WIEFP 2016

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CONTEXT

1. **Brief introduction of FPTCI, CMES**
2. **Research on hydraulic wind turbine of Yanshan University**

1. Brief introduction of FPTCI, CMES

1.1 Historical Evolution

1.2 Organizational Structure

1.3 Main Works

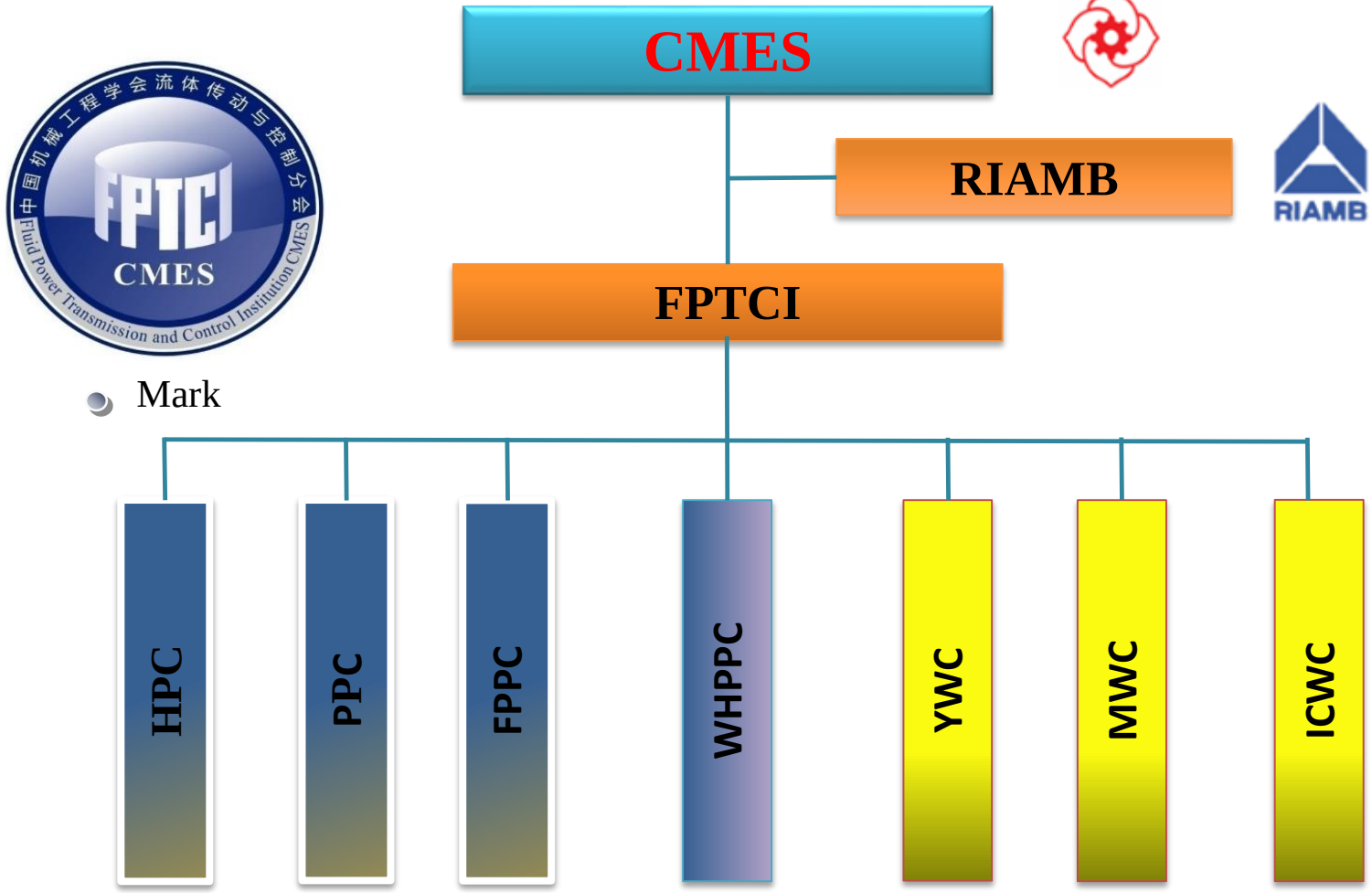
1.1 Historical Evolution

(1) The Fluid Power Transmission and Control Institution, Chinese Mechanical Engineering Society was established on April 13, 1987.

（2） Previous Committees

1st	A. 1987，34members
2nd	Oct. 1998，55members
3rd	Aug. 2002，52members
4th	Oct. 2006，78members
5th	Aug. 2011，101members
6th	Aug. 2015，123members

1.2 Organizational Structure



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1.3 Main Works

1.3.1 International conferences

From 1991, the international FPTCI was held once every four years. It was renamed as “International Conference on Fluid Power Transmission and Mechanical-Electrical Integration” in 2011(6th).

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1.3 Main Works

1.3.2 National conferences

The next national conference will be held in Huazhong University of Science and Technology three years later.

National Conference in Taiyuan, 2014

National Conference in Changchun, 2012

1.3 Main Works

1.3.3 International cooperation

In FESTO headquarter

The fourth china-japan hydrodynamic bilateral seminar

（1）In April 2007, the branch participated in international industry exhibition in Hanover, Germany.

（2）The fourth China-Japan hydrodynamic bilateral seminar was held in Tokyo in 2016.

1.3 Main Works

1.3.4 Website and Journal

(1) China hydraulic pneumatic website（http://www.yeyanet.com/sy）was built on January 8, 2001.
(2) Bsides the journal named “Chinese Hydraulics & Pneumatics”, which builds a good platform for hydraulic pneumatic indudtry technical.

2. Research on hydraulic wind turbine of Yanshan University

2.1 Research background

2.2 Brief introduction and classification

2.3 Present Condition of Researches

2.4 Wind turbine

2.5 Hydraulic main drive system

2.6 Low Voltage Ride Through control

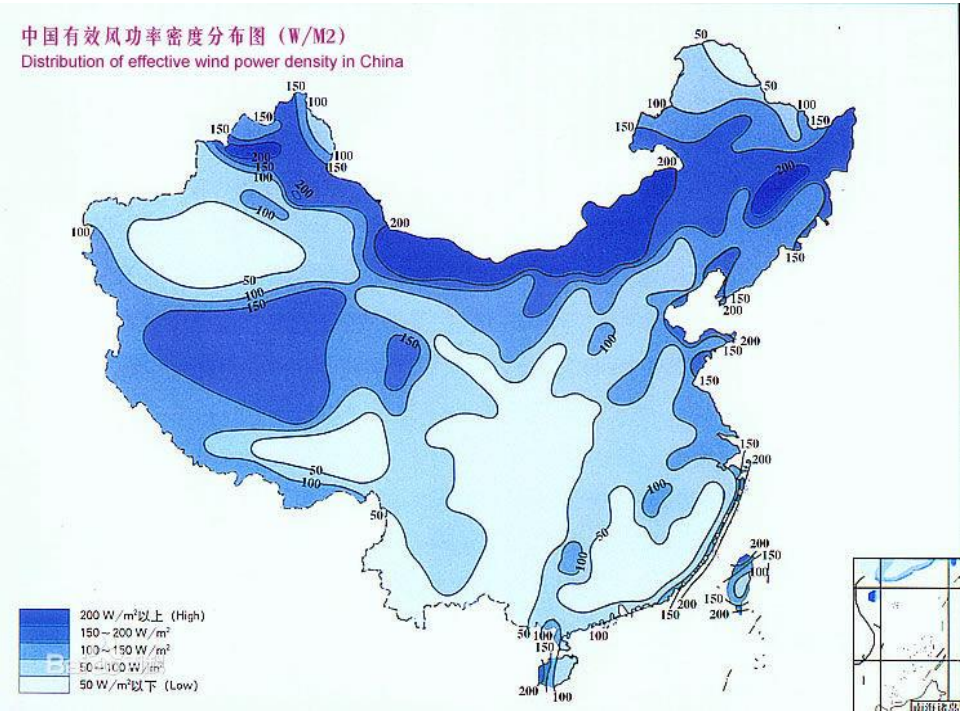
2.7 Test platform

2.8 Development Prospect

2.1 Research background

2.1.1 Wind energy resources

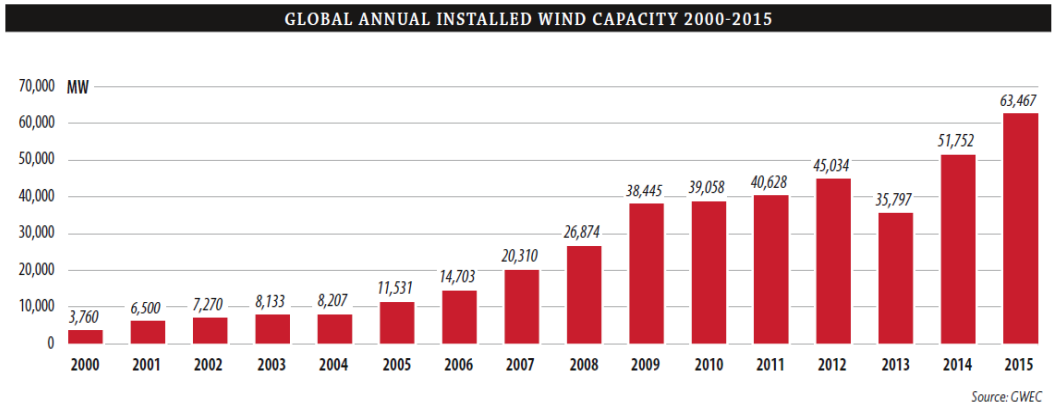
- Land of 10 m height from the ground wind energy resources reserves is about 4.35 billion KW.
- The development and utilization of wind energy reserves is about 750 million KW on the Sea of 10 m height .
- Land of wind energy resources in China are mainly distributed in three north regions (northeast, north, northwest, southeast coast and the islands.



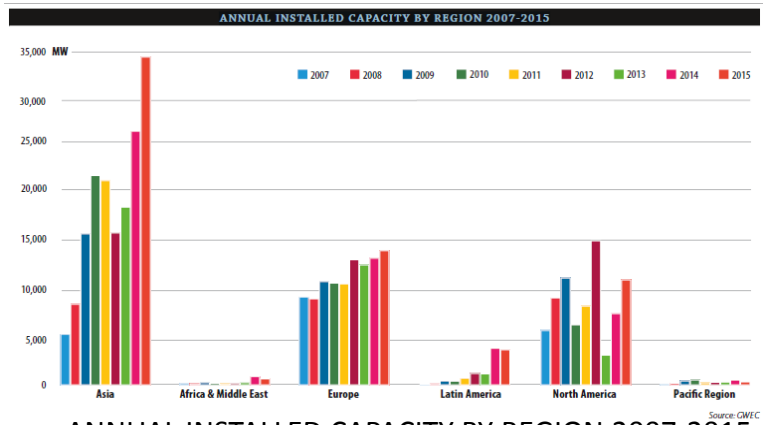
Effective wind power density distribution in our country

2.1 Research background

2.1.2 The market demand



GLOBAL ANNUAL INSTALLED WIND CAPACITY 2000-2015



ANNUAL INSTALLED CAPACITY BY REGION 2007-2015

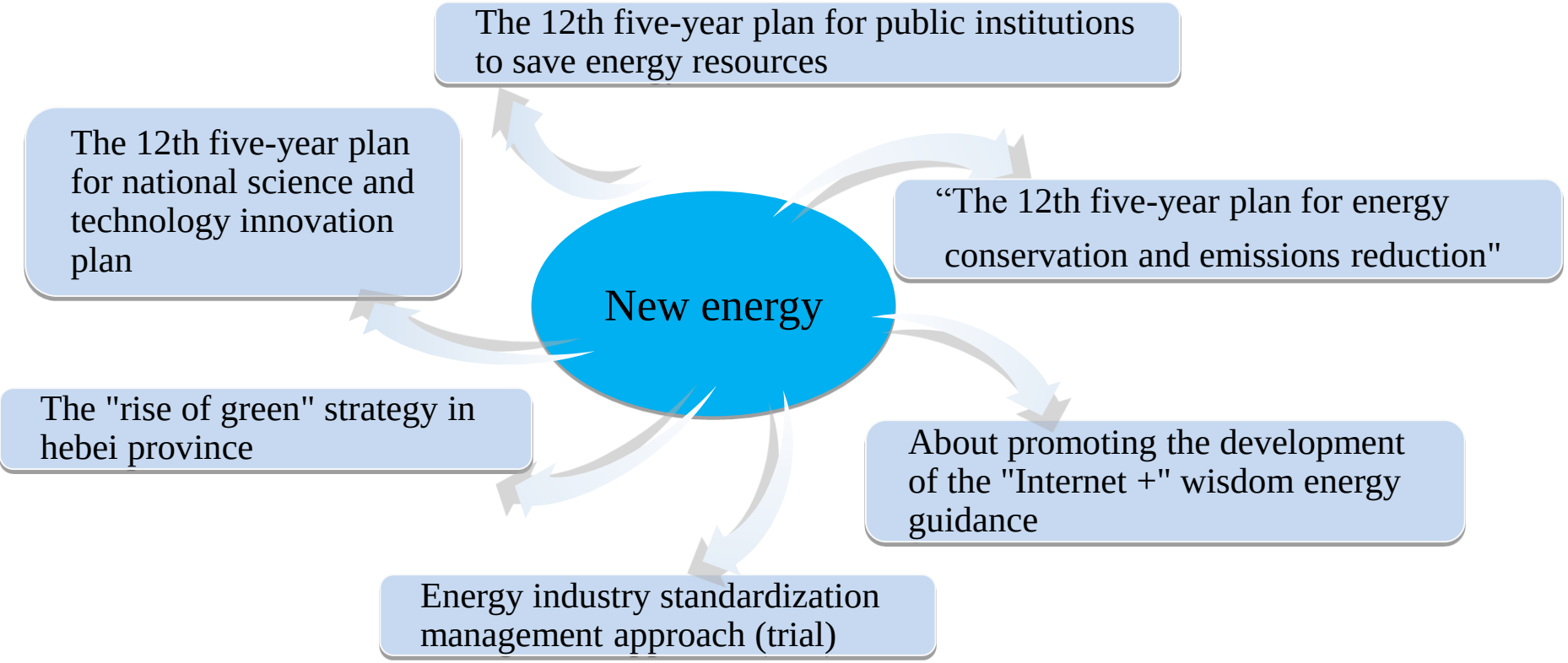
In 2015, the global wind power installed capacity hit a record high. Global new installed capacity of 11715 mw, up 22.64% from a year earlier.

Between 2007 and 2015, Asia, Europe, North America, the installed capacity is higher. In Asia the installed capacity is increasing year by year .

- China is the big country of Asia's abundant wind resources ,so wind power generators have very big market.

2.1 Research background

2.1.3 National policy



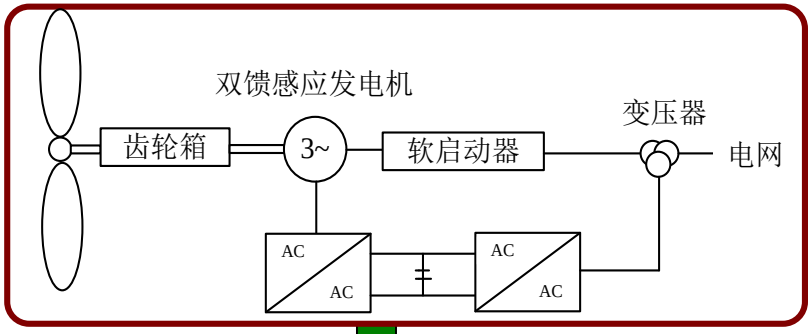
- Adapt to the need of the national major and low carbon green environmental protection requirements, building a resource-conserving and environmentally friendly industries.

