風力發電系統之驅動與控制
Drive and Control of Wind Turbine Systems

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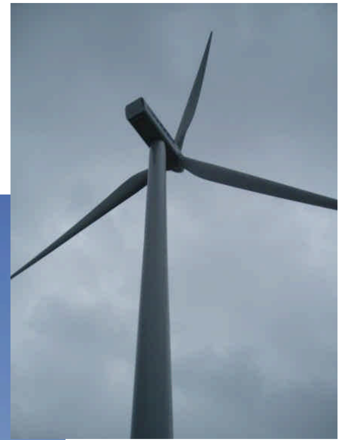
Outline

- An Overview of Wind Turbines
- Technologies of Large Wind Turbines
- Technologies of Small Wind Turbines
- Small VAWTs Made in Taiwan
- MPPT Design for VAWTs
- Design Case 1- Grid-Connected 10kW PMSG System
- Design Case 2 - Field-Oriented Controlled PMSG System with DC Load
- Design Case 3 - Intelligent Control for Induction Generator System



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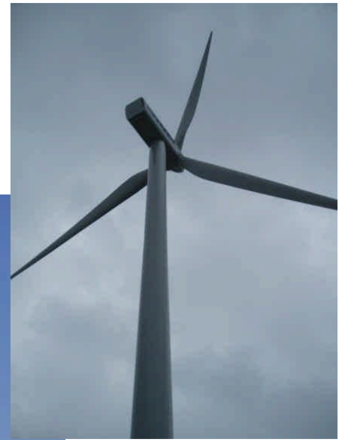
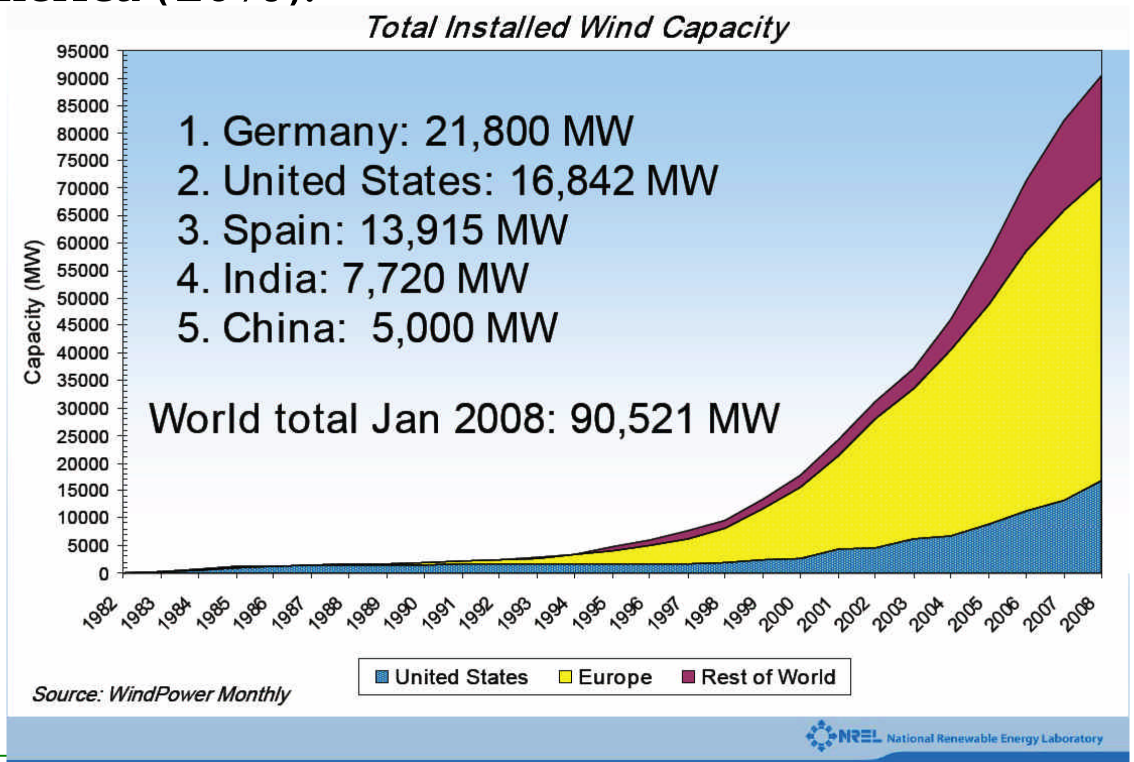


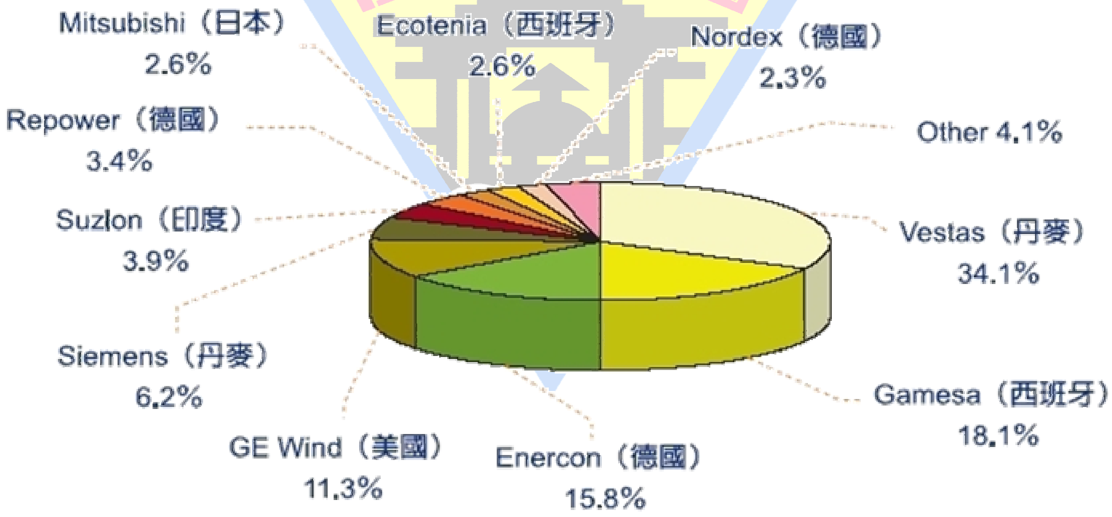
Install Capacity of Wind Power

- More than 60 countries have installed wind power with total capacity 90512MW by Jan. 2008. Most of them are installed in Europe (65%) and North America (20%).



