矩设定值	4352634	Nm	电机转速	10	rpm

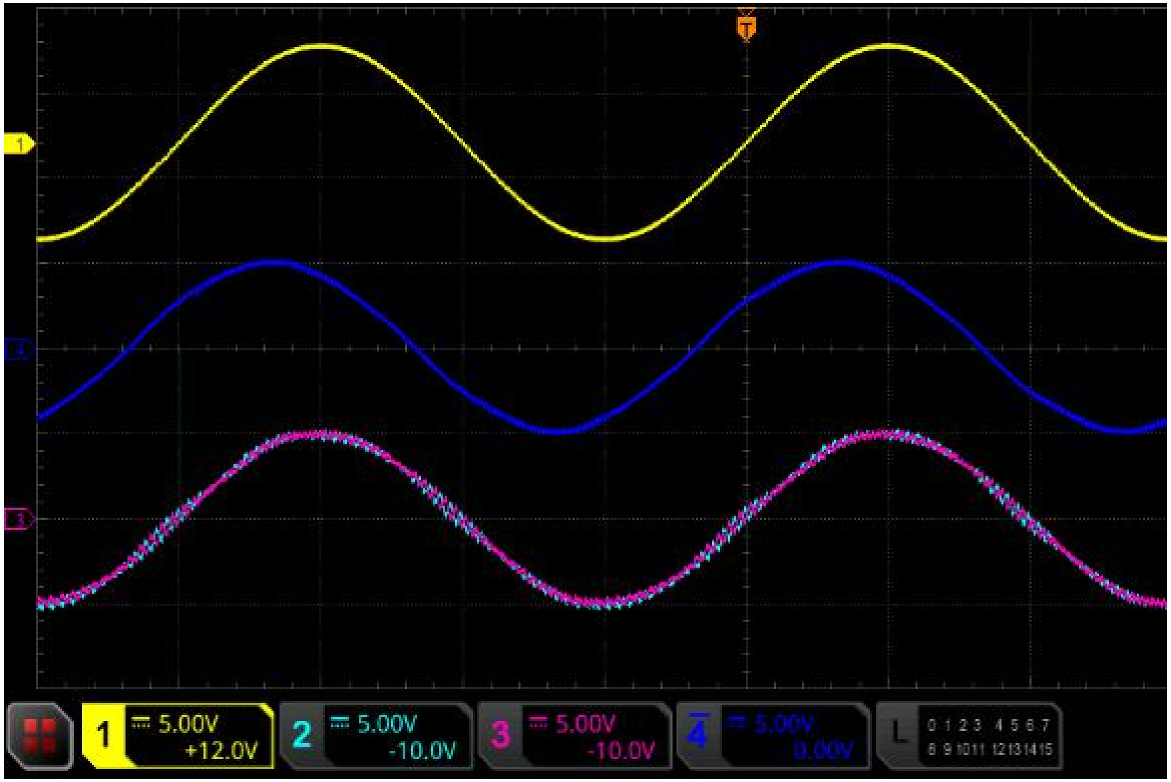
- **HIL Test FPGA Model**



- **HIL Desktop Testbench**

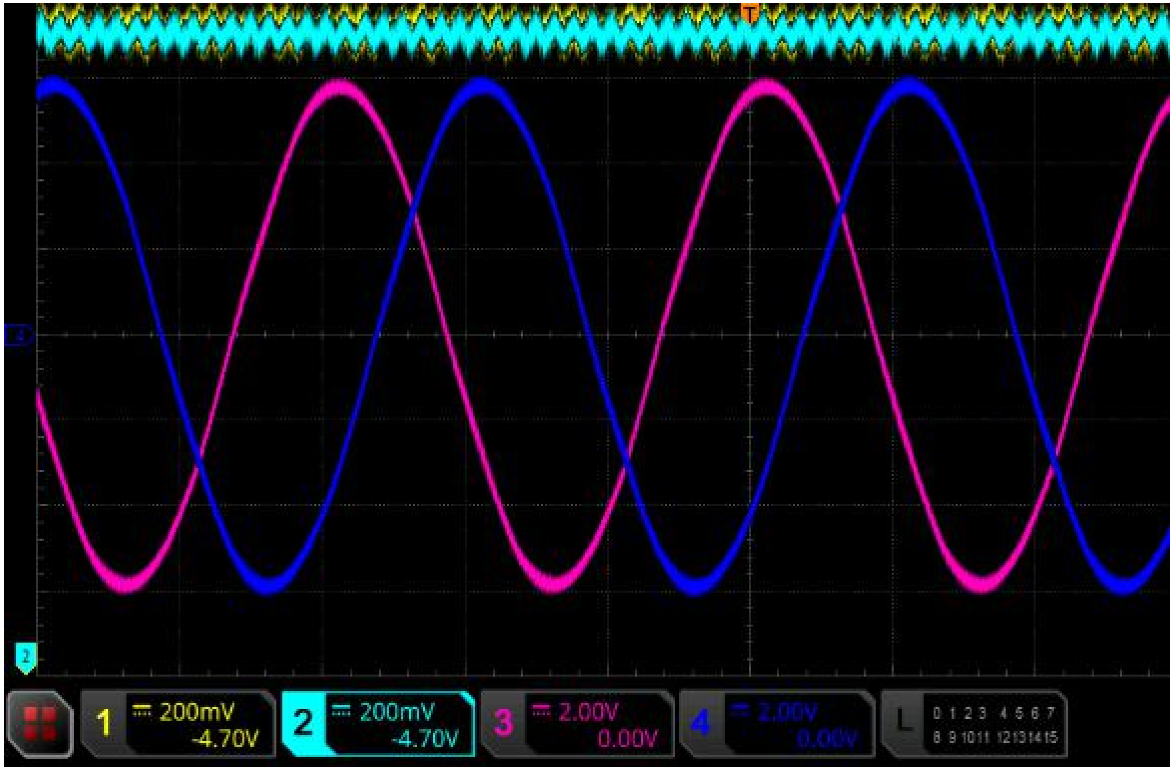


- **Scope Waves**



- Secondary Voltage
- Secondary Current 1
- Secondary Current 2
- Primary Current