2.1 Research background

2.1.4 The traditional wind turbine

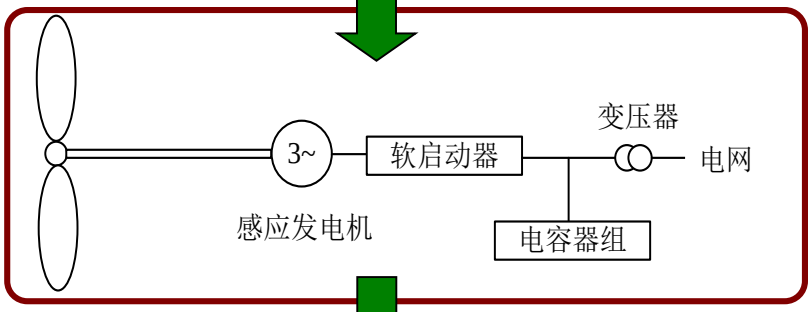
Gear box of high failure rate
Tower mass is heavy
Needing rectifier and inverter

DFIG



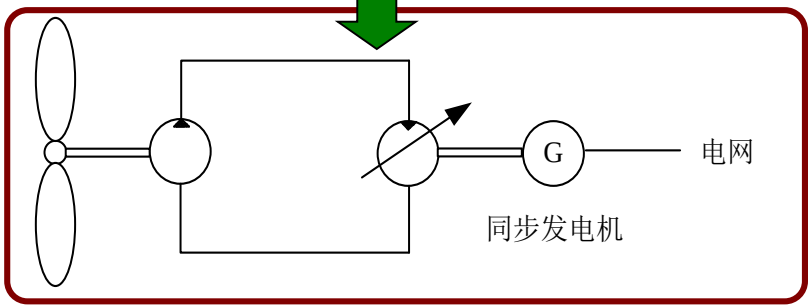
Tower mass is heavy
Needing rectifier and inverter

PMSM



Safe and reliable
Saving tower mass
Omiting the rectifier and inverter

HWT



2.1 Research background

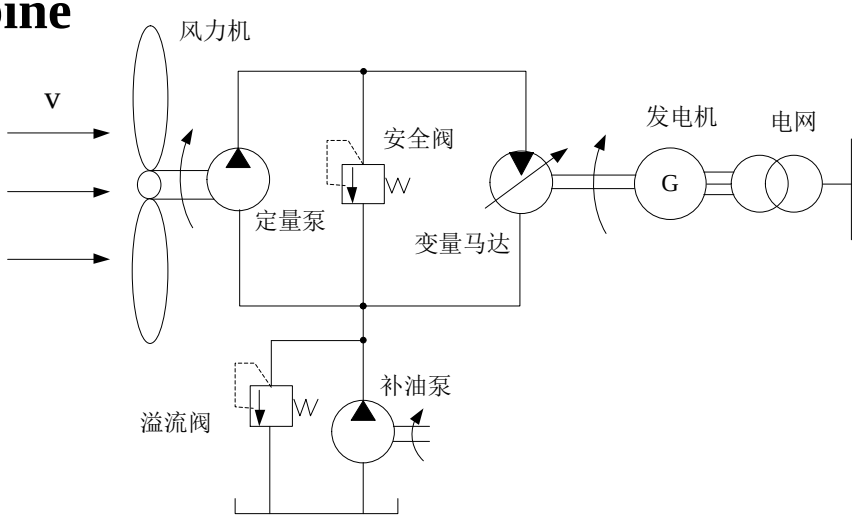
2.1.5 Advantages of hydraulic wind turbine

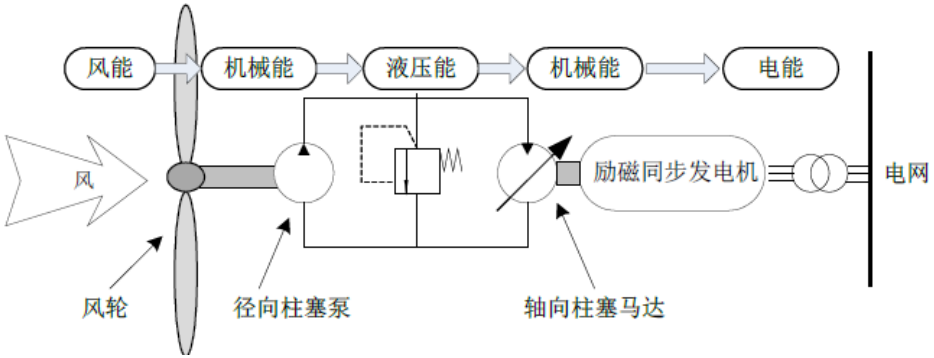
Engineering

1. advanced technology;
2. convenient installation ;
3. advanced structure;
4. Control system is high efficiency.

Technical

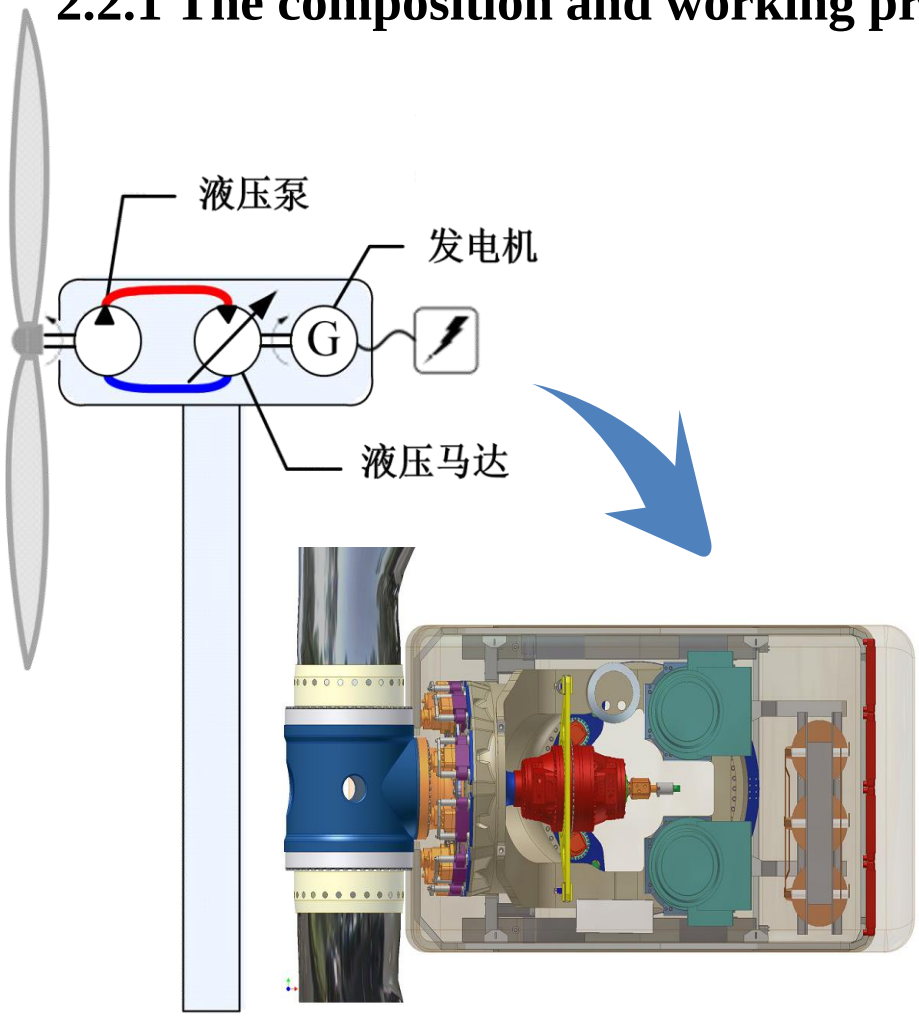
1. flexibility and high reliability;
2. low cost, easy to realize standardization;
3. tracking power easily,
4. wind turbine power series can be realized.





2.2 Brief introduction and classification

2.2.1 The composition and working principle



◆ Hydraulic wind turbine (HWT) is consist of wind turbine, a fixed displacement pump-various motor closed hydraulic drive system and synchronous generator.

◆ Wind turbine drives fixed displacement pump to export high pressure oil. Then the oil is exported to motor. Finally, motor drives generator generating electricity.

2.2 Brief introduction and classification

2.2.2 Classification

Vertical shaft

Horizontal shaft

According to the blade fixed axis orientation of wind turbine, it can be classified as followed.
（1）Horizontal shaft：it needs adjust orentation timely to keep consistent with wind.
（2）Vertical shaft：it can collect various orentation wind.

2.3 Present Condition of Research

2.3.1 Present Condition of Foreign Research

Chapp drive company

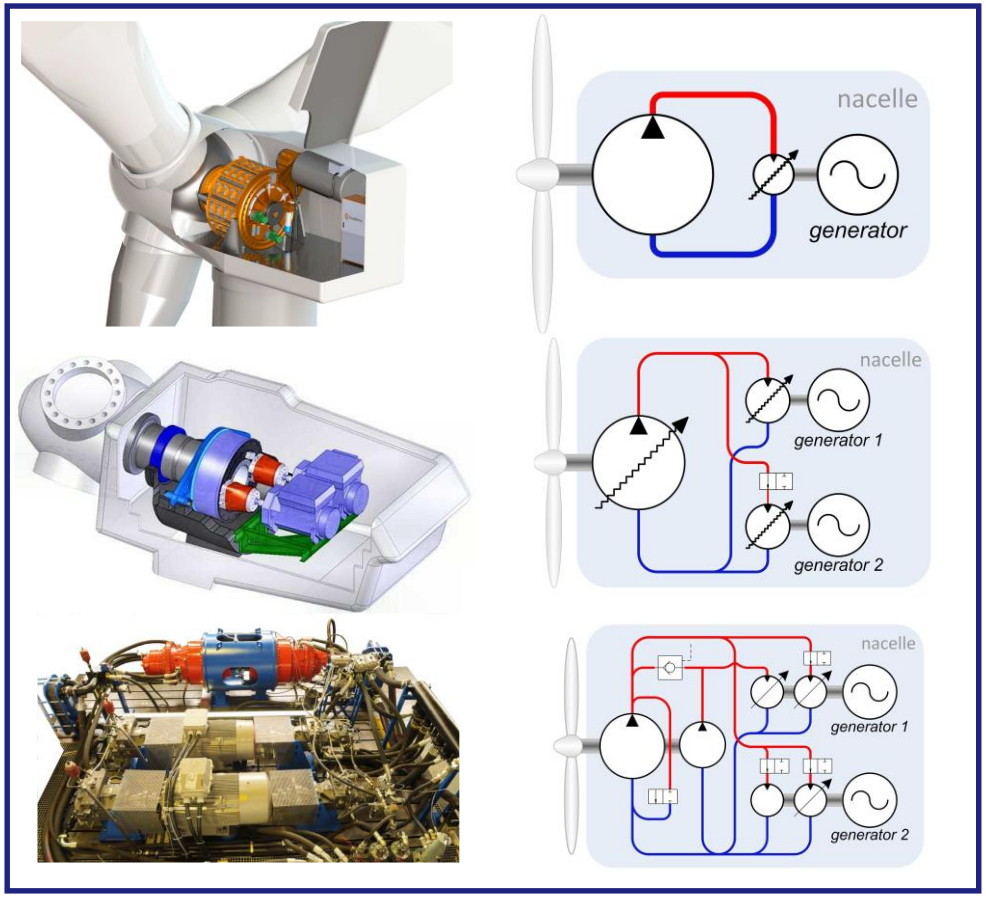
225kW、900kW、5MW types.
3 Europe patents，3.3MW and 6.6MW are under research.

Atos

Using Radial piston pump，purchased by Mitsubishi. 7MW “Sea Angel” was installed in 2015.

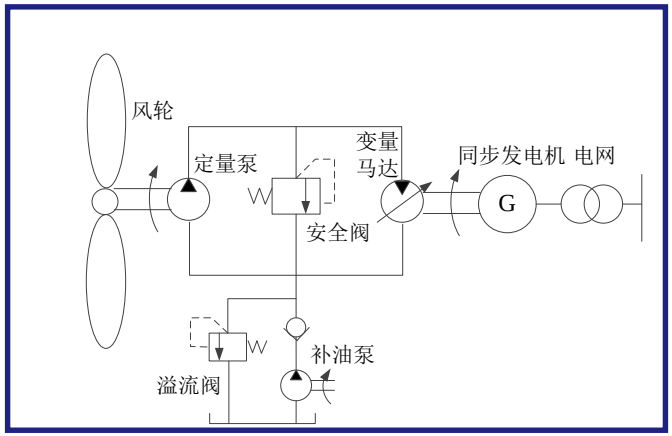
RWTH Aachen

Highest efficiency is 85%，speed control and pressure control .

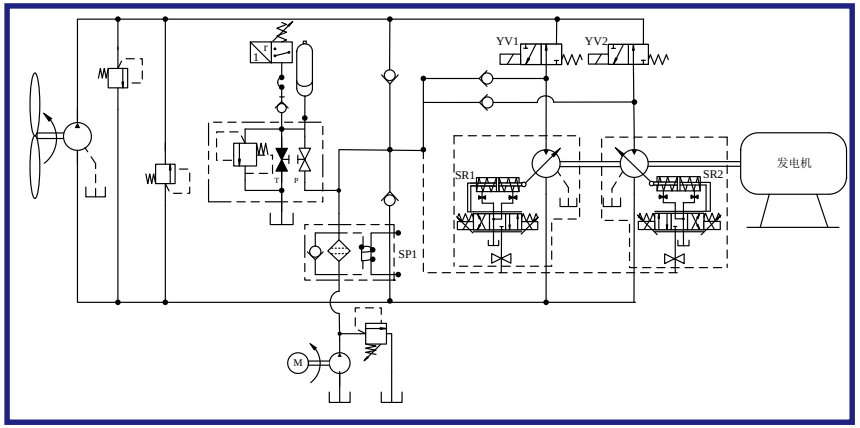


2.3 Present condition of research

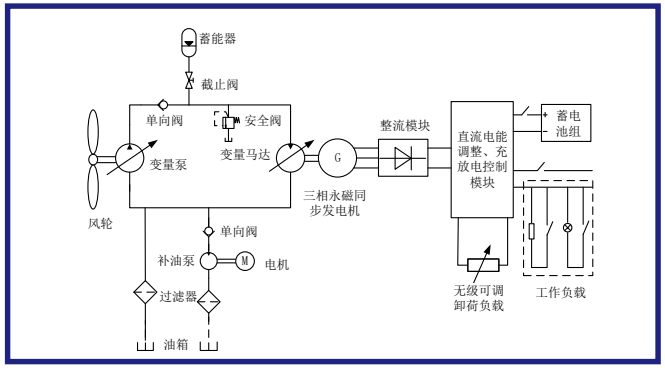
2.3.2 Present condition of domestic research



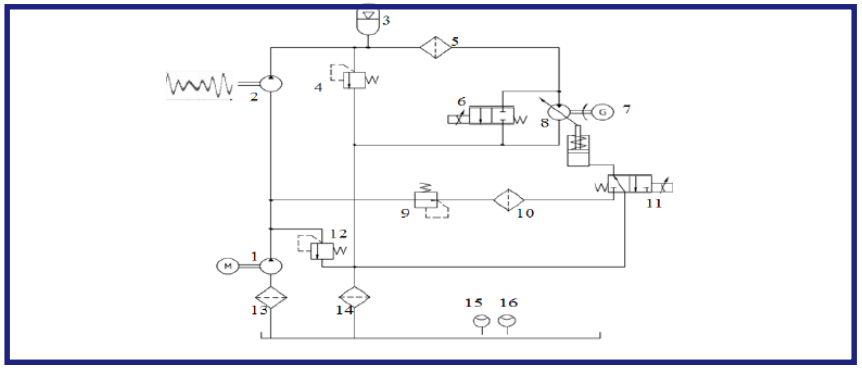
Yanshan University



Dalian university of technology



Zhejiang university



Shanghai Jiao Tong University

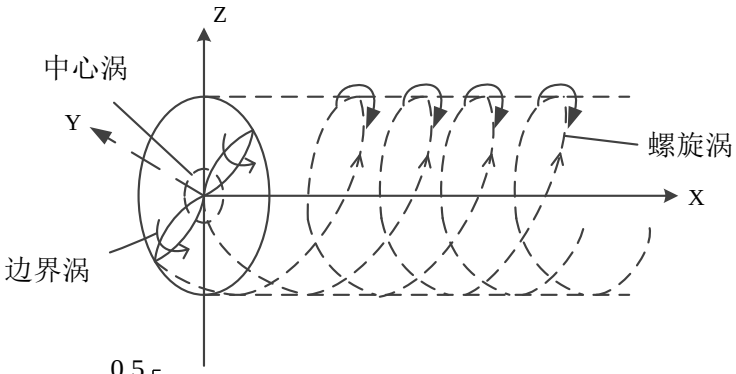
2.4 Wind turbine

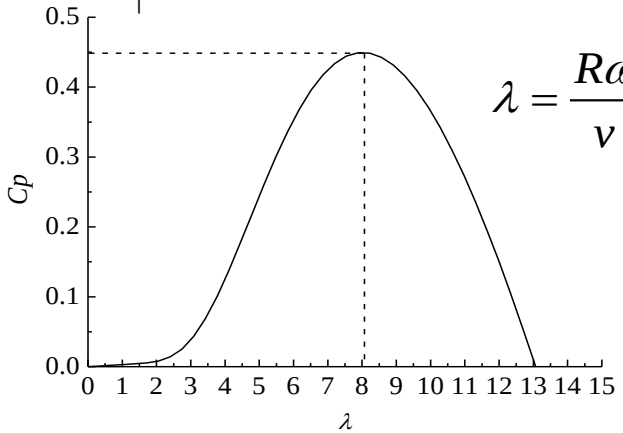
2.4.1 Wind turbine model

Output power and **pneumatic torque** of **wind turbine are**

$$P = \frac{1}{2}\rho A C_P(\lambda, \beta) v^3$$

$$T = \frac{P}{\omega}$$





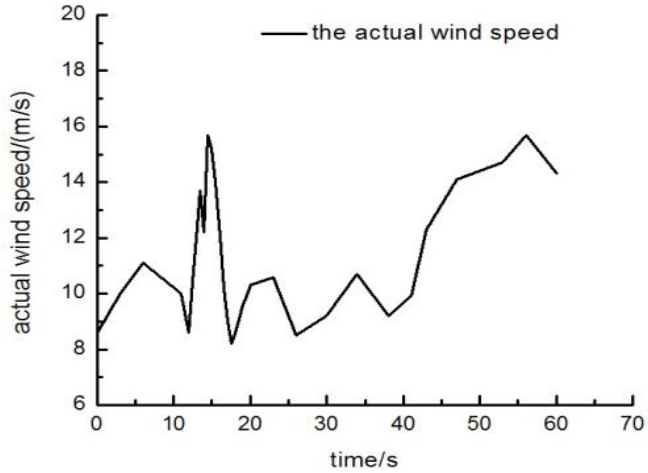
$$\lambda = \frac{R\omega}{v}$$

Key technology: The characteristics of wind turbine isstudied, and the efficiency of wind turbine is improved.