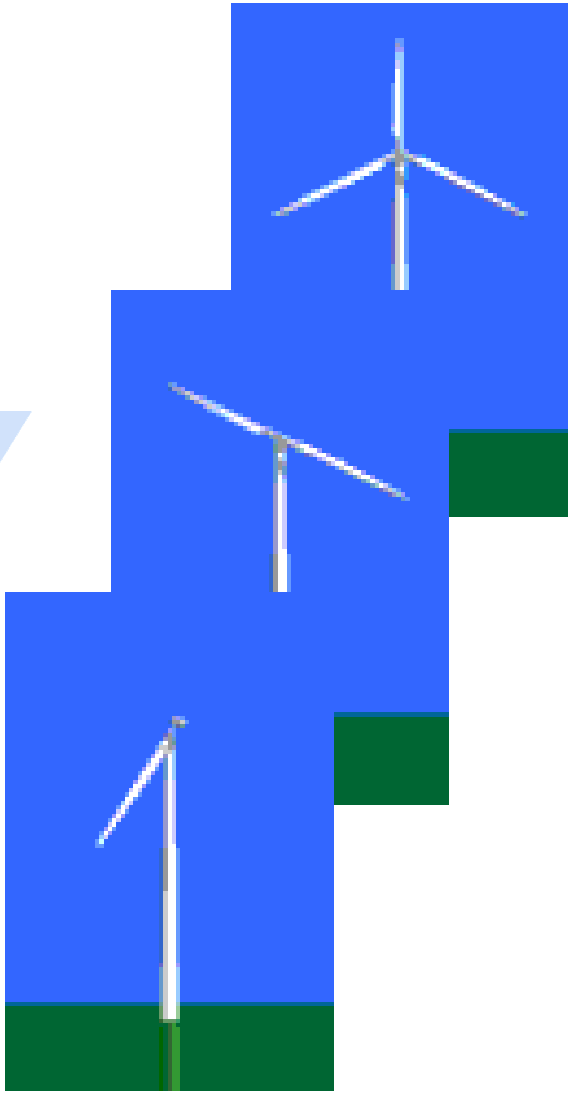
Top-10 Suppliers of Wind Power

Suppliers	Vestas	Gamesa	Enercon	GE Wind	Siemens	Suzlon	Repower	Mitsubishi	Ecotenia	Nordex
Type of Generator	IG	DFIG	SG	DFIG SG	SG	SG	DFIG	IG	DFIG IG	DFIG
Power	850kW ~ 3,000kW	850kW ~ 2,000kW	330kW ~ 2,300kW	1,500kW ~ 3,600kW	250kW ~ 3,600kW	950kW ~ 2,000kW	2,000kW ~ 5,000kW	600kW ~ 1,000kW	375kW ~ 3,000kW	1,500kW ~ 2,500kW



Types of Turbines

- Blade numbers: one, two, three
- Power-regulation: stall, active-stall, pitch
- Fixed-speed, variable speed
- With gearbox (difference types of gearboxes possible), without gearbox
- Asynchronous generator, synchronous generator (with permanent excitation or electrical excitation), double-fed induction generator, different voltage levels
- With inverter system, without inverter system
- Upwind, Downwind
- Onshore, Offshore



Construction Sites of Wind Turbines

- Wind speed increases with height and over open areas with no windbreaks. The best sites are on hilltops, the open plains, through mountain passes, and near the coasts of oceans or large lakes. Turbines are usually built in rows facing into the prevailing wind. It is important that the turbine be mounted at least 30 feet higher than existing structures, such as trees and buildings, within 300 feet to ensure consistent wind flow without turbulence. For the wind speed, 2 to 3 days in a week, at least 4.5~5.5 *m/s* for 2 to 3 hours or average wind speed for a year higher than 3.5 *m/s.*

Orientation - Horizontal Axis Wind Turbine (HAWT)

- These are the most common form of turbines and can be used for all sizes of turbines for both onshore and offshore. They normally have 2 or 3 blades that rotate a horizontal shaft connected to a generator. They are designed to move to face the wind (upwind) and can rotate round when operating. Small turbines rotate using a tail fixed to the rear of the blades while larger turbines use devices to detect wind speeds and direction and a motor to move the turbine towards the wind. They can generate electricity at low wind speeds. Other designs operate in a downwind mode.

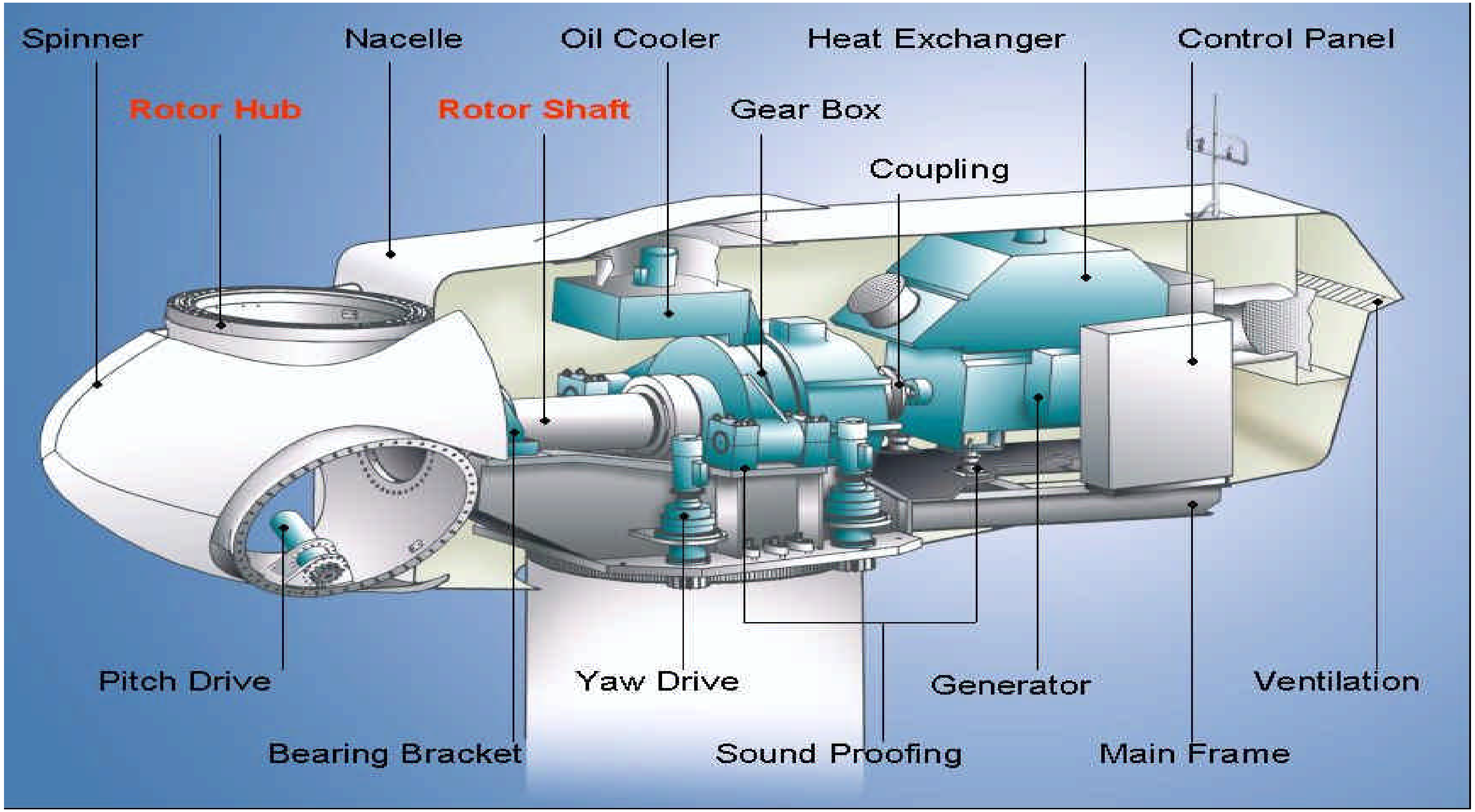
HAWT

Orientation - Vertical Axis Wind Turbine (VAWT)