- **Scope Waves**



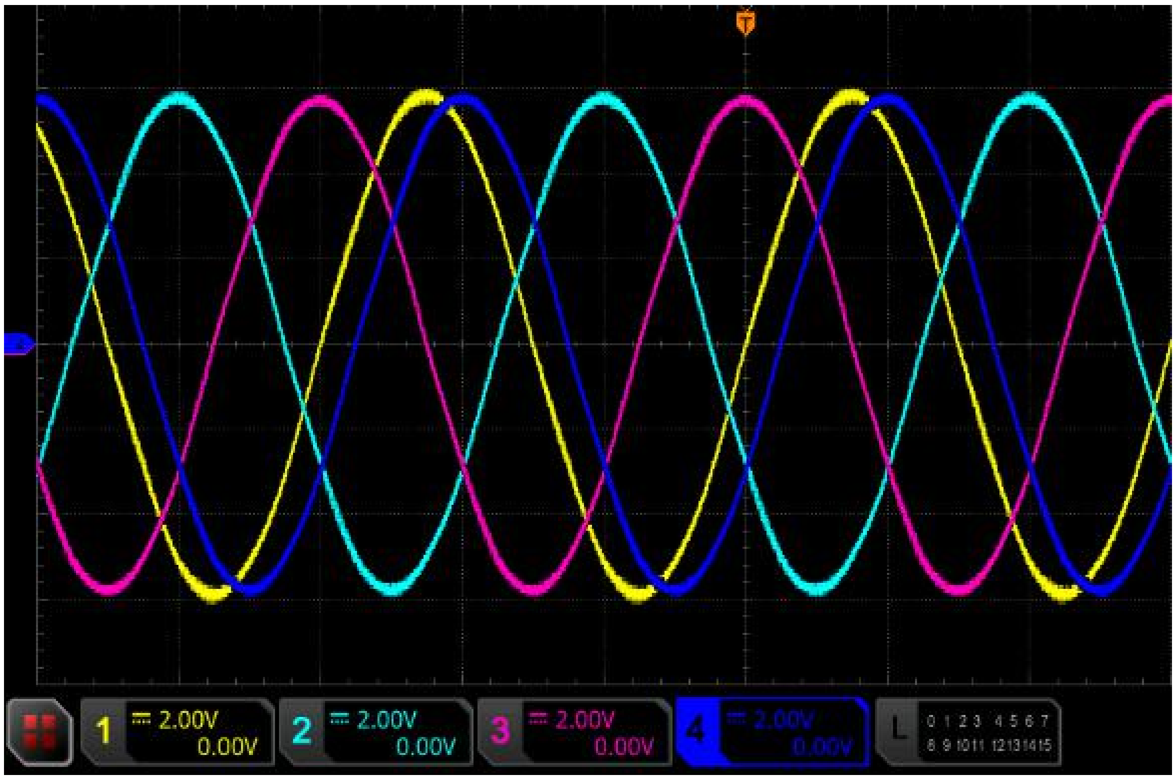
DC-Link Voltage 1

DC-Link Voltage 2

Motor Phase A Current

Motor Phase B Current

- ## Scope Waves



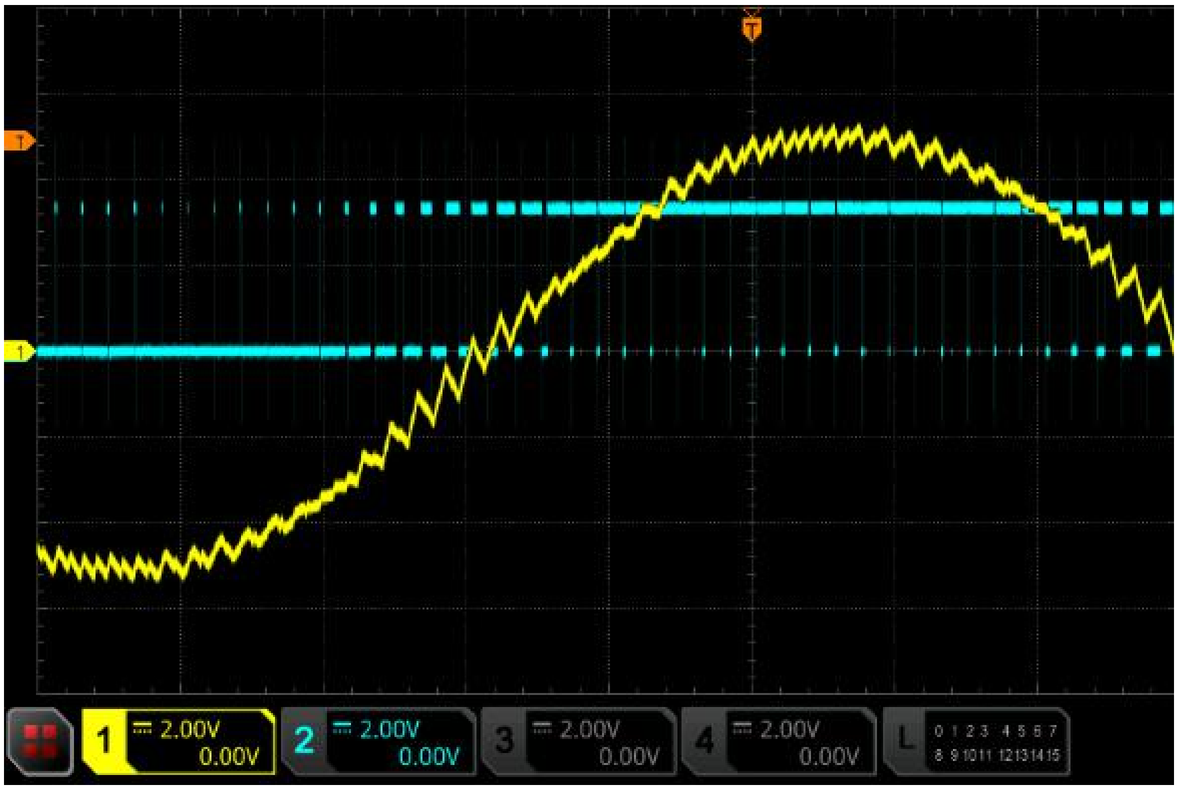
Motor Phase C Current

Motor Phase D Current

Motor Phase E Current

Motor Phase F Current

- **Scope Waves**



Secondary Current 1

Line Converter PWM

- **Scope Waves**

Motor Phase A Current

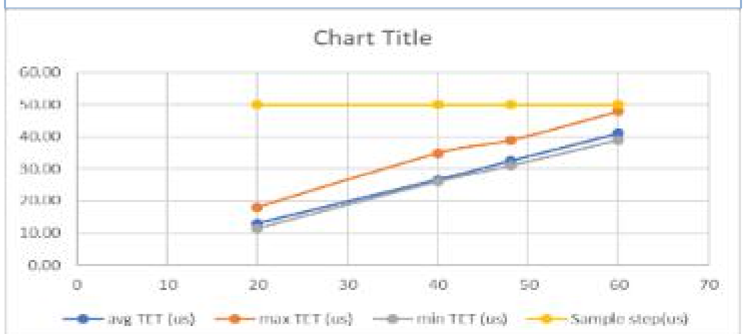
Motor Converter PWM

风电变流器核心控制算法的测试与验证
Test and Verification of Wind Power Converter Core Control Algorithm