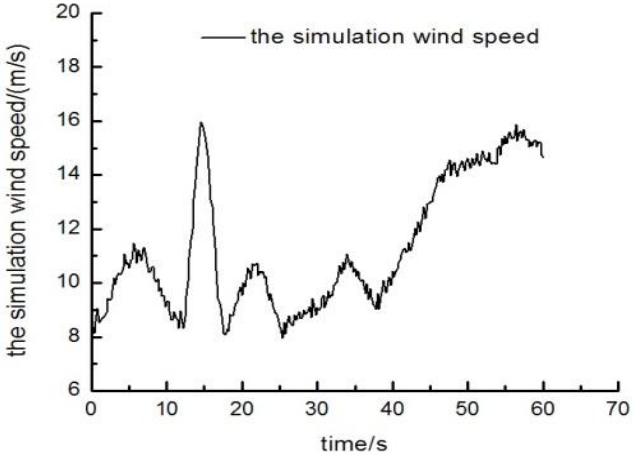
2.4 Wind turbine

2.4.2 Wind energy and wind turbine operation area

Although Wind speed has certain randomness , it still has a certain distribution principle. Mathematical method is used to describe wind characteristics. Blow picture is the relevant data in a wind farm.



The actual wind speed curve



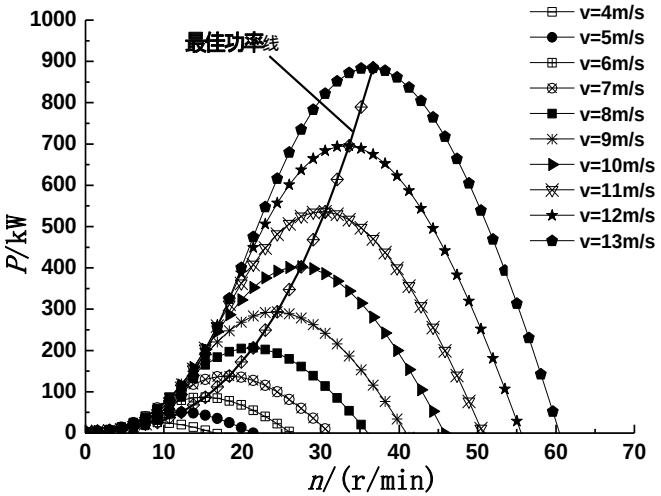
The simulation wind speed curve

Key technology:The wind speed model is simplified to a sum of four typical wind speed： basic wind, intermittent wind, varied wind and random wind.

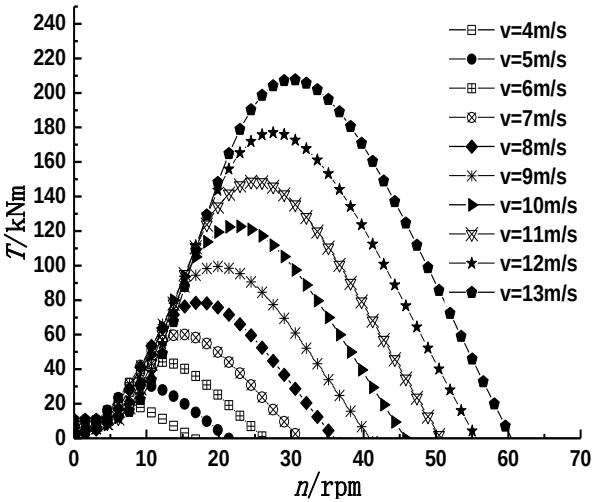
2.4 Wind turbine

2.4.2 Wind energy and wind turbine operation area

◆ A study about 850kW wind turbine has been conducted，the relevent curve of wind turbine speed obtained as followed.

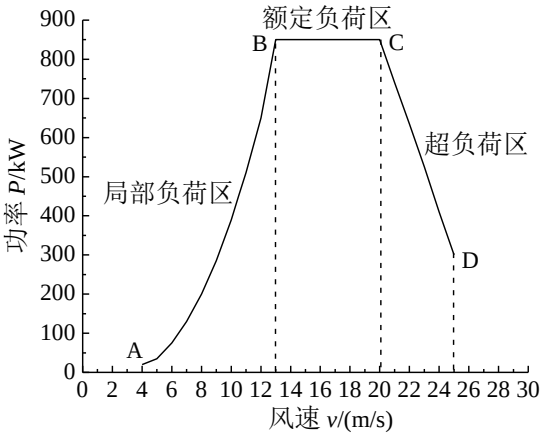


Wind turbine power output characteristic curve



Wind turbine pneumatic torque characteristic curve

◆ Analyze of running area



Output power of wind turbine

A~B： **Local load area；**
B~C： **Rated load area；**
C~D： **Exceed load area .**

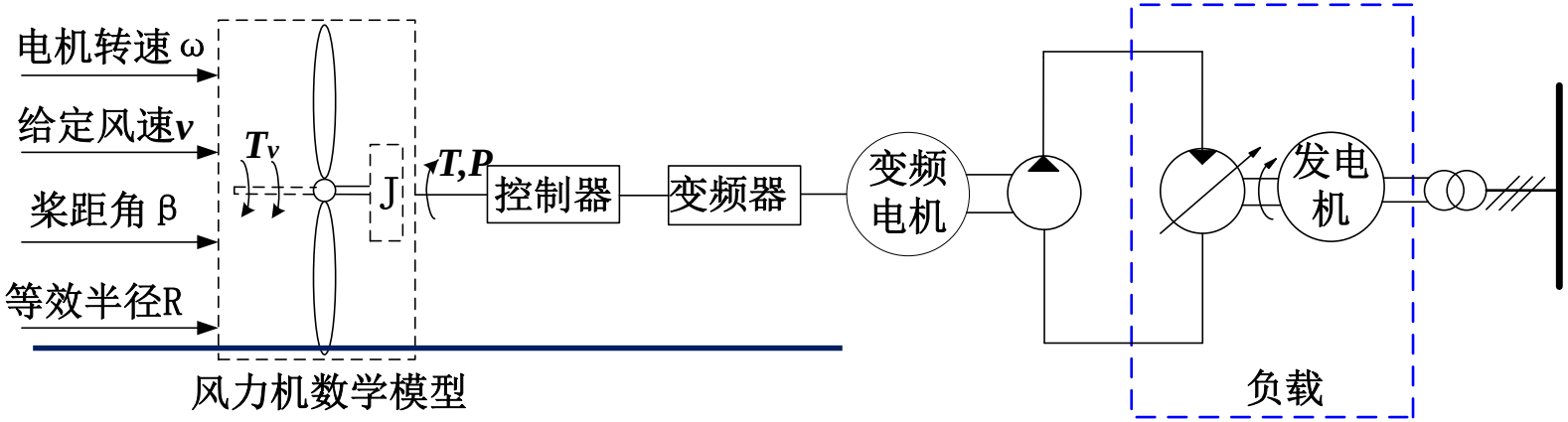
Keytechnology: The high precision wind turbine model is proposed.

（ Model accuracy of more than 95 % .

2.4 Wind turbine

2.4.3 Wind turbine analog simulation research

There are no actual wind condition in lab. Variable frequency generator simulates wind turbine characteristics.



Analog simulation of wind turbine must meet the following three similarconditions
(1) Same wind energy utilization coefficient ; (2) Similar power;
(2) (3) Similar moment of inertia

Key technology: Wind turbine analog simulation method.

2.5 Hydraulic main drive system

2.5.1 Quasi-synchronization grid control

Five conditions of connected to Grid

① The same waveform ;

② The same phase sequence ;

③ The same frequency;

④ **The same magnitude** ;

⑤ **In the same phase .**

For the state grid frequency **:**
50Hz±(0.1~0.2)Hz

→

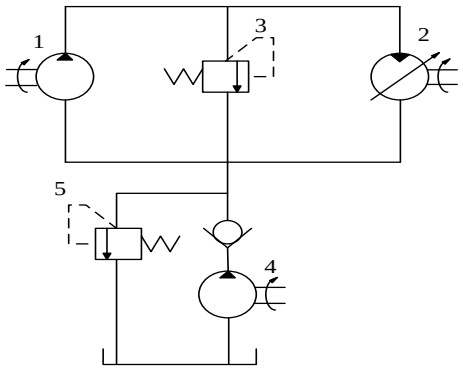
The range of motor speed **:**
1500 ±6r/min

→

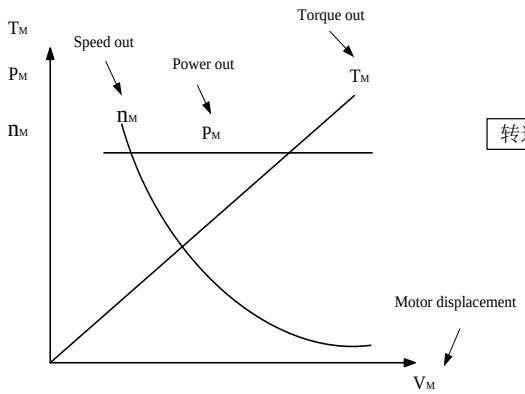
Grid control mode:
（**Penecon-temporaneous method**）

2.5 Hydraulic main drive system

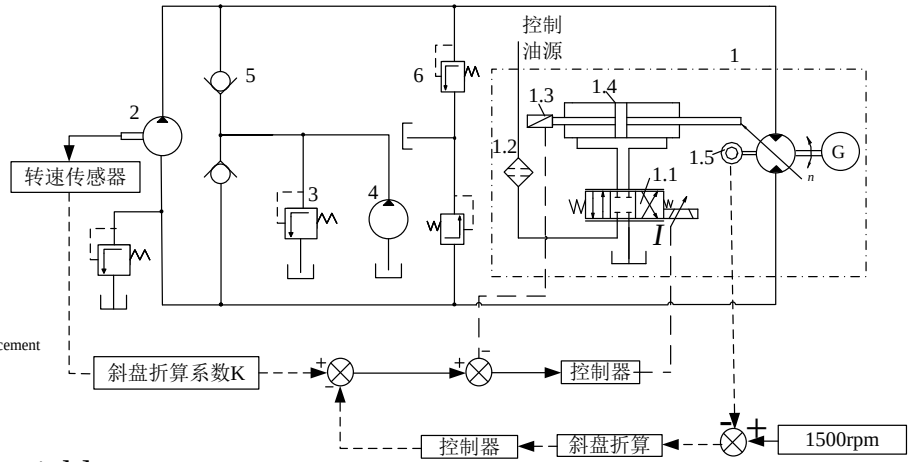
2.5.1 Speed control-Flow steady speed feedback control mode



•Fixed displacement pump- variable motor closed circuit diagram



•Fixed displacement pump- variable operating characteristic curve



•Flow feedback pump- variable motor speed control system schematic

- The frequency allowable value of ± 0.2Hz before connect to grid.
- synchronous generator speed is 1500 ± 6r / min

- Motor displacement reference value is given by the calculation of system

.

- **Key technology:** Speed control system control method of fixed displacement pump-variable motor and Steady speed output control method of HWT.

2.5 Hydraulic main drive system

2.5.1 Speed control - Based on the speed of the feedback linearization control mode

◆ **Controlling output option and Tracking target choose**

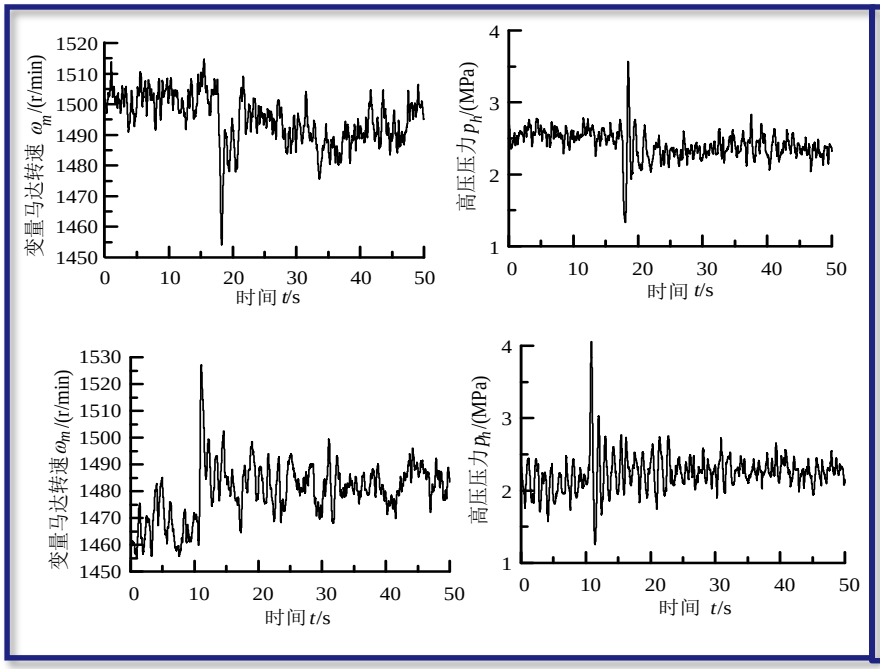
$$y=\begin{cases} h_1(x)=D_p\omega_p p_{h1}=D_p x_1 x_2 \\ h_2(x)=p_{h2}=x_3 \end{cases}$$

$$U_E=\frac{D_p\omega_p-C_{t1}p_{h1}+\left(V_1/\beta D_p\omega_p\right)\left(D_p p_{h1}\dot{\omega}_p-v_1\right)}{K}$$

$$\gamma=\frac{KU_E-C_{t2}p_{h2}-\frac{V_2}{\beta}v_2}{K_m\omega_m}$$

$$y_{1\mathrm{d}}=K_{\mathrm{P}}\omega_{\mathrm{p}}^3=K_{\mathrm{P}}x_1^3$$

$$y_{2\mathrm{d}}=p_{h2d}=\frac{B_m\omega_{md}+T_L}{D_m}$$



Experiment

➢ **Key technology：** Wind turbine under the condition of the wind speed changes grid-connection control smoothly .

2.5 Hydraulic main drive system

2.5.1 Speed control -Based on dynamic cover control variable motorangular speed control

Various motor control law is consist of 3 portion as followed.