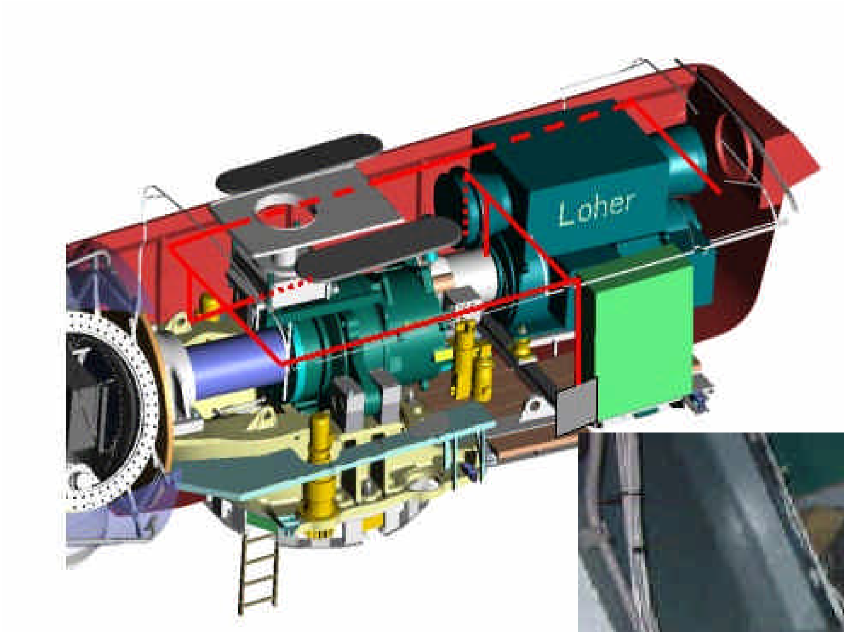
- These are less efficient at using wind power because they do not orientate themselves to wind direction and need a higher wind speed to operate. However, they are less susceptible to wind speed fluctuations, are virtually silent and have minimal vibration. The smaller versions can be visually less obtrusive than their HAWT counter part. Most modern turbines have been horizontal axis systems but VAWTs are being developed for small scale and domestic use.