- **Wind Power Farm Real Time Simulation on Multi-Core**

  - SimPowerSystem Model: power_wind_dfig_avg
  - Speedgoat Performance Real- Time Target Machine，CPU: i7 4.2GHz 4 Core
  - Software: MATLAB2019B。
  - The performance is evaluated by the Task Execution Time(TET) of the model.
  - 60 power_wind_dfig_avg model can parallel run within 50 us

Number of models	avg TET (us)	max TET (us)	min TET (us)
20	13.02	18.00	11.50
40	26.66	35.00	26.00
48	32.52	39.00	31.00
60	41.07	48.00	39.00



Wind Power Farm Real Time Model On Concurrent Execution Mode

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Wind energy generation systems - Part 21-1: Measurement and assessment of electrical characteristics - Wind turbines

- **IEC 61400-21-3:2019**

Wind energy generation systems – Part 21-3: Measurement and assessment of electrical characteristics – Wind turbine harmonic model and its application

- **IEC 61400-21-3:2019**

Wind energy generation systems – Part 21-3: Measurement and assessment of electrical characteristics – Wind turbine harmonic model and its application

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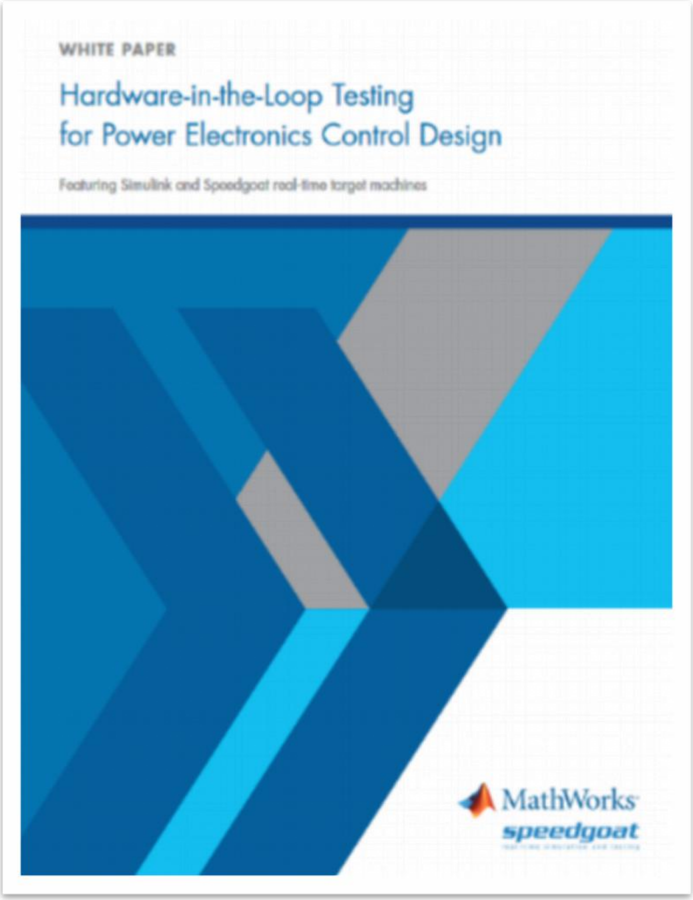
- **More information**

Visit our Power Electronics website
https://www.speedgoat.com/applications-industries/industries/power-electronics

Visit our Power Systems website
https://www.speedgoat.com/applications-industries/industries/power-systems-real-time-simulation

Read our latest whitepapers with MathWorks:

- HIL Testing for Power Electronics Control
- FPGA-based Rapid Control Prototyping of Permanent Magnet Synchronous Motor
- Renewable Grid Integration Studies with Simscape Electrical



总结
Summary

- **HW and SW for RCP**

- Speedgoat
  - Mobile Realtime Target Machine
  - IO323 FPGA Module
  - FPGA Bitstream file

- MathWorks
  - MATLAB/Simulink
  - MATLAB/Simulink Coder
  - HDL Coder
  - Simulink Real-Time

总结
Summary

- **HW and SW for HIL**

- Speedgoat
  - Performance Realtime Target Machine
  - IO334 FPGA Module
  - IO3XX-21 FPGA rear plug-ins
  - HDL Coder Integration Package
- MathWorks
  - MATLAB/Simulink
  - MATLAB/Simulink Coder
  - HDL Coder
  - Simulink Real-Time
  - Simscape
  - Simscape Electrical

谢谢聆听！
Thank you for attention！

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