(1) Reference value of motor angular
(2) Compensation value of motor angular corresponding to system leaking
(3) Compensation value of motor angular corresponding to system pressure transient adjustment

$$S_1 = \omega_m - \omega_{md}$$

$$S_2 = p_{h2} - p_{h2d}$$

$$\bar{p}_{h2} = \frac{(-k_1 S_1 + \dot{\omega}_{md}) J_m + B_m \omega_m + T_e}{K_m \gamma \eta_{mm}}$$

$$\tau_1 \dot{p}_{h2d} + p_{h2d} = \bar{p}_{h2}$$

Dynamic cover controller

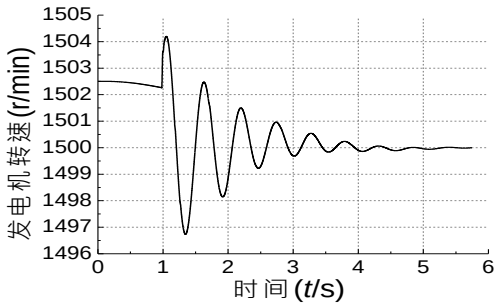
$$\gamma = \frac{D_p \omega_p - C_{tp} p_{h1} - (-k_2 S_2 + \dot{p}_{h2d}) \frac{V_{02}}{\beta_e}}{K_m \omega_m} = \frac{D_p \omega_p}{K_m \omega_m} - \frac{C_{tp} p_{h1}}{K_m \omega_m} - \frac{(-k_2 S_2 + \dot{p}_{h2d}) V_{02}}{K_m \omega_m \beta_e}$$

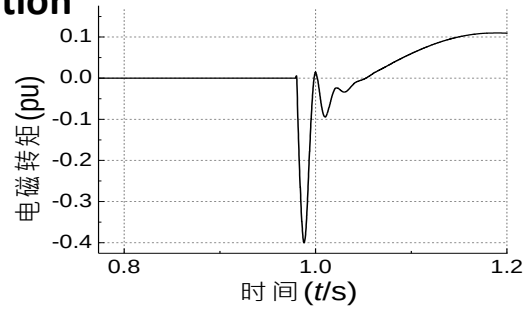
➢**Key technology：** Adjusting hydraulic system output speed by controlling the variable motor angular

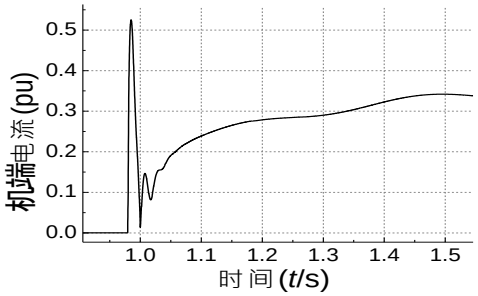
2.5 Hydraulic main drive system

2.5.1 Speed control-Experiment and simulation

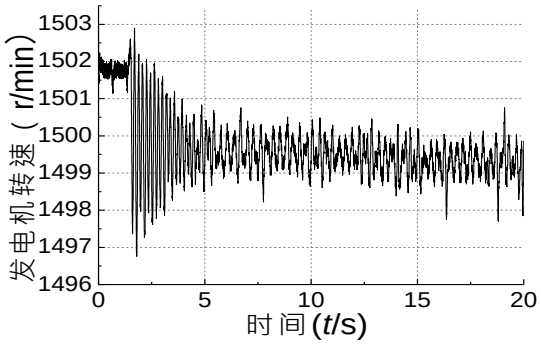
Grid impact characteristics simulation

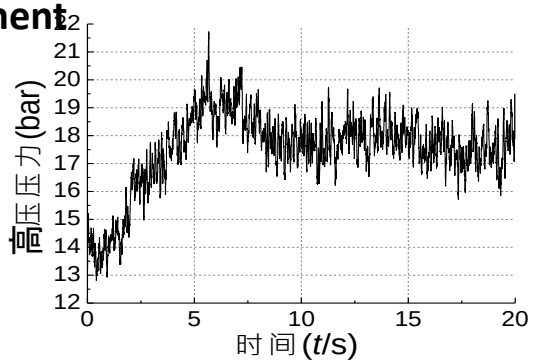


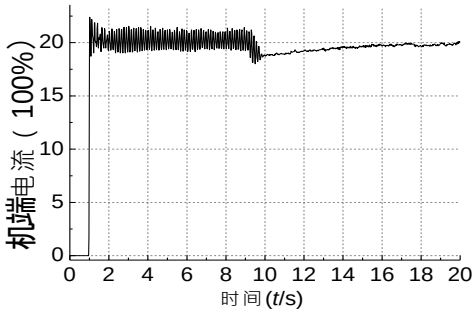




Grid impact characteristic experiment



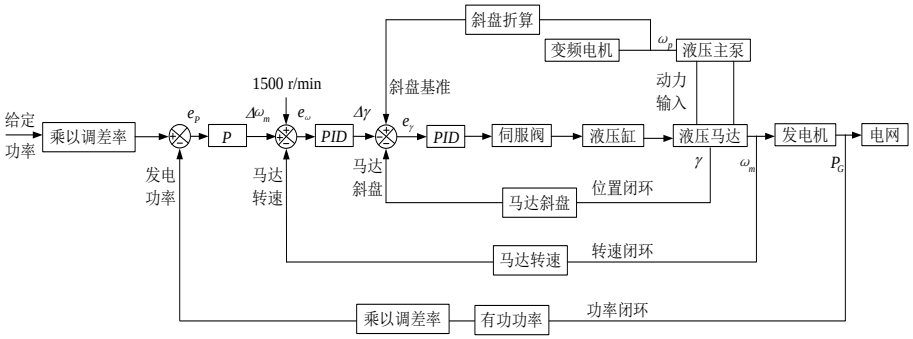


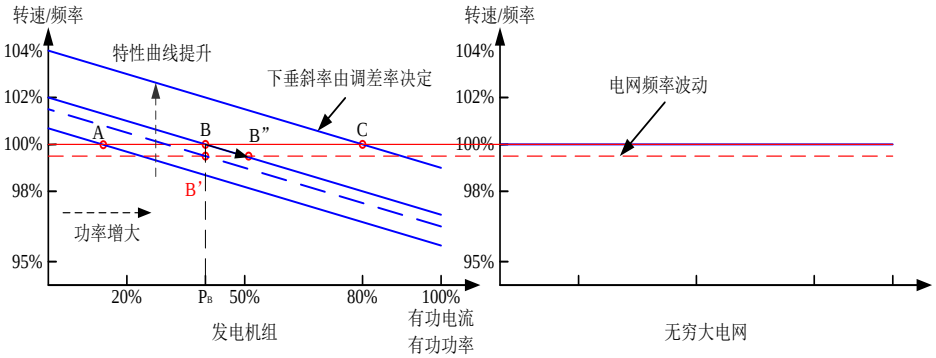


- Voltage and frequency offset have less impact on grid, and a greater influence on the phase Angle difference.
- Generator in the grid point impact current control under 30% of the rated current, phase Angle impact at about 4°.

2.5 Hydraulic main drive system

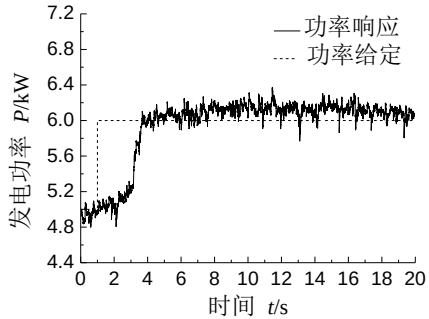
2.5.2 Main drive system power control—Active power control



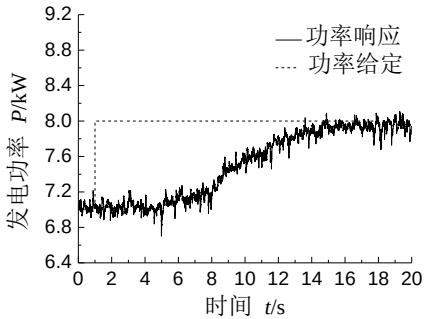


Position closed-loop control ; motor speed closed-loop control ; power closed-loop control

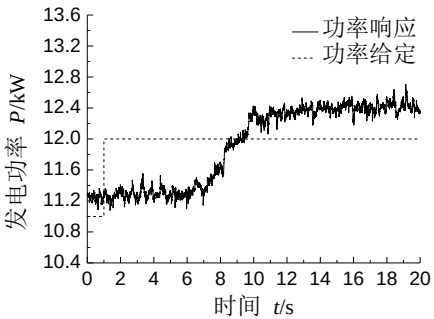
Using **droop characteristic** control scheme to establish the linear relationship between speed and power



a) Rp=500r/min



b) Rp=700r/min



c) Rp=900r/min

P=0.3
I=0.1
Pw=1kW

Key technology: Power control can be realized by using the **droop characteristic** method.

2.5 Hydraulic main drive system

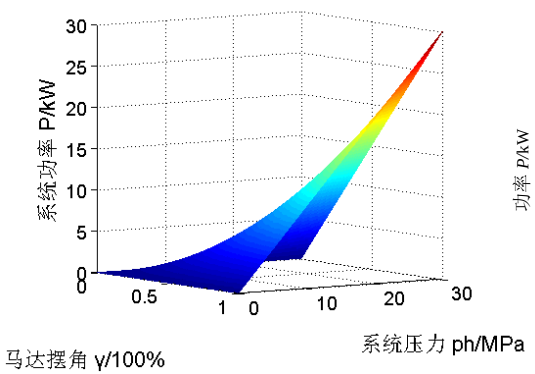
2.5.2 power control—Active Power Control Online Optimization of Power Controller

The power of the motor angular transfer function:

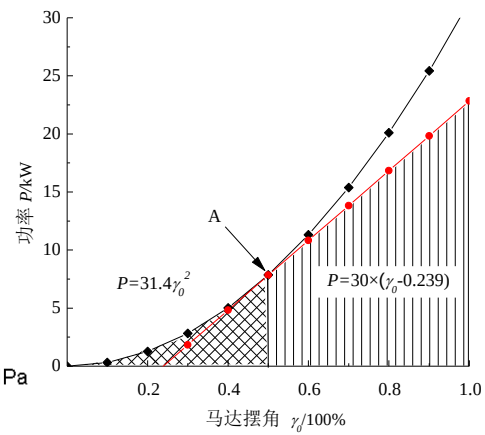
$$\frac{p_h}{\gamma} = -\frac{K_m\omega_{m0}/C_t}{(1+\frac{V_0}{C_t\beta_e}s)}$$

The system pressure of angular transfer function of the motor:

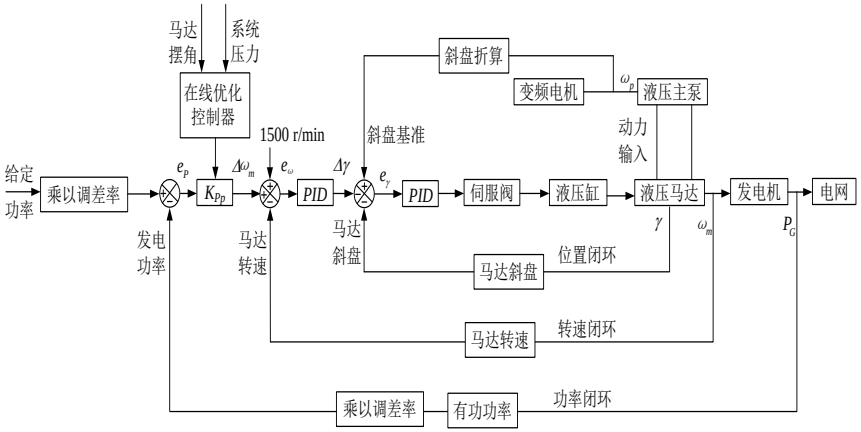
$$\frac{p_h}{\gamma} = -\frac{K_m\omega_{m0}/C_t}{(1+\frac{V_0}{C_t\beta_e}s)}$$



Power three-dimensional workspace



Power up interval

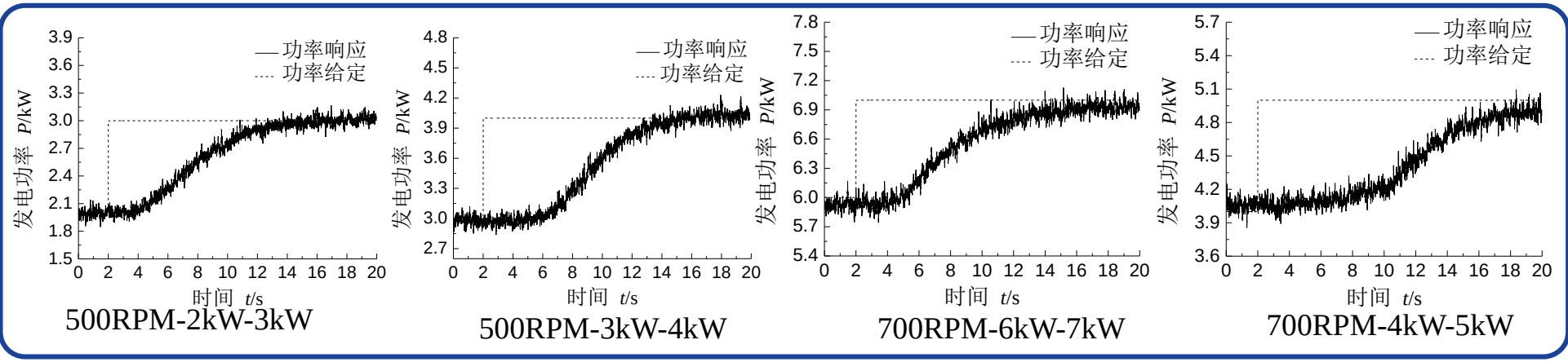


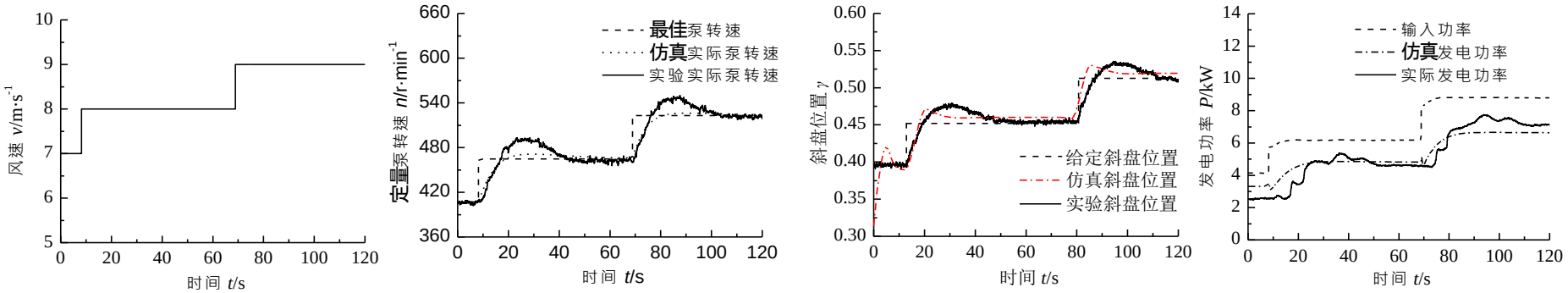
Control block diagram of online optimal power control

Key technology: The relationship between the variables and the system is nonlinear. The initial swing angle and pressure are different, so are **power response characteristics of the system**. According to the **initial pressure of the system** and the **initial swing angle of the motor**, **the gain value of the power control link is determined**.