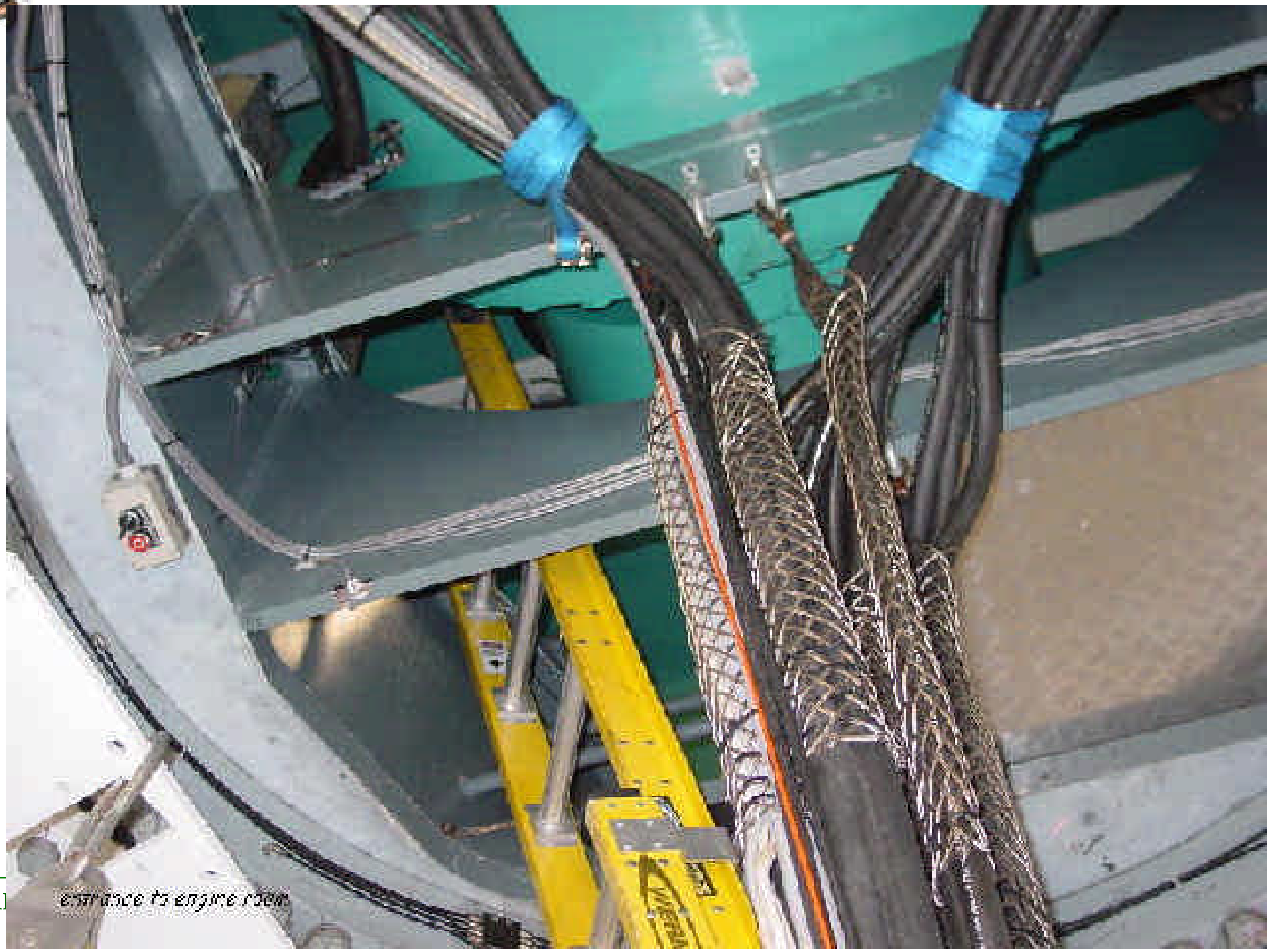
VAWT

Viewing of Nacelle



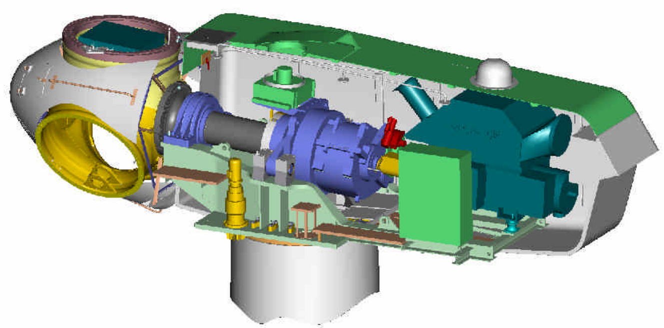
Entering Nacelle



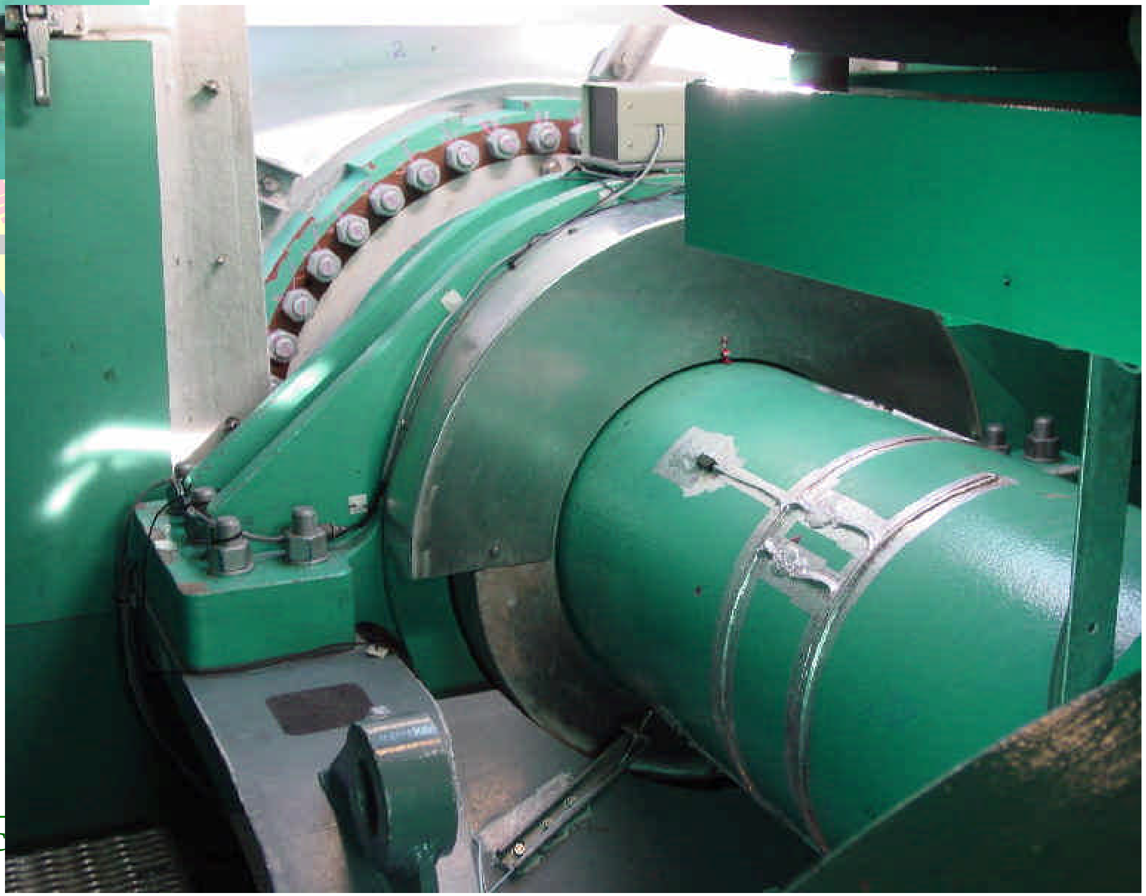


Inside The Nacelle

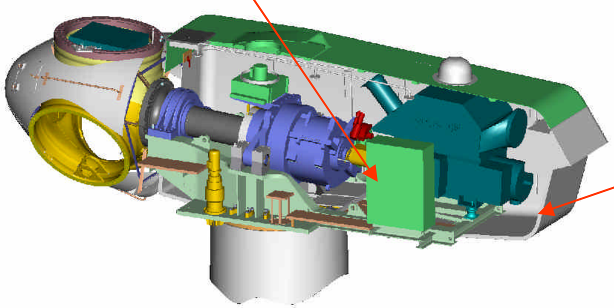
Back End



Front End

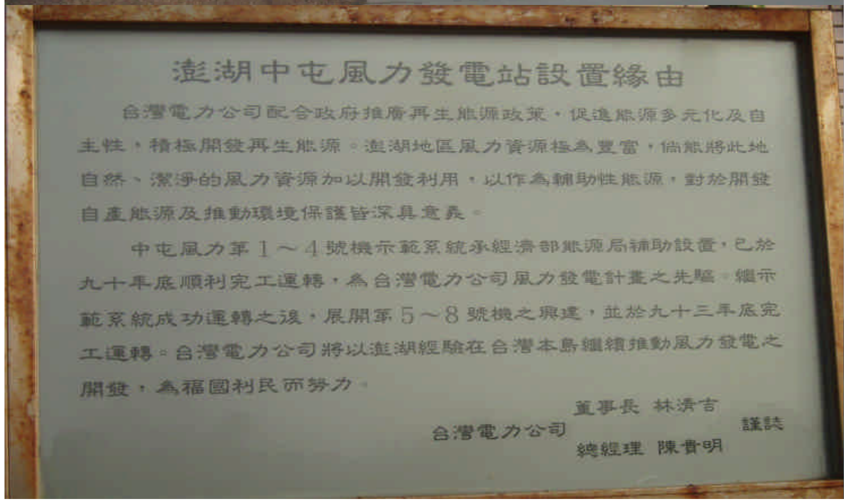


Feel The Movement



On Top of Roof
(Front Side)

澎湖中屯風力發電站
瞬間總發電量 4961 瓩
機組型式:ENERCON E-40
額定輸出:600 kW
機組總高:67.85 M
葉片直徑:43.7 M
額定風速:13 M/S
商轉日期:93年12月22日
機組供應商:ENERCON
承攬商:中興電工機械股份有限公司
建造單位:台灣電力公司
風速(公尺/秒) 發電量(瓩)
一號機 18.0 632
二號機 18.8 616
三號機 22.1 629
四號機 21.4 612
五號機 14.2 604
六號機 16.3 619
七號機 16.6 611
八號機 15.4 637