2.5 Hydraulic main drive system

2.5.2 power control—experimental verification

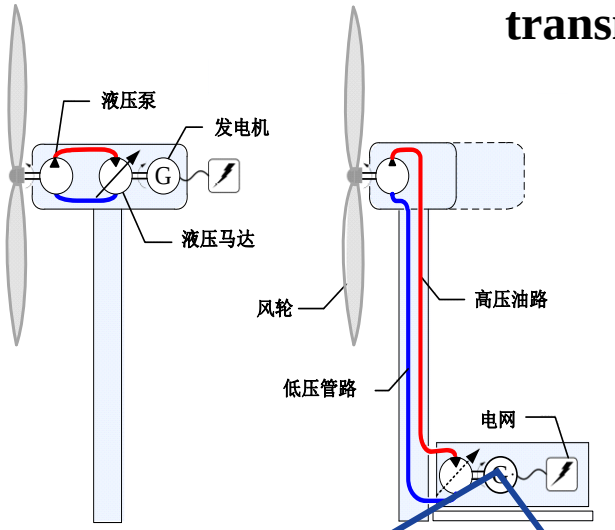




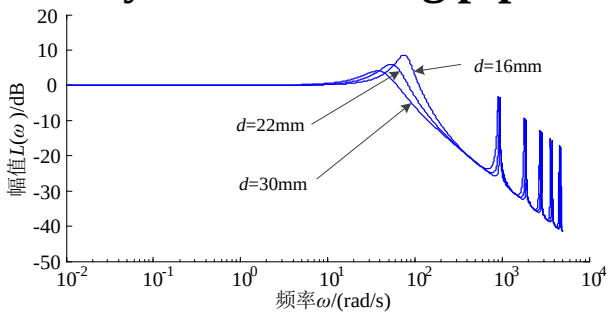
Key technology :Under the condition of low wind speed, the optimal control theory is used to realize the **maximum control of the power tracking and power smoothing.**

2.5 Hydraulic main drive system

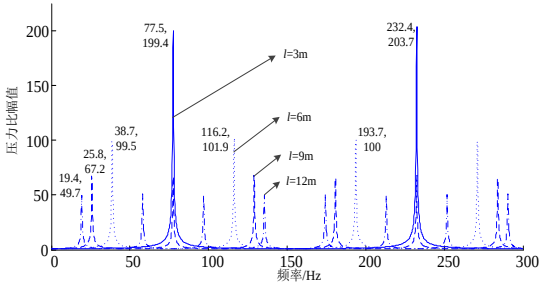
2.5.3 Research on the characteristics and the steady speed control of the main transmission system with long pipeline



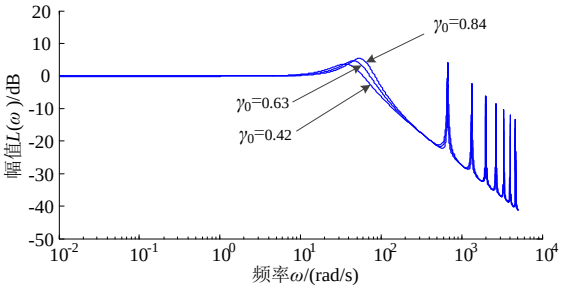
With the increase of hydraulic pipeline, the **stiffness** of the system is reduced . So that the unit is more likely to **produce resonance under the random wind frequency excitation.**



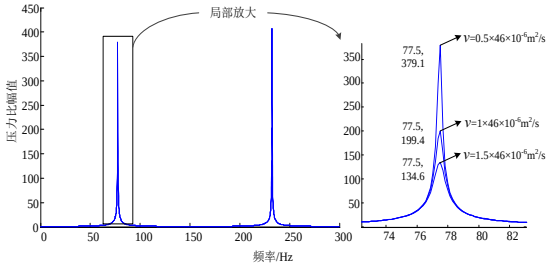
◆Effect of **pipe diameter**



◆Effect of **oil density** on sysytem pressue



◆Effect of **motor swing angle**

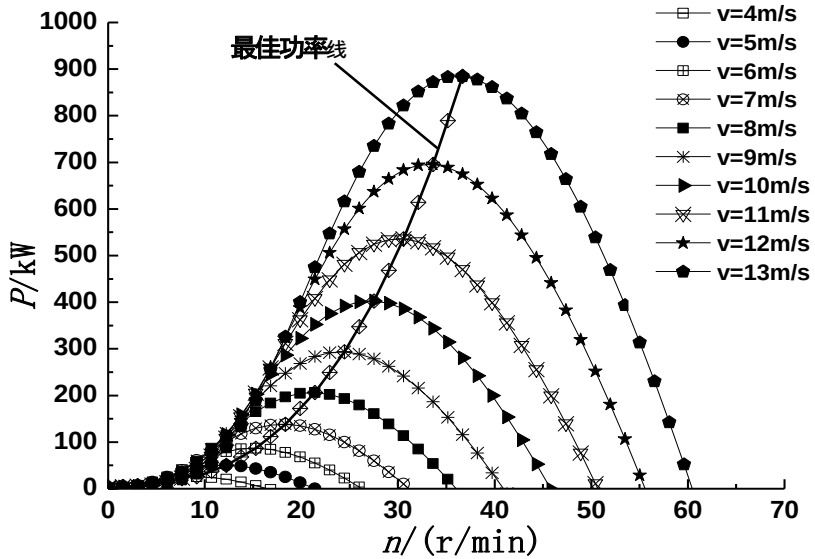


◆Effect of **pipe diameter** on sysytem pressue

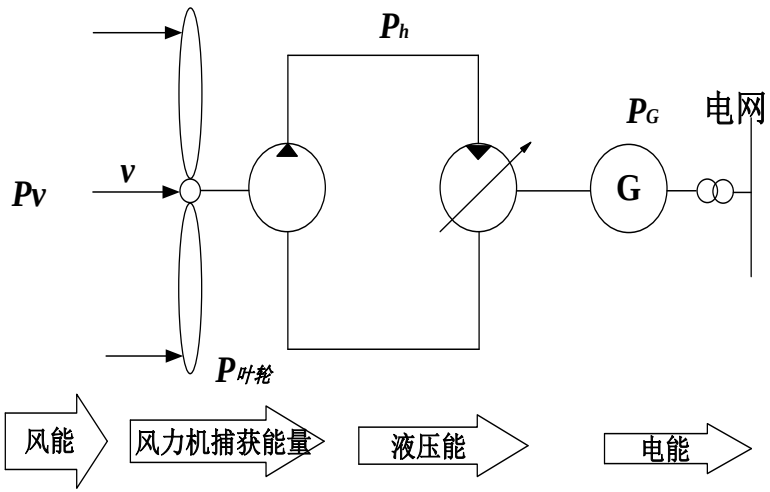
Key technology : The influence of system parameters, including **pipe length, diameter and steady speed control strategy** are also studied.

2.5 Hydraulic main drive system

2.5.4 Maximum Power Point Tracking (MPPT)Control —Control target



Wind turbine power output characteristic curve



Energy transfer of HWT

- **Essence: Control wind turbine's rotate speed.**
- **Purpose: Get more energy from wind.**

Key technology: There is a optimal power point in each wind speed, the controller can quickly track the best power point.

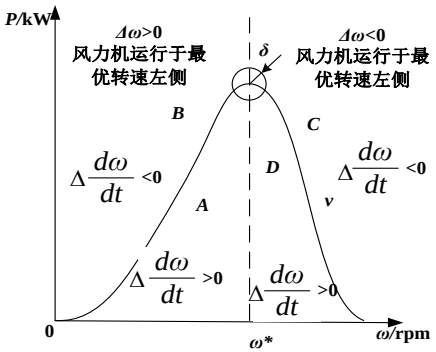
2.5 Hydraulic main drive system

2.5.4 MPPT Control —Control method

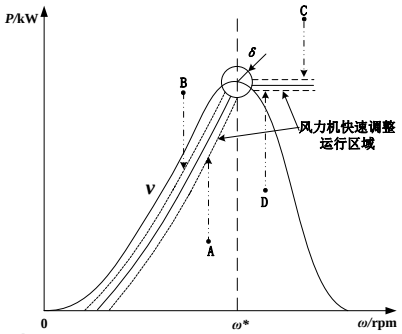
◆**MPPT Control Method for Hydraulic Wind Turbine**

HWT is different from traditional wind turbine, so MPPT control method is proposed, which divides into the following four steps:

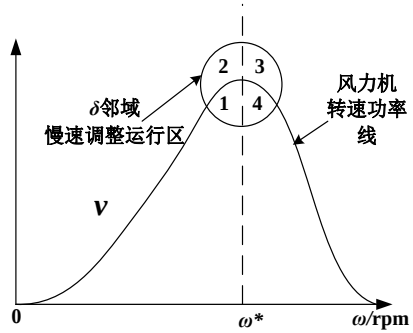
(1)Operation condition judgement(2)Quick adjustment(3) Slow adjustment(4) MPPT result judgement



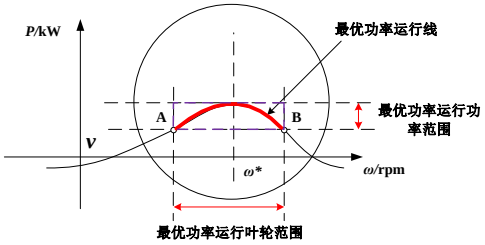
Operation condition judgement



Quick adjustment



Wind turbine slow adjustment



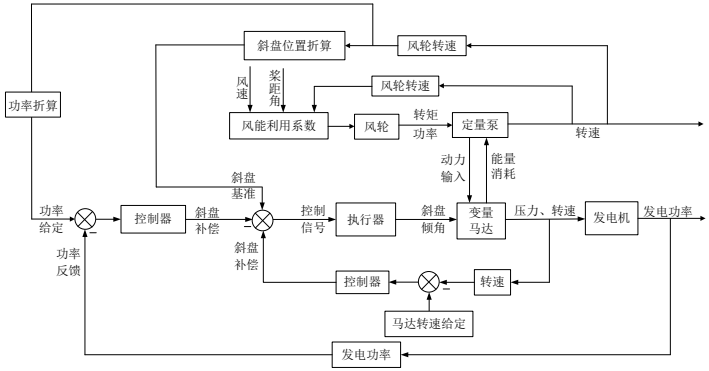
MPPT operating area

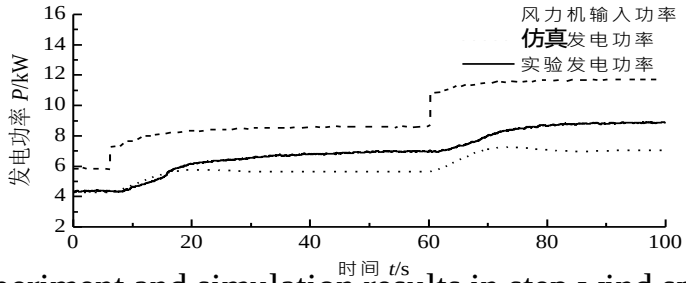
Key technology： Prosed a new MPPT control method for HWT

2.5 Hydraulic main drive system

2.5.4 MPPT Control —Control method

a) Based on wind power

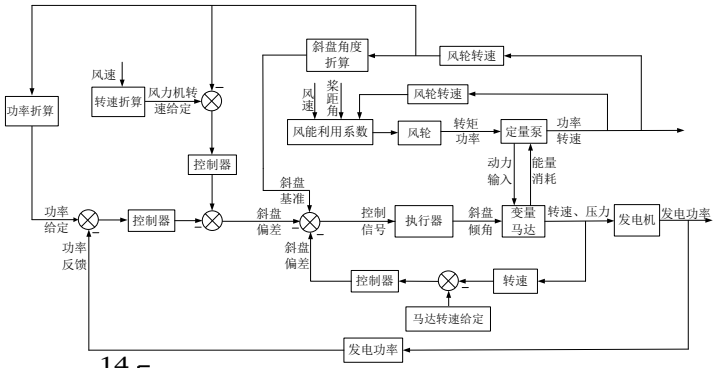


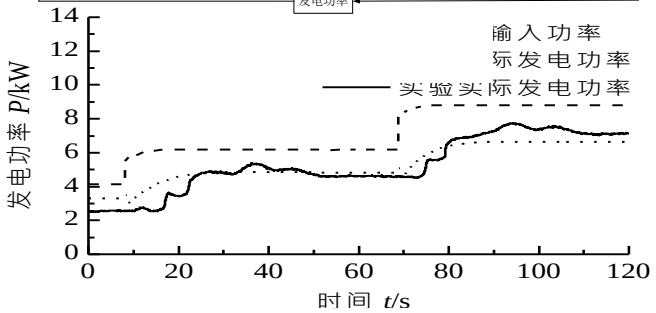


Experiment and simulation results in step wind speed

Conclusion: when the tracking process is completed the final stable point deviates from MPP.

b) Based on wind power and speed





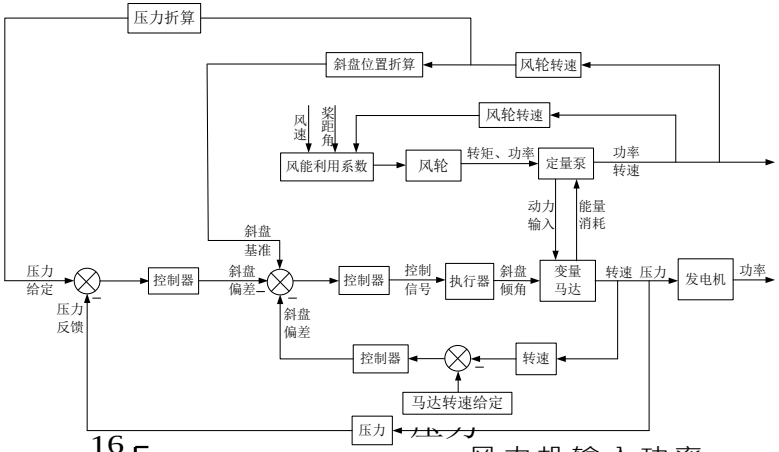
Experiment and simulation results in step wind speed

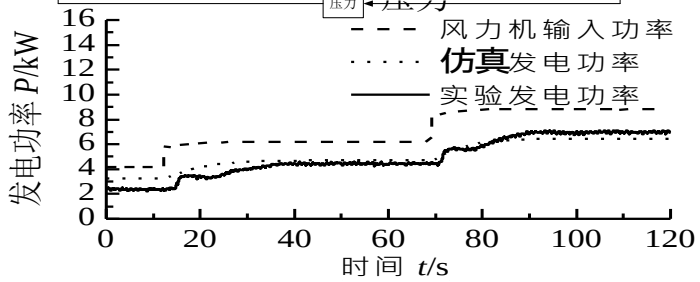
Conclusion: This method added speed control loop, it overcomes the shortcomings of MPPT control method based on wind power.