澎湖中屯風力發電站設置緣由
台灣電力公司配合政府推廣再生能源政策，促進能源多元化及自主性，積極開發再生能源。澎湖地區風力資源極為豐富，倘能將此地自然、潔淨的風力資源加以開發利用，以作為輔助性能源，對於開發自產能源及推動環境保護皆深具意義。
中屯風力第1～4號機示範系統承經濟部能源局補助設置，已於九十年底順利完工運轉，為台灣電力公司風力發電計畫之先驅。繼示範系統成功運轉之後，展開第5～8號機之興建，並於九十三年底完工運轉。台灣電力公司將以澎湖經驗在台灣本島繼續推動風力發電之開發，為福國利民而努力。
台灣電力公司 董事長 林清吉 總經理 陳貴明 謹誌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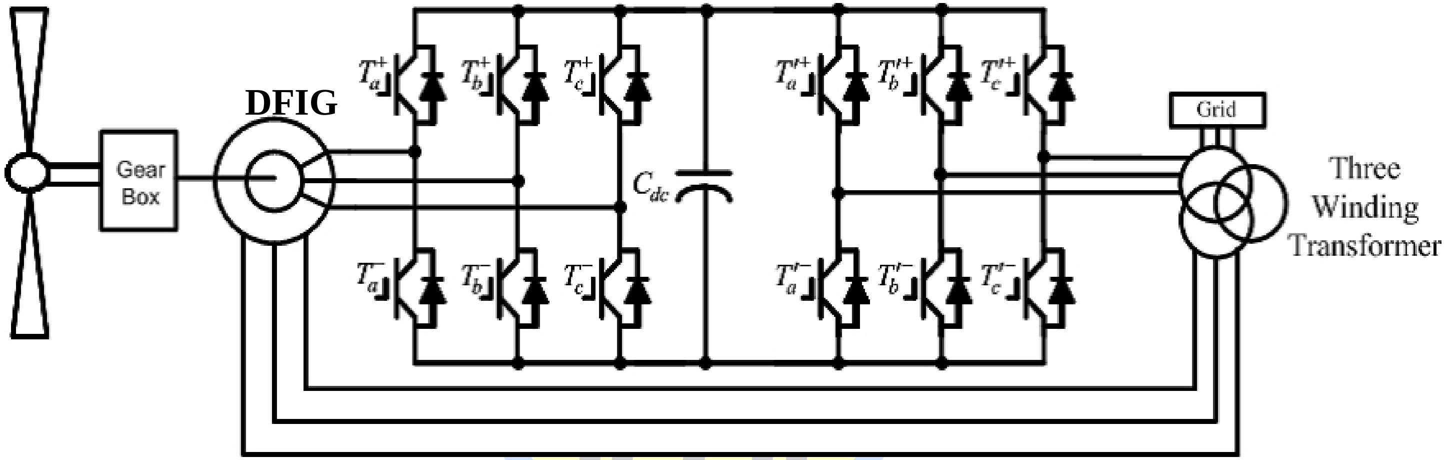
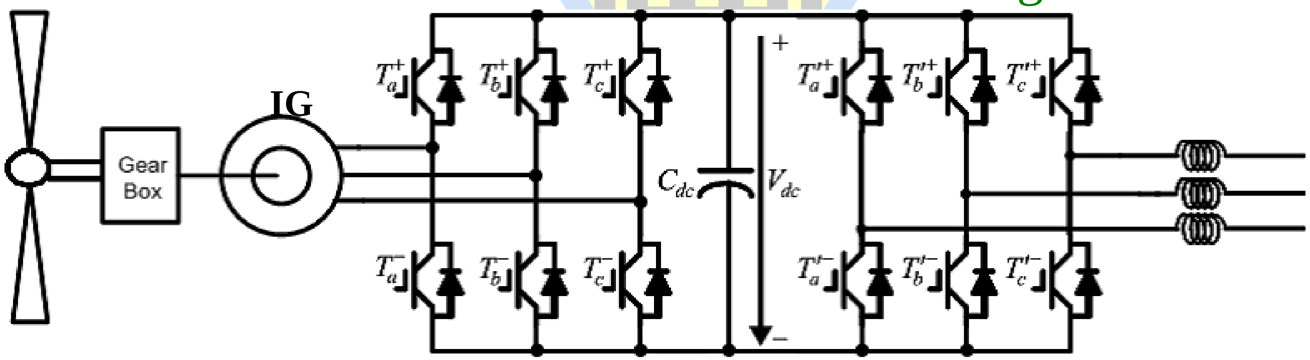
Wind Turbine Configurations

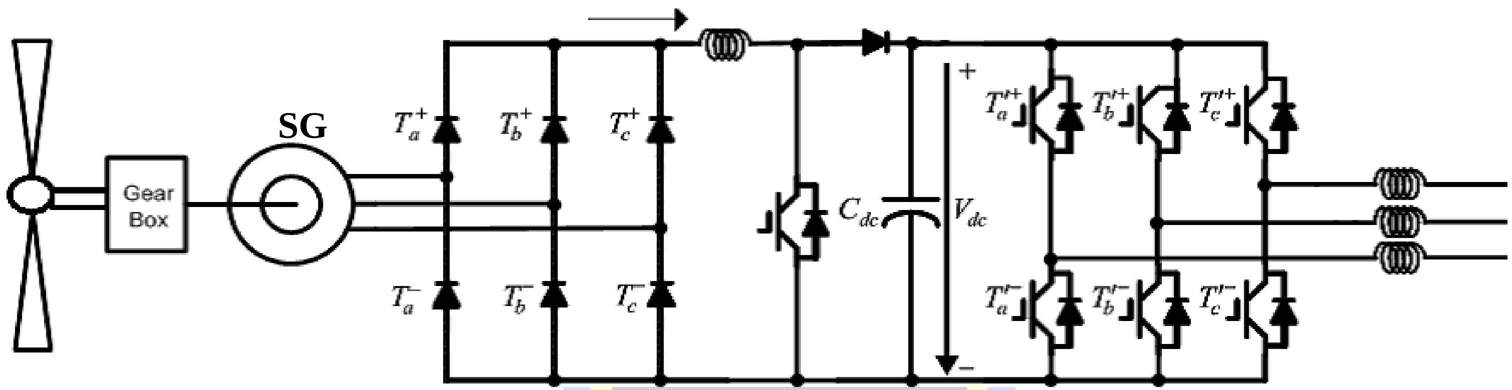


Double-fed Induction Generator using Converters

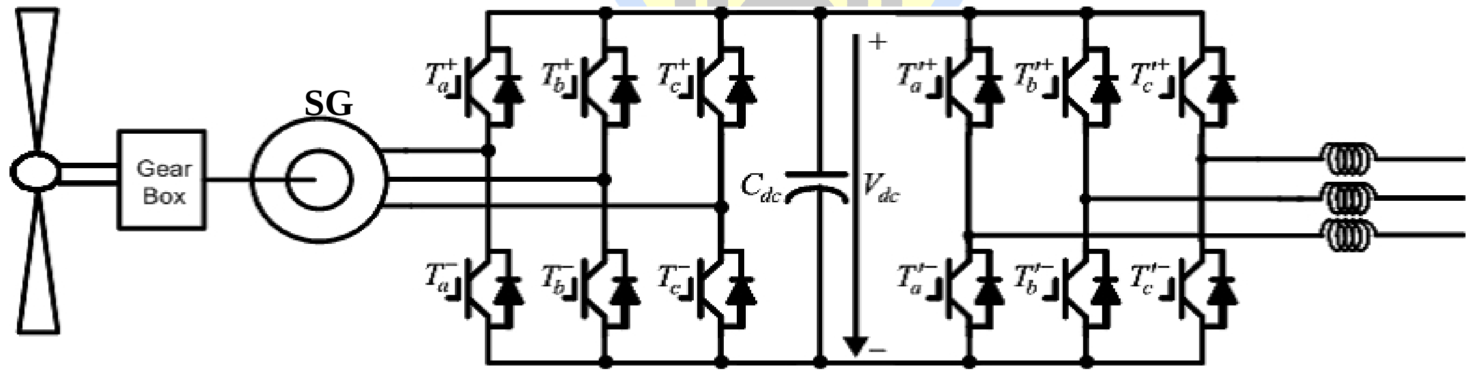


Induction Generator Using Converters

Wind Turbine Configurations



Synchronous Generator Using Rectifier and Converters



Synchronous Generator Using Converters

Large HAWTs (250kW~5MW)

- Advantages
  - Able to deliver electricity at lower cost than smaller turbines, because foundation costs, planning costs, etc. are independent of size.
  - Well-suited for offshore wind plants.
  - The manufacturing technology is mature.
  - The high voltage of the generator is suitable for grid-connection.
  - The cost is relatively low for around US$1000/kW.
  - Produce one kWh and reduce CO2 emission for about 0.64 kilograms.
  - Variable blade pitch, which gives the turbine blades the optimum angle of attack.

Large HAWTs (250kW~5MW)

- Disadvantages
  - Unable to turn at low wind speeds. Only fit the seashore and spacious area.
  - Installation Sites must fulfill the environment evaluation requirements.
  - An area of 200 meters radius can't live in people for the installation place .
  - Produce low frequency noise.
  - The earthquake and typhoon such natural calamities may cause the harm.
  - Influence the safety of aviation (2MW wind turbine is about the height of the Statue of Liberty).
  - The tall towers and blades up to 90 meters long are difficult to transport. Transportation can now cost 20% of equipment costs.
  - Tall WTs are difficult to install, needing very tall and expensive cranes and skilled operators.
  - Massive tower construction is required to support the heavy blades, gearbox, and generator.
  - Reflection on tall WTs may affect side lobs of radar installations creating signal clutter, although filtering can suppress it.
  - Downwind variants suffer from fatigue and structural failure caused by turbulence.
  - HAWTs require an additional yaw control mechanism to turn the blades toward the wind.

Wind Technologies of the Future

- Advanced Rotors

  (1) High strength-to-weight ratio carbon fibers are incorporated into high-stress areas.

  (2) Make a thick and structurally efficient blade airfoil shape to improve aerodynamic performance.

  (3) Control the blade's aerodynamic response using pitch control to reduce the fatigue load.

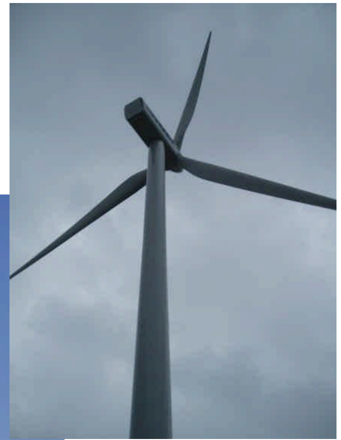
- Advanced Drive Trains

  To build direct-drive generator that eliminates the gearbox. PMSG designs tend to be quite compact and lightweight and reducing losses.

- Innovative Towers

  Self –erecting tower to eliminate the need for cranes

Outline

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Typical Applications of Small Wind Turbines *Farms, Homes, Businesses*

Off-Grid Water Pumping

- Supplies water for 120 head of cattle
- 1 kW, 9-ft rotor, 30-ft tower
- Produces ~ 2,000 kWh/yr
- Offsets ~ 1.5 tons CO_2/yr
- Costs ~ $4,000 installed

Supplementing Grid Power

- Connected to utility grid through house/farm wiring
- 3 kW, 15-ft rotor, 23-ft tower*
- Produces ~ 5,000 kWh/yr
- Offsets ~ 3.8 tons CO_2/yr
- Costs ~ $10,000

Options: On or Off the Grid?

Stand-Alone System

- Batteries to store excess power
- Charge controller
- Inverter (DC to AC)
- Back-up power source for complete energy independence

Grid-Connected System

- Inverter (DC to AC)
- Annual wind speed $\geq$10 mph (4.5 m/s)
- Customer motivated by high utility prices, self sufficiency, or environmental concerns

Modern Small Wind Turbines *High Tech, High Reliability, Low Maintenance*

- Small turbines range from 400 W to 100 kW
- Only 3-4 moving parts means very low maintenance
- 20- to 40-year design life
- Proven technology – 150,000 installed; over a billion operational hours
- Substantial cost-reduction potential
- Generators- PMSG due to its compact size, high power density and easy to control

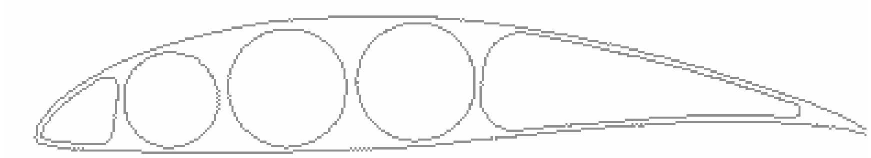
(Not to scale)

Historic Barriers to Small Wind Energy Systems

- Economics: Low production volume & historical lack of public funding = high costs
- Small wind upstaged by large-scale projects and other technologies
- Zoning / Permits: 35-ft height restriction in residential zones, noise, nimby attitudes
- Onerous interconnection requirements
- Low public awareness

New Technology is Lowering Costs

- Advanced airfoils
- "Super-magnet" generators
- Low cost manufacturing
- Smart power electronics
- Very tall towers
- "Stealth" low noise & visual impact



Wind Turbines below 2kW

SUPERWIND 350	350W
AIR X	400W
INCLIN 250	250W
RUTLAND 913	250W
RUTLAND FM1803	750W
ML 300 BUTTERFLY	300W
INCLIN 600	600W
WHISPER 100	900W
WHISPER 200	1000W
INCLIN 1500	1500W
ML 1500 SHARK	1500W
SG 280S	1500W
SG 280SK	1800W
GRT 2000	2000W
SKYSTREAM 3.7	1800W

Wind Turbines - 3kW TO 5kW

WHISPER 500	3200W
INCLIN 3000	3000W
WESTWIND 3KW	3000W
ML 3000 AIR	3000W
SG 400	3000W
WESTWIND 5KW	5000W
WT 8P	8000W
WT 10P	10000W
WT 50	50000W
FORTIS ALIZE	10000W
SG 500	5/6000W
GRT 8000	8000W
INCLIN 6000 NEO	6000W
INVENTUS 6	6000W
WEST WIND 10KW	10000W
WEST WIND 20KW	20000W
TURBEX-P	20000W

Superwind 350

- Rated Power：350W
- Cut-in Wind Speed：3.5m/s
- Rotor Diameter：1.2m
- Blades：3-Polypro/carbon glass reinforced
- Weight：11.5Kg
- Rated Wind Speed：12.5m/s
- Voltage：12/24VDC
- Tower：Pipe
- Generator: PMSG