2.5 Hydraulic main drive system

2.5.4 MPPT Control —Control method

c) Based on system pressure

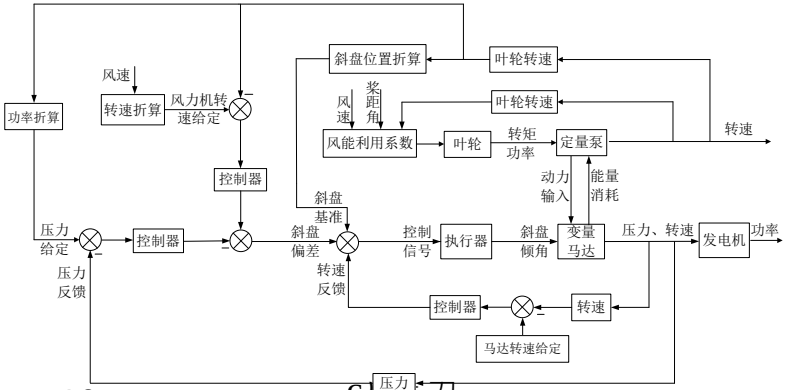


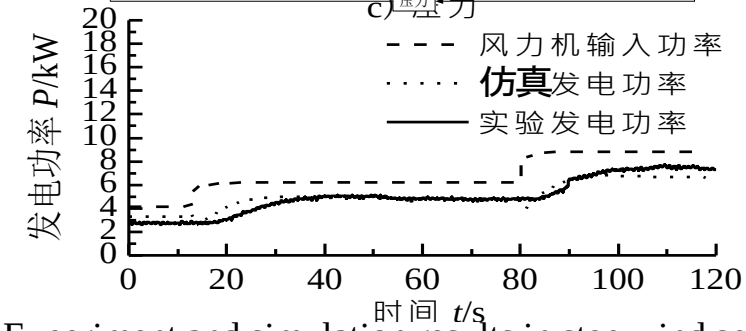


Experiment and simulation results in step wind speed

Conclusion: The system pressure is accurately controlled, but the system also deviates from MPP.

d) Based on system pressure and wind turbine rotation speed





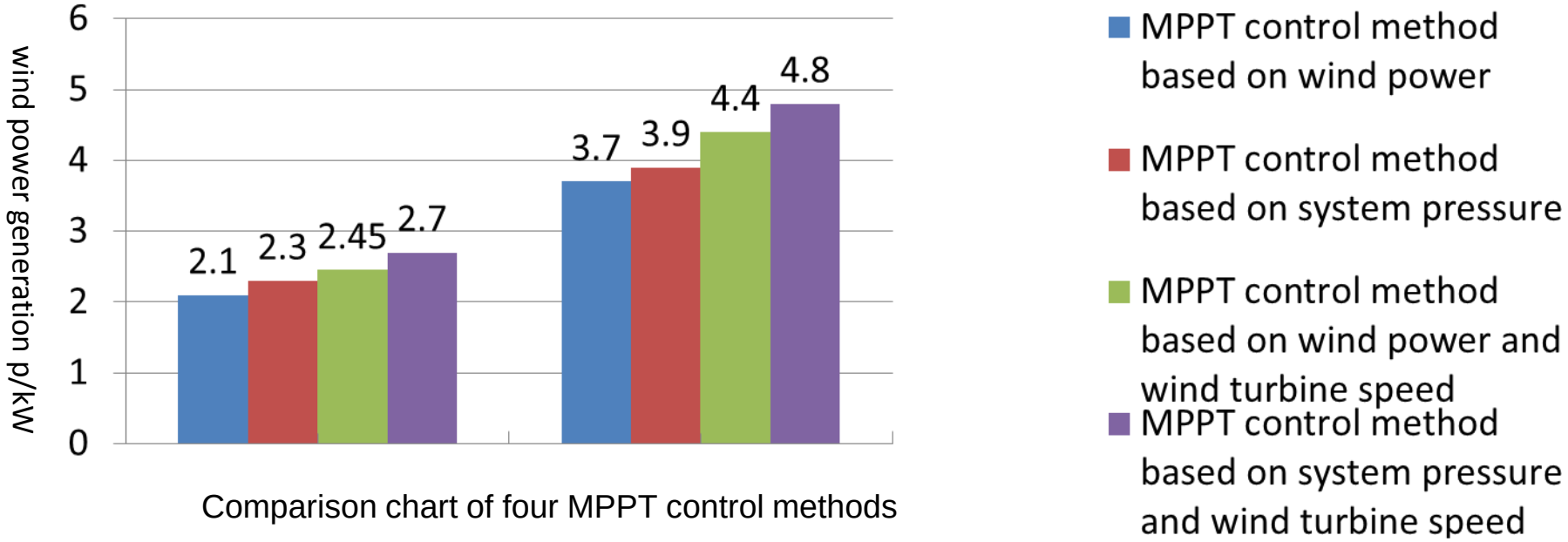
Experiment and simulation results in step wind speed

Conclusion: The system is completely coincident with the MPP when the tracking process is completed.

2.5 Hydraulic main drive system

2.5.4 MPPT Control —Control method

In order to compare the results of four MPPT control methods ,the experimental data is as followed.



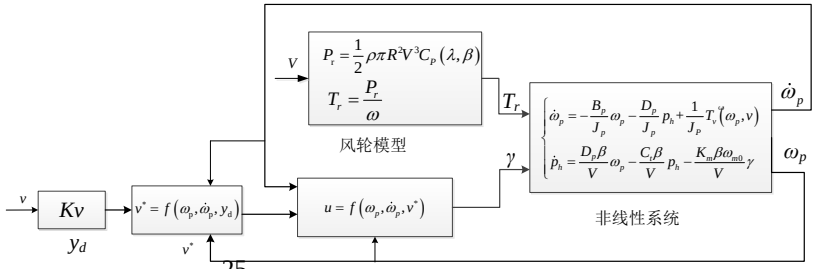
Comparison chart of four MPPT control methods

Key technology: MPPT control method based on wind based on system pressure<based on wind power and wind turbine speed <based on system pressure and wind turbine speed

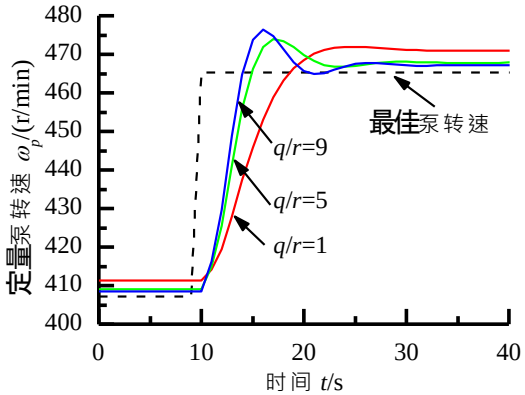
2.5 Hydraulic main drive system

2.5.4 MPPT Control —Control method

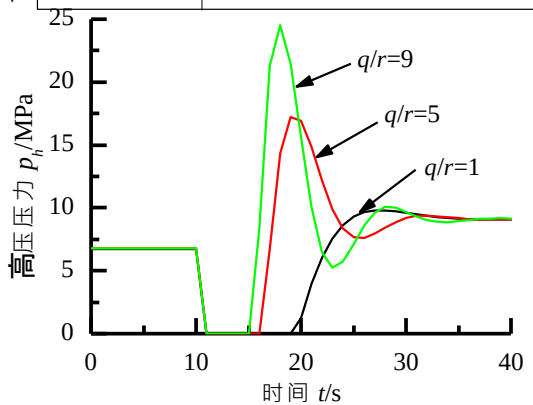
e) Based on wind turbine using feedback linearization method



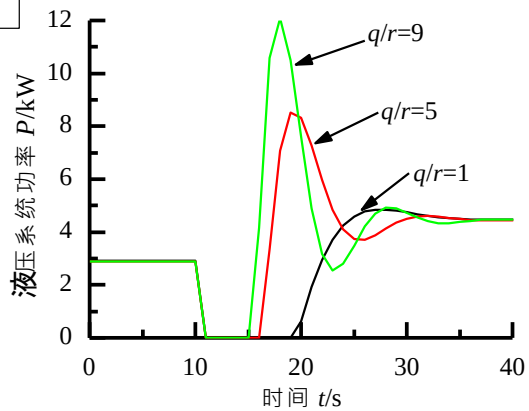
Simulation modal



Quantitative pump speed response curve



System pressure curve



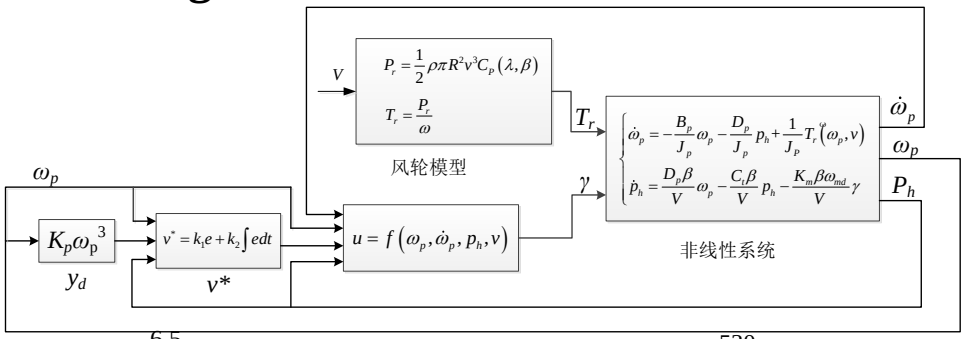
System frequency curve

Key tecnology: The tracking accuracy of the system increases with the increase of q/r ,but the out put power is relatively large.

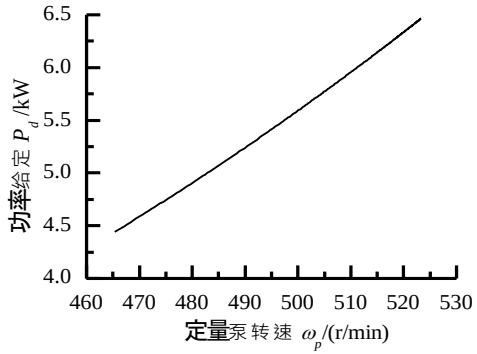
2.5 Hydraulic main drive system

2.5.4 MPPT Control —Control method

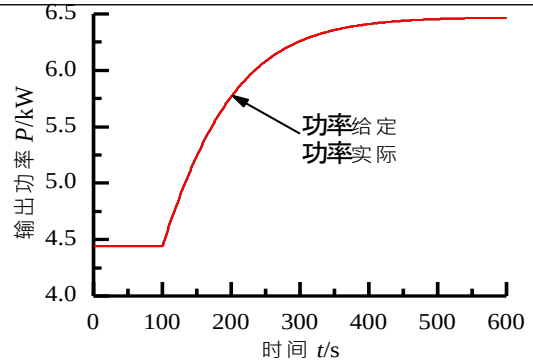
e) Based on output power using feedback linearization method



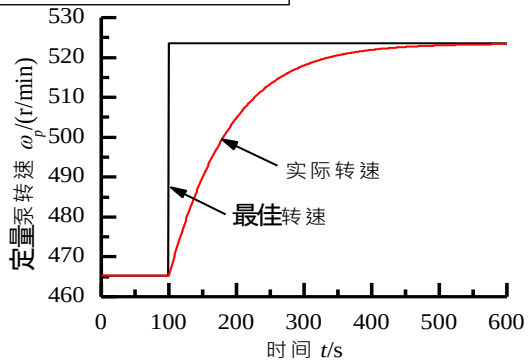
Simulation model



Quantitative pump speed response curve



System pressure curve

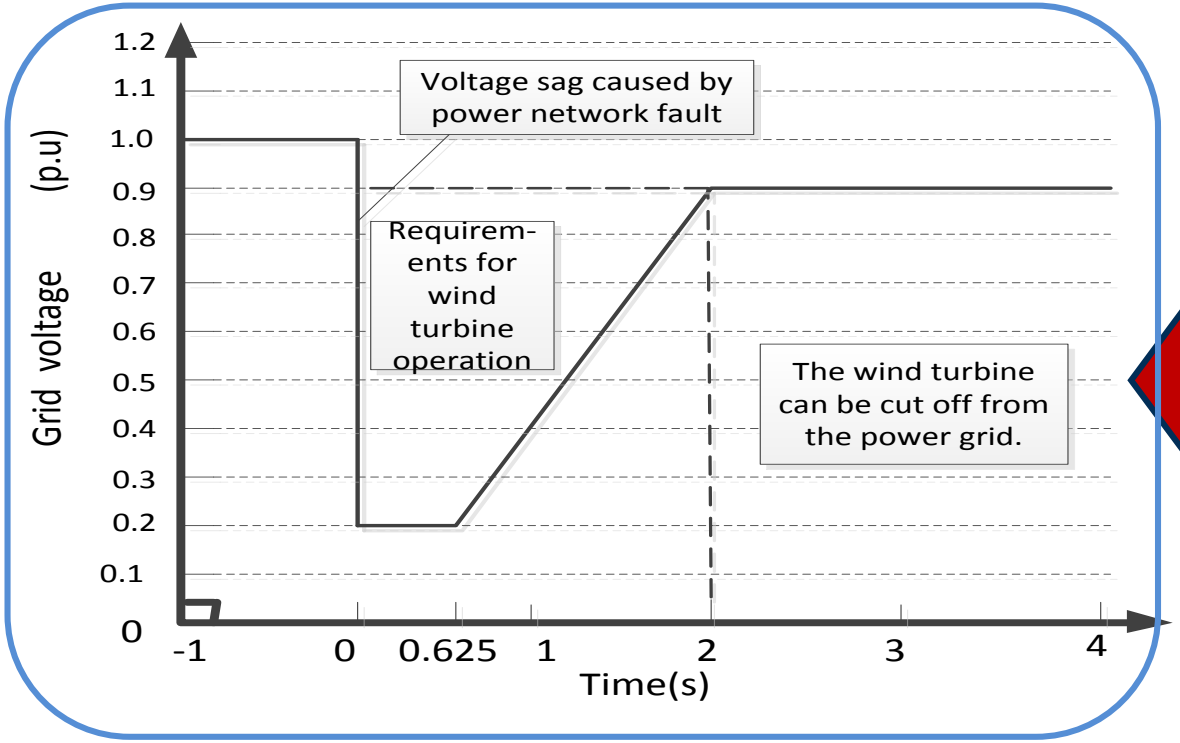


System frequency curve

Key technology: The tracking time is longer, but the output power is relatively stable and it is easy to be accepted by the power grid.

2.6 Low voltage ride through

2.6.1 Research background



LVRT specifications for wind turbines in China

Wind turbines should be able to maintain the low voltage ride through capability of 0.625 seconds when the voltage drop to 20% rated voltage.

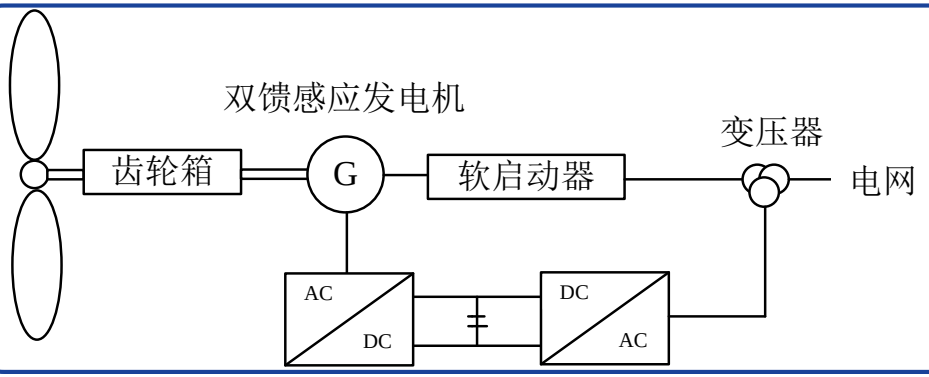
The wind farm and the network voltage can be recovered to 90% of the rated voltage in 2 seconds after the fall, the wind power unit should have the ability to run in uninterrupted power grid.

During the power grid fault period without cutting out of the wind turbine, the active power in the fault should be removed after the power of at least 10% of the rated power / second change to the state before the fault.

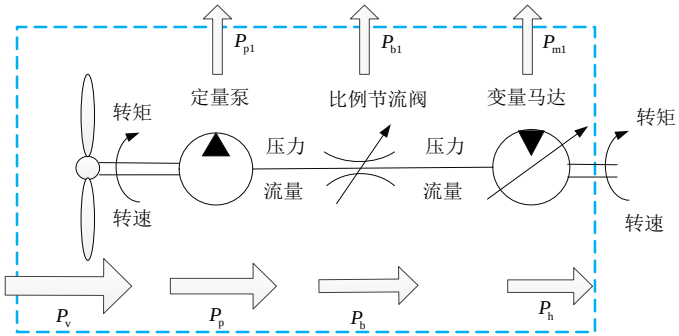
The grid codes is differ from countries to countries, just taking China for a instance.

2.6 Low voltage ride through

2.6.1 Research background



DFIG is mostly used Crowbar protection circuit to decrease the rotor current converter, **which cannot be adopted in HWT.**



Power loss:

(1) Fixed displacement pump: $P_{p1} = p_{h1} D_p \omega_p (1-\eta_{pv})$

(2) Proportional throttle valve: $P_{b1} = Q_b (p_{h1} - p_{h2})$

(3)Various motor: $P_{m1} = p_{h2} K_m \gamma \omega_m (1-\eta_{mv})$

- **Self-preservation**—Adjust hydraulic transmission power quickly.
- **Not to take off power grid**—Ensure steady speed output;
- **Support**—Steadily provide reactive power.