Rutland 913

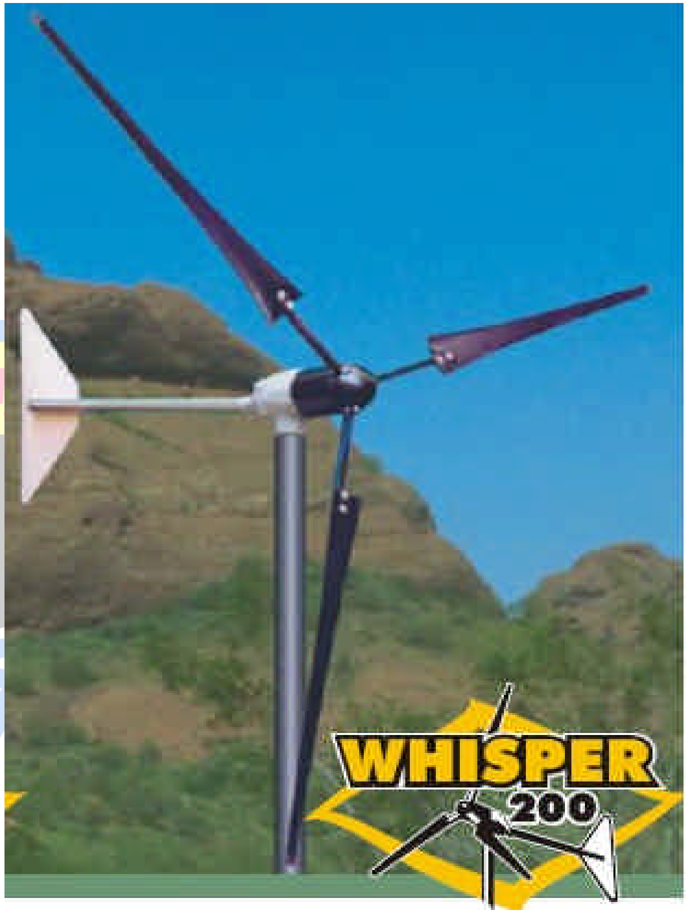
- Rated Power：250W
- Cut-in Wind Speed：3.5m/s
- Rotor Diameter：0.9m
- Blades：6-Polypro/carbon glass reinforced
- Weight：10.5Kg
- Rated Wind Speed：13m/s
- Voltage：12/24VDC
- Tower：Pipe

ML 300 Butterfly

- Rated Power：300W
- Cut-in Wind Speed：3.7m/s
- Rotor Diameter：1.3m
- Blades：3-Polypro/carbon glass reinforced
- Weight：7Kg
- Rated Wind Speed：15.0m/s
- Voltage：12/24VDC
- Tower：Pipe

Whisper 200

- Rated Power：1000W
- Cut-in Wind Speed：3.1m/s
- Rotor Diameter：2.7m
- Blades：3-Polypro/carbon glass reinforced
- Weight：30Kg
- Rated Wind Speed：11.6m/s
- Voltage：12/24/48VDC
- Tower：Pipe



Skystream 3.7

- Rated Power：1800W
- Cut-in Wind Speed：3.5m/s
- Rotor Diameter：3.72m
- Blades：3-Polypro/carbon glass reinforced
- Weight：70Kg
- Rated Wind Speed：9.0m/s
- Voltage：120/240VAC
- Tower：Pipe

ML 1500 Shark

- Rated Power：1500W
- Cut-in Wind Speed：3.7m/s
- Rotor Diameter：3.2m
- Blades：3-Polypro/carbon glass reinforced
- Weight：40Kg
- Rated Wind Speed：15.0m/s
- Voltage：24/48VDC
- Tower：Pipe

WT 8P

- Rated Power：8000W
- Cut-in Wind Speed：3.5m/s
- Rotor Diameter：5.4m
- Blades：3-Polypro/carbon glass reinforced
- Weight：400Kg
- Rated Wind Speed：12.0m/s
- Voltage：24/400V
- Tower：Pipe
- Low Noise(38dB at the PMSG side

Small HAWTs (400W~100kW)

- **HAWT advantages**
  - The tall tower base allows access to stronger wind in sites with wind shear.
  - Easy to install compared to large one.
- **HAWT disadvantages**
  - HAWTs have difficulty operating in near ground, turbulent winds.
  - HAWTs are difficult to install compared with VAWTs.
  - Their height makes them obtrusively visible across large areas.
  - Downwind variants suffer from fatigue.
  - HAWTs require an additional yaw control mechanism to turn the blades toward the wind.
  - Noise problem at high rotating speed.
  - High cost, US$~3000/kW

Small VAWTs (400W~100kW)

- **VAWT advantages**
  - No massive tower structure is needed.
  - As the rotor blades are vertical, no yaw mechanism is needed.
  - A VAWT can be located nearer the ground, making it easier to maintain the moving parts.
  - VAWTs have a higher airfoil pitch angle, giving improved aerodynamics while decreasing drag at low and high pressures.
  - Straight bladed VAWT designs with a square or rectangular crossection have a larger swept area for a given diameter.
  - VAWTs have lower wind startup speeds than HAWTs.
  - VAWTs may be built at locations where taller structures are prohibited.
  - VAWTs situated close to the ground can take advantage of locations where passes funnel the wind and increase wind speed.
  - VAWTs do not need to turn to face the wind if the wind direction changes.
  - VAWT blades are easily seen and avoided by birds.
- **VAWT disadvantages**
  - VAWTs do not take advantage of the stronger wind at higher elevation.
  - Most VAWTs have low starting torque.
  - While VAWTs' parts are located on the ground, they are also located under the weight of the structure above it, which can make changing out parts near impossible without dismantling the structure.
  - High cost, US$~3000/kW

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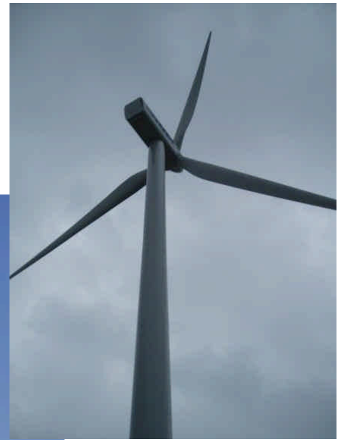

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Small VAWTs Made in Taiwan

HiEnergy (300W-3kW)

iWIND (300W-10kW)