2.6 Low voltage ride through

2.6.2 Coupling analysis of hydraulic system

The hydraulic main driving system mathematical model

(1)Fixed-displacement pump

$$Q_p = D_p \omega_p - C_{tp} p_{h1}$$

$$\dot{\omega}_p = \frac{1}{J_p}\left(T_w - \frac{D_p p_{h1}}{\eta_{mp}} - B_p \omega_p\right)$$

(2)proportional throttle valve

$$X_v = K U_E$$

$$Q_b = C_d W X_v \sqrt{\frac{2}{\rho}(p_{h1} - p_{h2})} = C_d W X_v \sqrt{\frac{2 p_L}{\rho}}$$

(3)Various motor

$$Q_m = K_m \gamma \omega_m + C_{tm} p_{h2}$$

$$\dot{\omega}_m = \frac{1}{J_m}\left(K_m \gamma p_{h2} \eta_{mm} - B_m \omega_m - T_e\right)$$

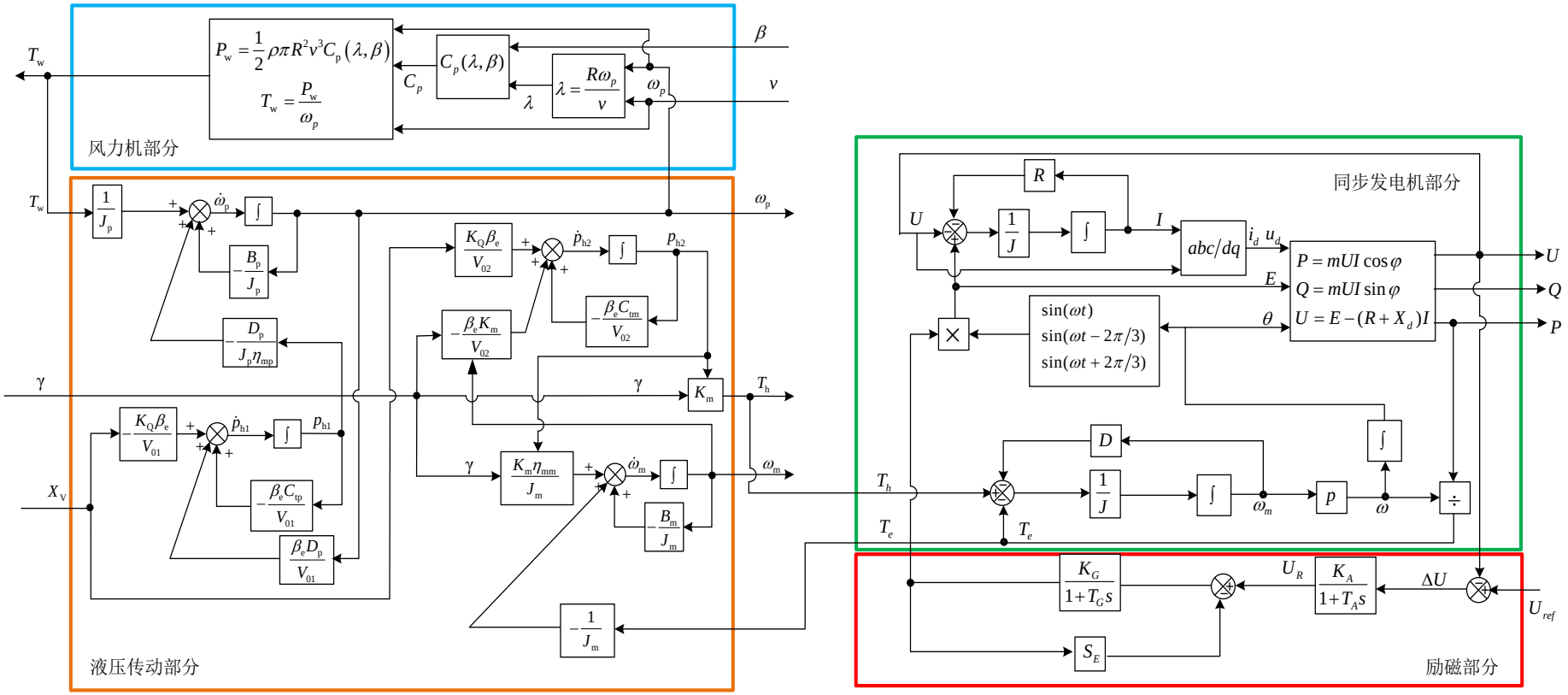
(4) Hydraulic pipeline

$$\dot{p}_{h1} = \frac{\beta_e}{V_{01}}(D_p \omega_p - C_{tp} p_{h1} - K_q X_V)$$

$$\dot{p}_{h2} = \frac{\beta_e}{V_{02}}(K_q X_V - K_m \gamma \omega_m - C_{tm} p_{h2})$$

2.6 Low voltage ride through

2.6.2 Coupling analysis of hydraulic system

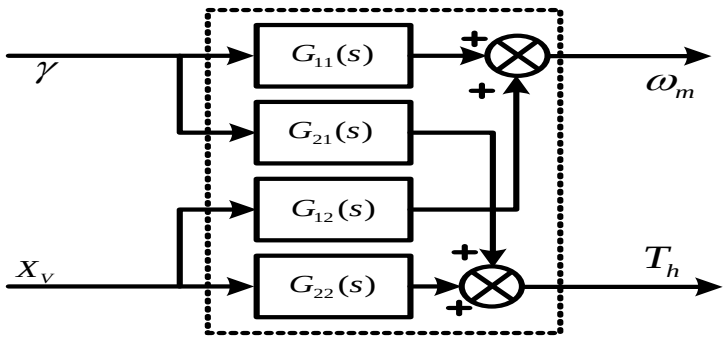


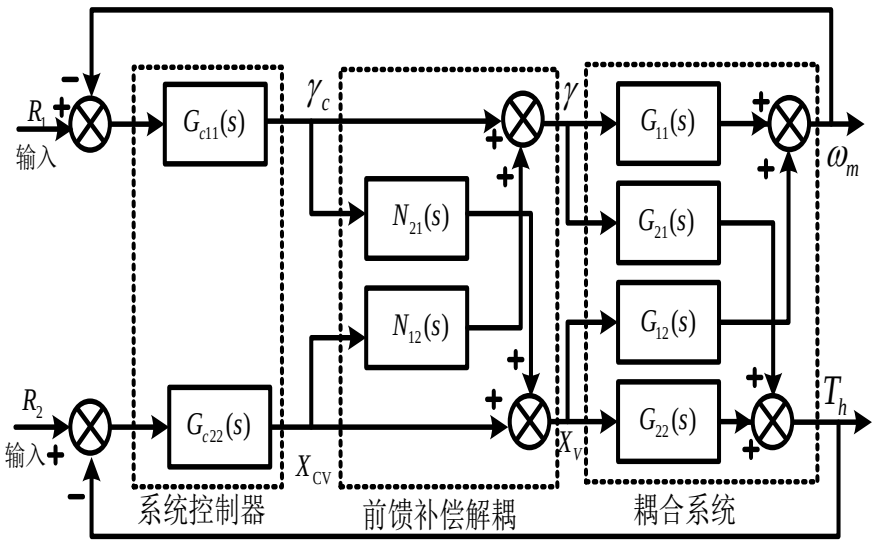
Key technology: Considering generator load characteristic and the energy of the wind turbine capture input, the coupling mathematical model is presented.

2.6 Low voltage ride through

2.6.2 Hydraulic system output decoupling algorithm

The transfer function matrix of the diagonal elements of the said output is affected by other input, so there are certain coupling control system.





$$\begin{bmatrix} \omega_m \\ T_h \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \begin{bmatrix} \gamma \\ X_v \end{bmatrix}$$

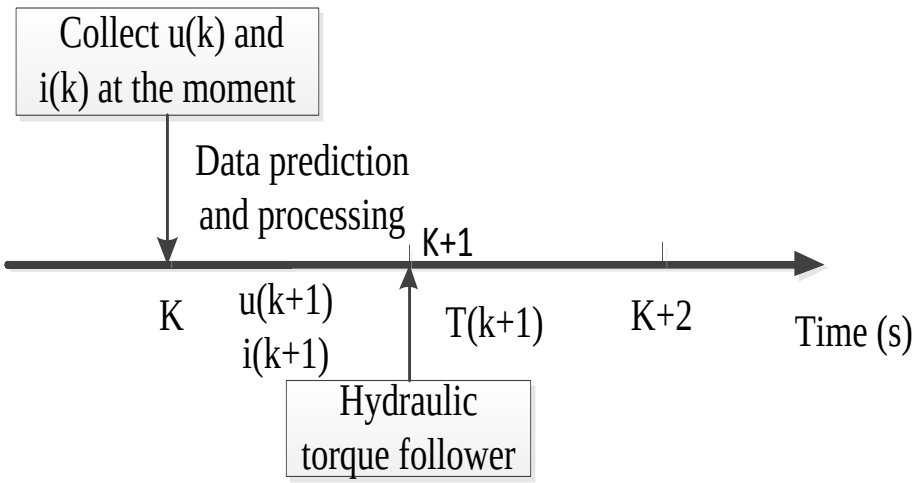
Key technology: The feed-forward compensation decoupling control method is used to remove the coupling between the control circuit.

2.6 Low voltage ride through

2.6.3 LVRT control – Torque control

$$\begin{cases} \begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{pmatrix} = K \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \lambda_1 & \lambda_2 & -\lambda_3 & \lambda_4 \\ -\lambda_4 & \lambda_3 & -\lambda_2 & \lambda_1 \\ -\lambda_3 & -\lambda_4 & \lambda_1 & \lambda_2 \end{pmatrix} \begin{pmatrix} \dot{\beta}_1 \\ \dot{\beta}_2 \\ \dot{\beta}_3 \\ \dot{\beta}_4 \end{pmatrix} \\ \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} \end{cases}$$

The electromagnetic torque state observer



The hydraulic torque following diagram based on time delay compensation in the actual system

Key technology: A prediction state observer based on time-delay and an method relied on adjusting the proportional throttle valve opening to dynamic compensating electromagnetic torque fluctuation are presented.

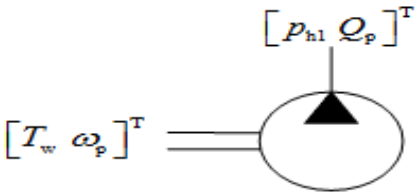
2.6 Low voltage ride through

2.6.4 LVRT control - Energy hierarchical control method

The energy transmission model

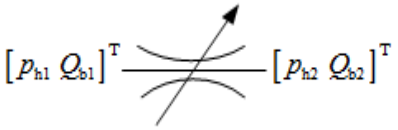
Fixed-displacement pump

$$\begin{bmatrix} p_{h1} \\ Q_p \end{bmatrix} = \begin{bmatrix} \frac{1}{D_p} & -\frac{Js+B_p}{D_p} \\ -\frac{C_{tp}}{D_p} & \frac{D_p^2 + C_{tp}(Js+B_p)}{D_p} \end{bmatrix} \begin{bmatrix} T_w \\ \omega_p \end{bmatrix}$$



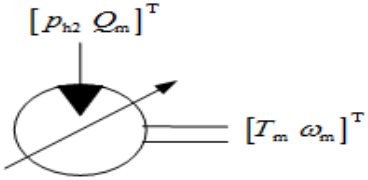
proportional throttle valve

$$\begin{bmatrix} p_{h2} \\ Q_{b2} \end{bmatrix} = \begin{bmatrix} 1 & -\frac{\rho Q_{b1}}{2C_d^2 X_v^2} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} p_{h1} \\ Q_{b1} \end{bmatrix}$$



Various motor

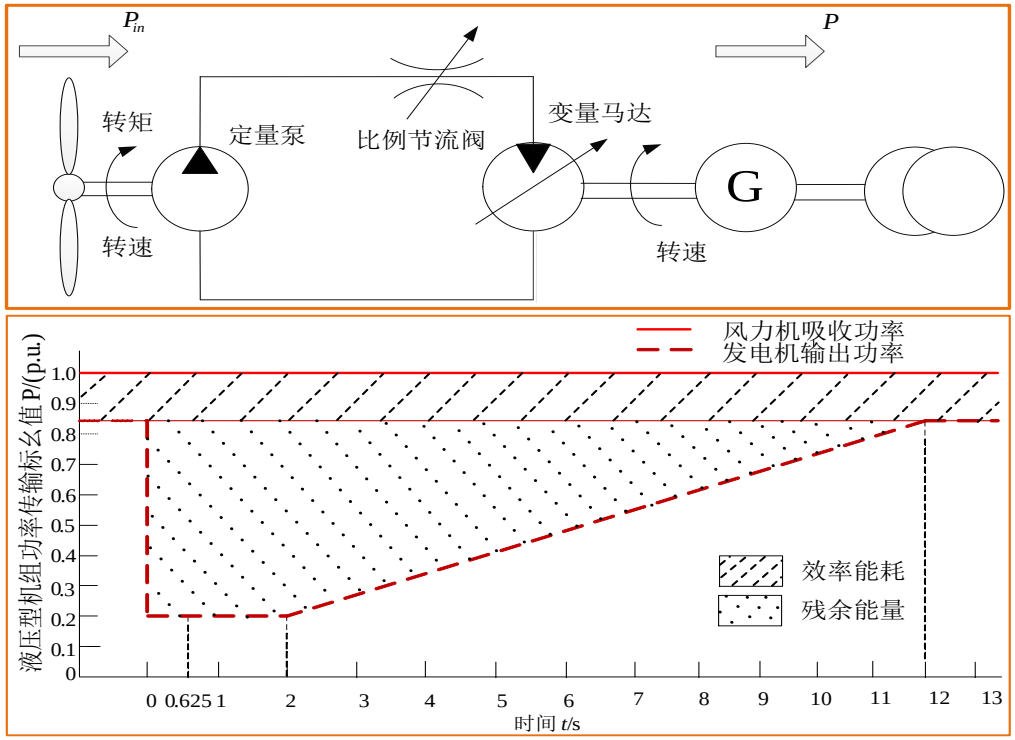
$$\begin{bmatrix} T_h \\ \omega_m \end{bmatrix} = \begin{bmatrix} -\frac{C_{tm}(Js+B_m)}{K_m\gamma} & \frac{(Js+B_m)}{K_m\gamma} \\ -\frac{C_{tm}}{K_m\gamma} & \frac{1}{K_m\gamma} \end{bmatrix} \begin{bmatrix} p_{h2} \\ Q_m \end{bmatrix} + \begin{bmatrix} T_e \\ 0 \end{bmatrix}$$



The input and output side energy eigenstate is analyzed respectively, which can get the energy transfer model of HWT.

2.6 Low voltage ride through

2.6.4 LVRT control - Energy hierarchical control method



Low voltage through the energy flow diagram

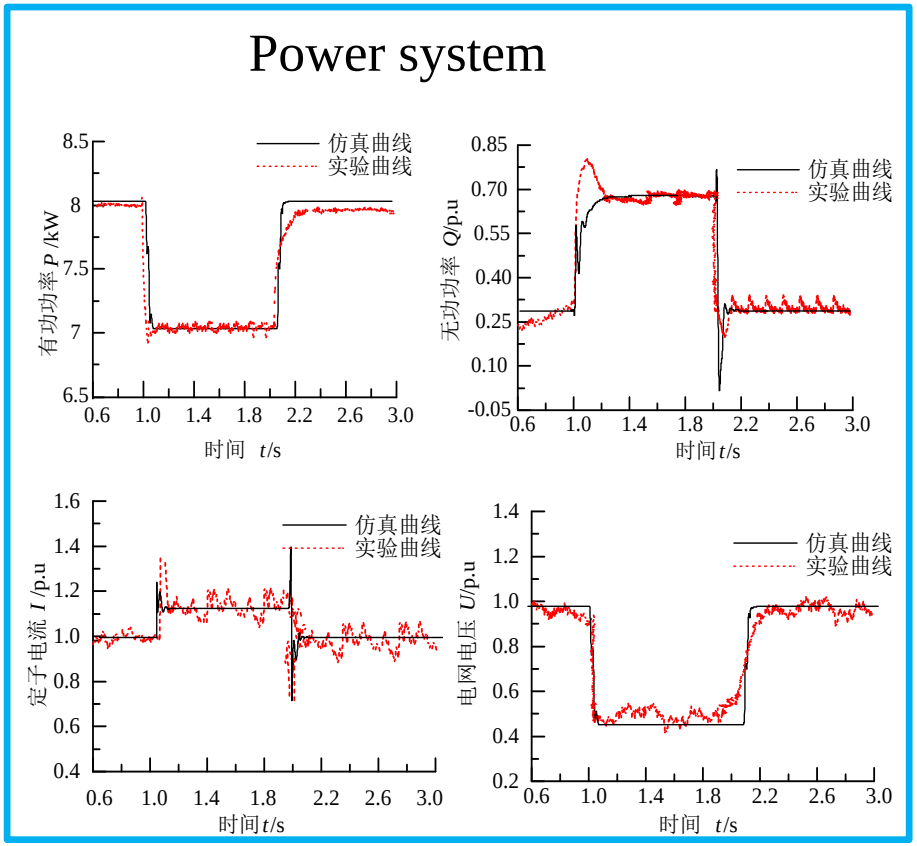
（1）Through the adjustable blade abandon the wind, the wind turbine inertial energy storage, proportional throttle coordination control to control unit to transmit power.

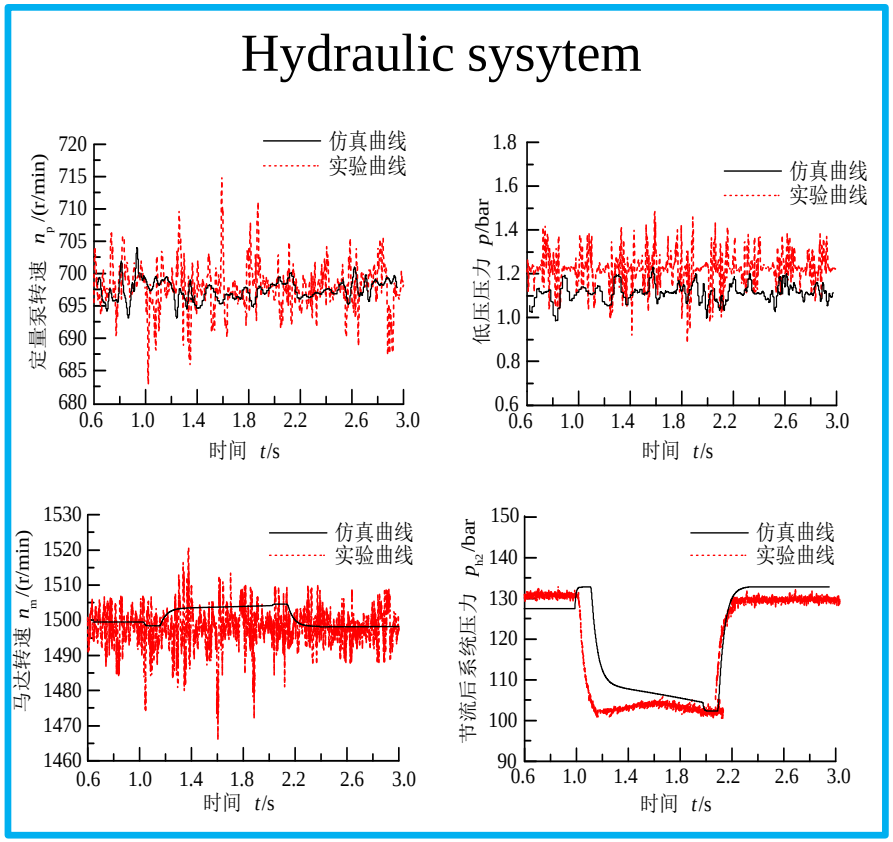
（2）Eventually in the process of the low voltage across, residual energy storage, dissipation and release.

Key technology: Achieved in the process of LVRT, the excess energy dissipation and storage control method.

2.6 Low voltage ride through

2.6.5 Experiment

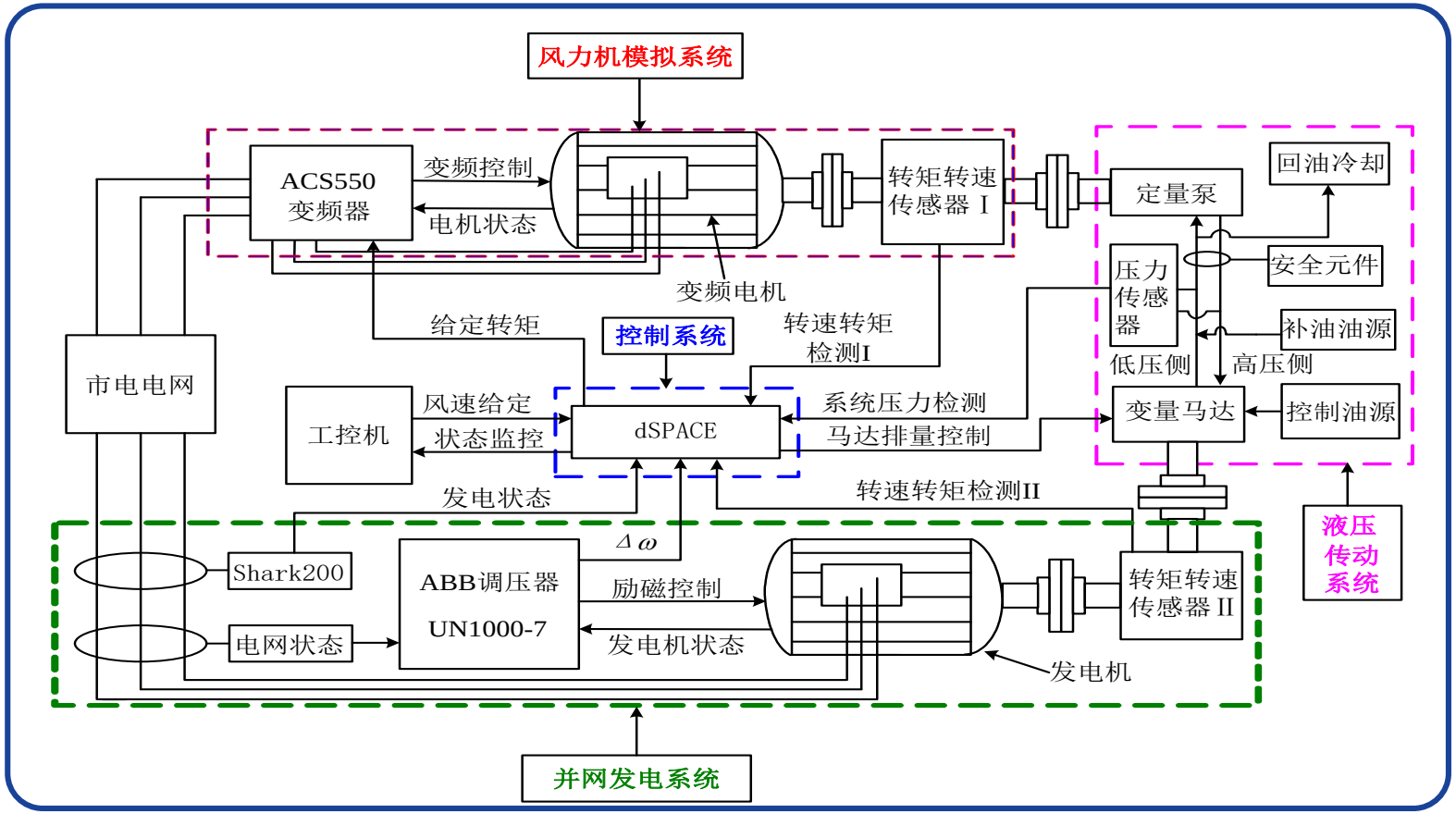




According to the experimental results, it can be seen that the proposed control method has obtained the good effect.

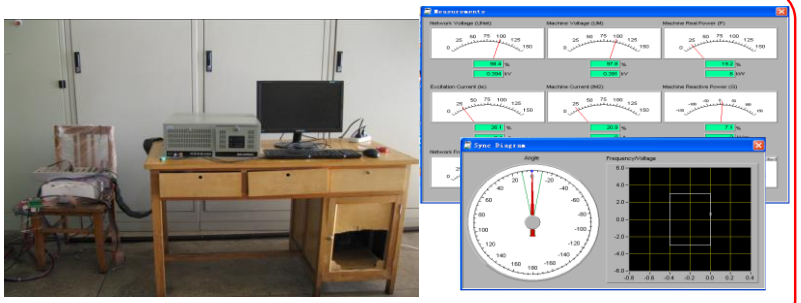
2.7 Test platform

2.7.1 30kVA HWT test platform

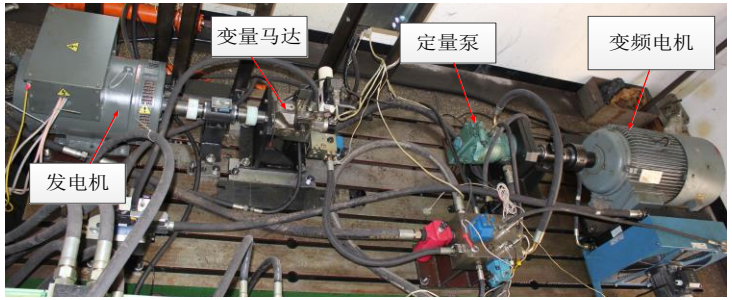


2.7 Test platform

2.7.2 The whole physical picture test platform

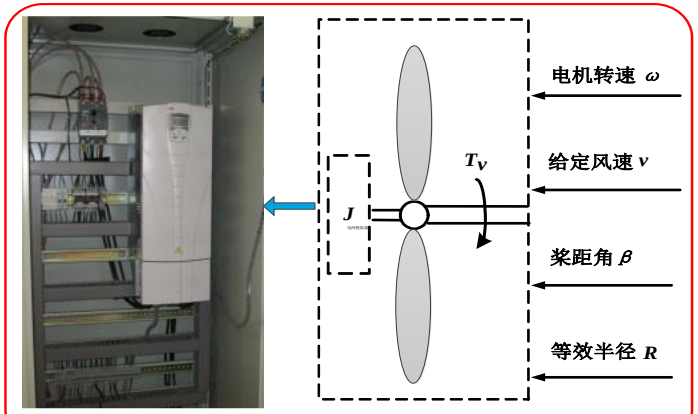


工控机与控制器　　系统采集监控



液压传输系统

电网模拟器　　主控制柜　　并网控制柜　　变频柜

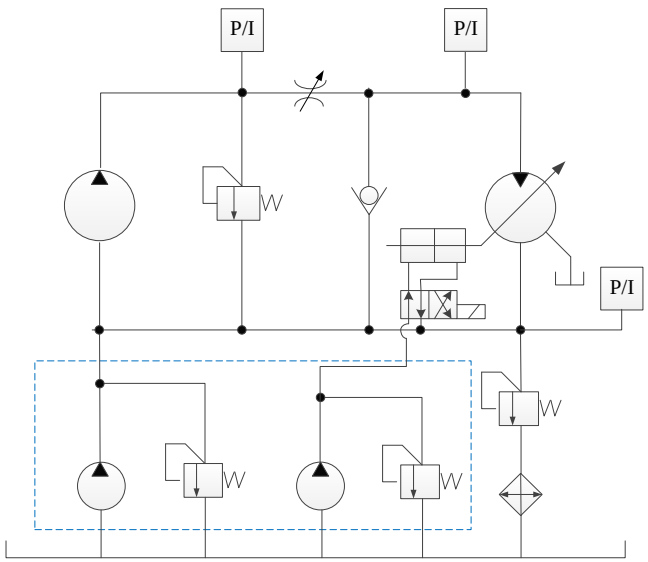


变频器　　风力机模型模拟

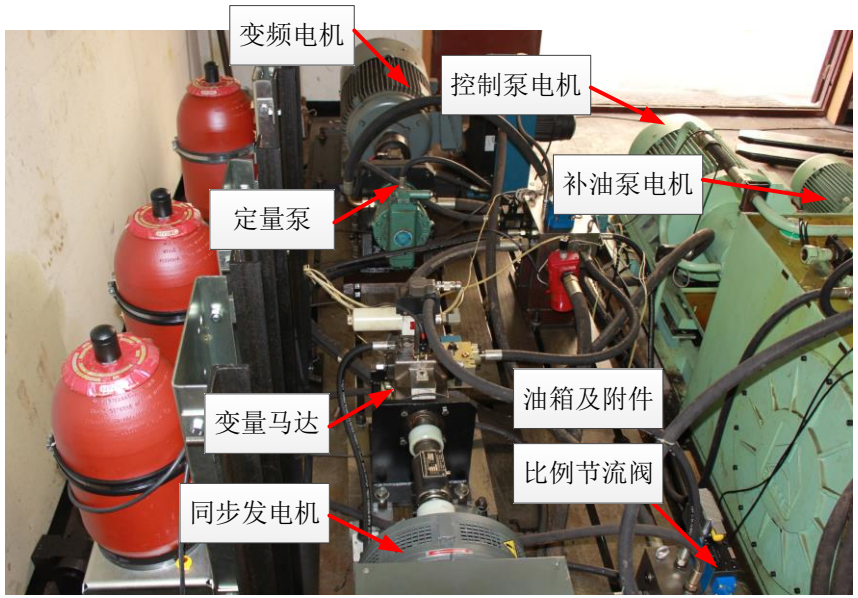
2.7 Test platform

2.7.3 Hydraulic main drive system

A fixed displacement pump - various motor is used in the transmission system. Composition principle and hydraulic transmission system is shown below.



a) The principle of the hydraulic drive system

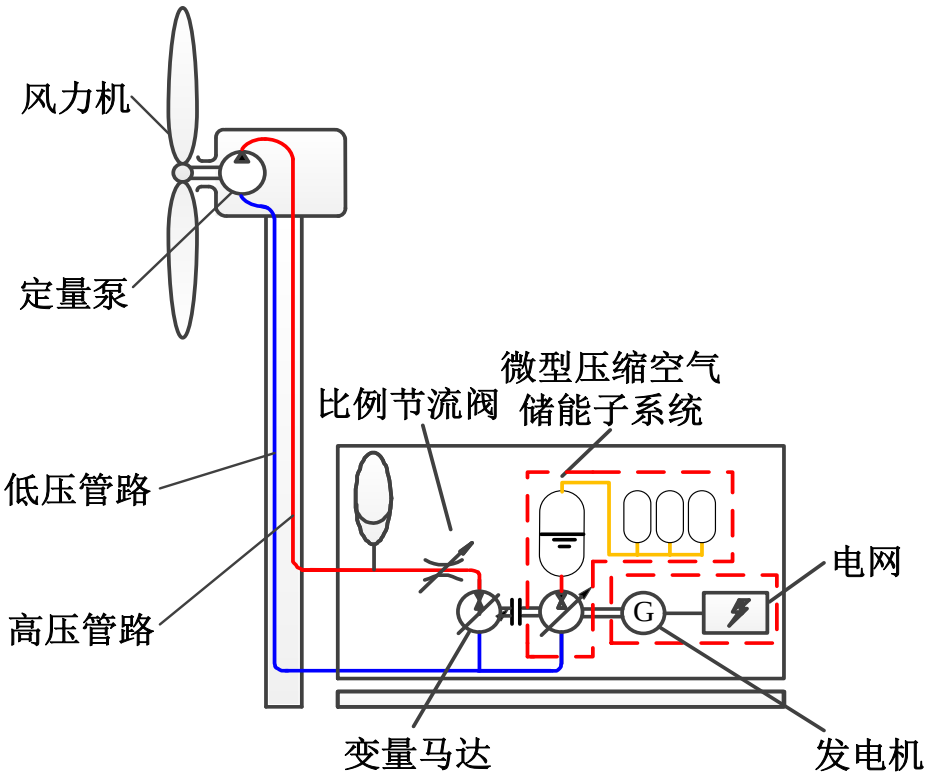


b)) Hydraulic drive system physical figure

Hydraulic system diagram

2.8 Development Prospect

2.8.1 HWT with storage system



Schematic diagram of hydraulic wind turbine with energy storage system

（1） Due to the intermittency and stochastic fluctuation of wind, the existing system have no ability to "cut the valley and fill peak" .

（2） The energy storage system can store or release power according to the electric load. So that the hydraulic wind turbine can adjust the peak power of consumption and grid frequency.

Therefore, the development of energy storage type hydraulic wind turbine will be a trend.

2.8 Development Prospect

2.8.2 Application in non-grid connected wind power system

（1） HWT, connected power grid, supports high-energy-consuming factories such as electrolytic aluminum factory, seawater desalination factory.

(2) In this way, large-scale wind power can be fully utilized without conventional power grid being efficient and low-cost.

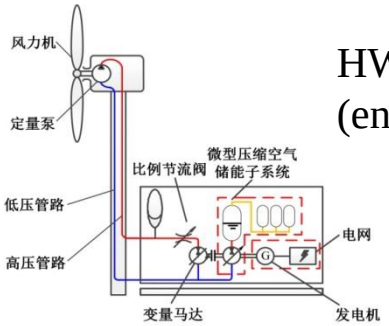
aluminum electrolysis industry

Seawater desalination

2.8 Development Prospect

2.8.3 Application in smart Grid

Hydraulic wind turbine, combined with photovoltaic power generation, wave power generation and other clean energy sources, can compose smart grid to supply power to the islands far away from the mainland.



HWT with ESS
(energy storage systems)

photovoltaic power generation

Residential electricity

THANK YOU !