- Rated Power：3kW
- Rated Speed：12m/s
- Stop Speed ：13.5m/s
- PMSG
- Taiwan

- Rated Power：300W
- Rated Speed：12m/s
- Stop Speed ：16m/s
- PMSG
- Taiwan

Wind Turbines

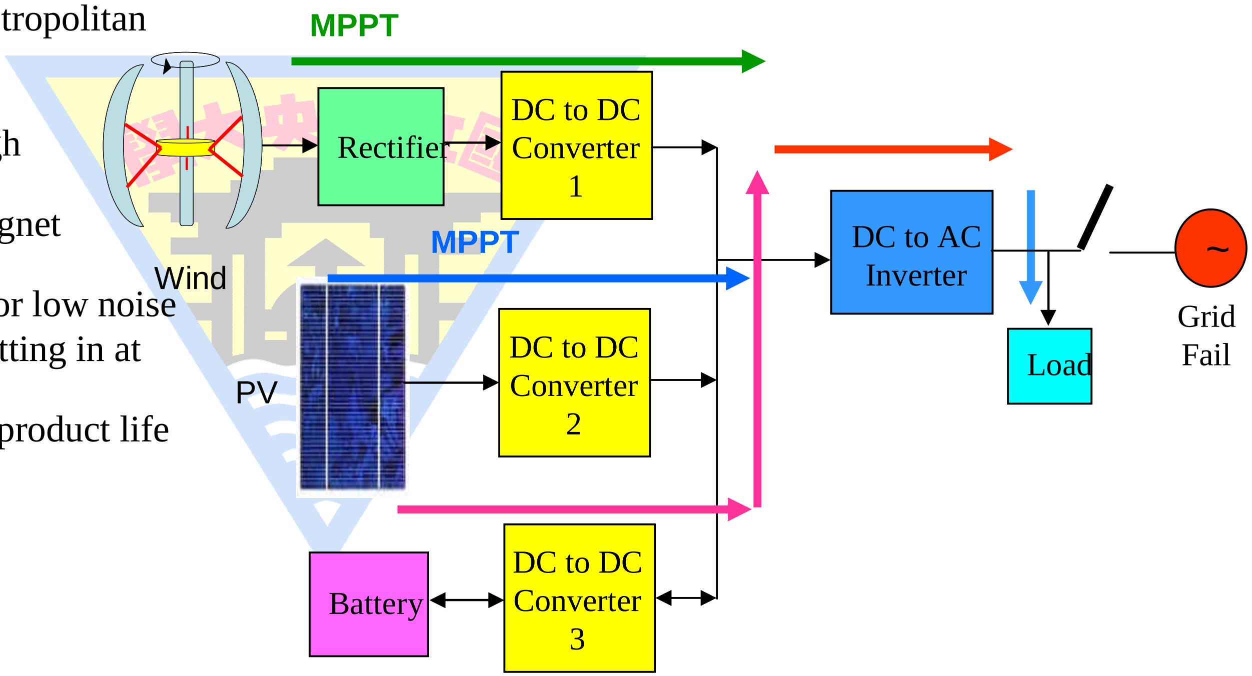
- Type: Small (under 100kW) & Vertical Axis (VAWT)
- Features:
  - Very low noise making
  - No dominant-wind-direction requirement
  - Power generation starts in slight winds
  - Portable electricity
  - Non-destructive installing methods

Start-up at 1m/s wind speed

Non-destructive installing methods

Small VAWT System Composition

- Rotor Blades:
  1. Anti-UV, Acid-alkali-resistant
  2. Heat-&-cold-resistant
  3. Omni-wind-directional
  4. Safe Blades for urban/metropolitan areas
- PM Generator:
  1. Flux-concentrated for high efficiency
  2. Disk-type Permanent Magnet Generator
  3. Low-speed high-torque for low noise
  4. No cogging torque for cutting in at low wind speed
  5. Directly-driving extends product life
- MPPT Controller:
  1. Wind/PV hybrid type
  2. AC type
  3. AC standalone type
  4. AC grid-tied type
- Pole and Base:
  1. Portable Mini type
  2. Moveable Small type
  3. Fixed type



Super Designs of Rotor Blades

- Lift-type of sub blades alter resistance for assistance from winds to raise the rotational efficiency of turbines.
- Special design of sub blade kits raise wind-energy-absorbing capacity.
- Distorted main blades have high wind-absorbing coefficient, and enable start-up in breeze.
- Wind-collecting design enlarges the swept areas for electricity generation.
- Magnet-floating design of blades reduce rotational resistance to enhance electricity generation and extend turbine life.
- Super light blade materials raise rotational efficiency and their small centrifugal force prolongs turbine life.
- Safe blade design lowers the possibility of harms from blades to personnel.

Wind-Power-Dedicated PM Generators

- Cell Power Wind-Power-Dedicated Generators are 3-phase AC permanent-magnet synchronous ones. They are very flat and slim in shape, look very beautiful and easy to get fixed. Their special flux-concentrating designs greatly promote their efficiency; we call them high-efficiency flux-concentrating generators. Cell Power generators are featured with no cogging torque and high torque, very suitable for the application of start-up in slight winds. They are also applicable to the driving systems of various electric vehicles.

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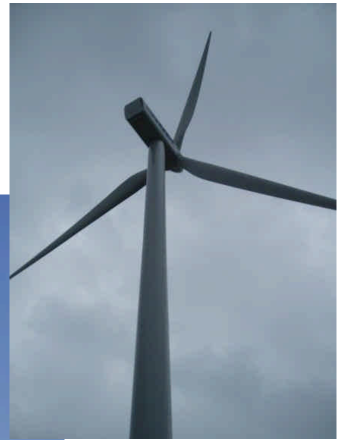
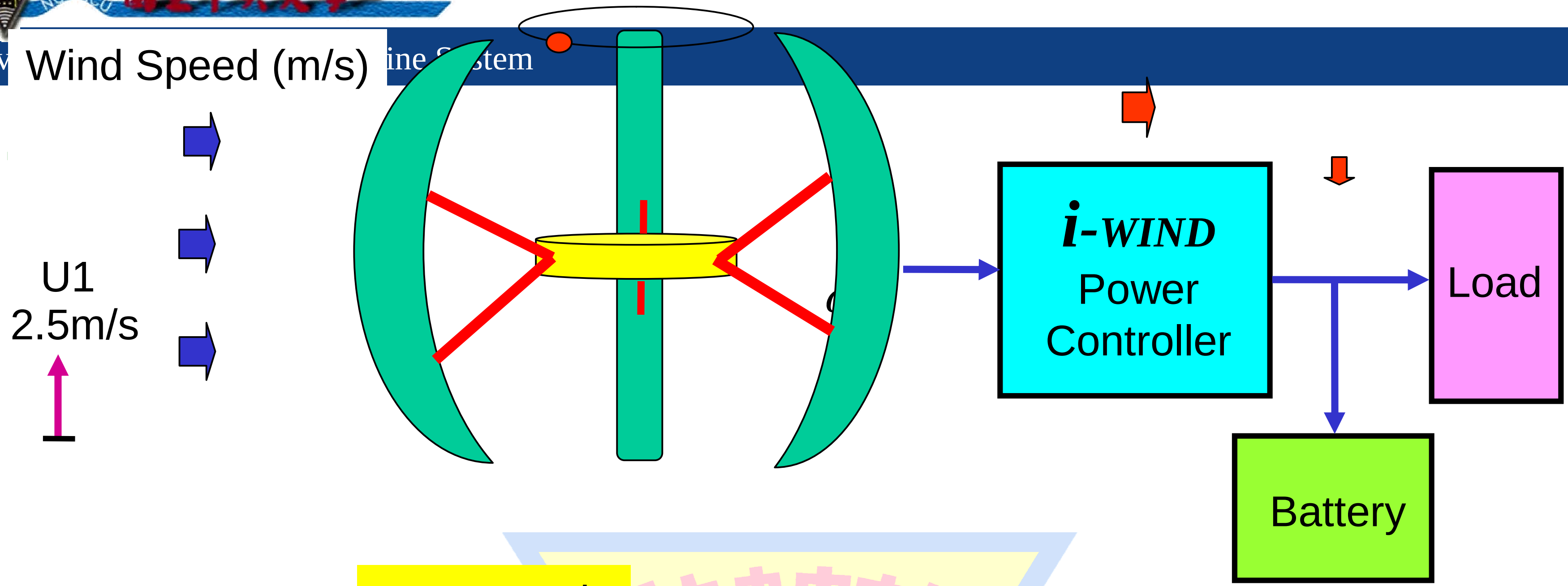
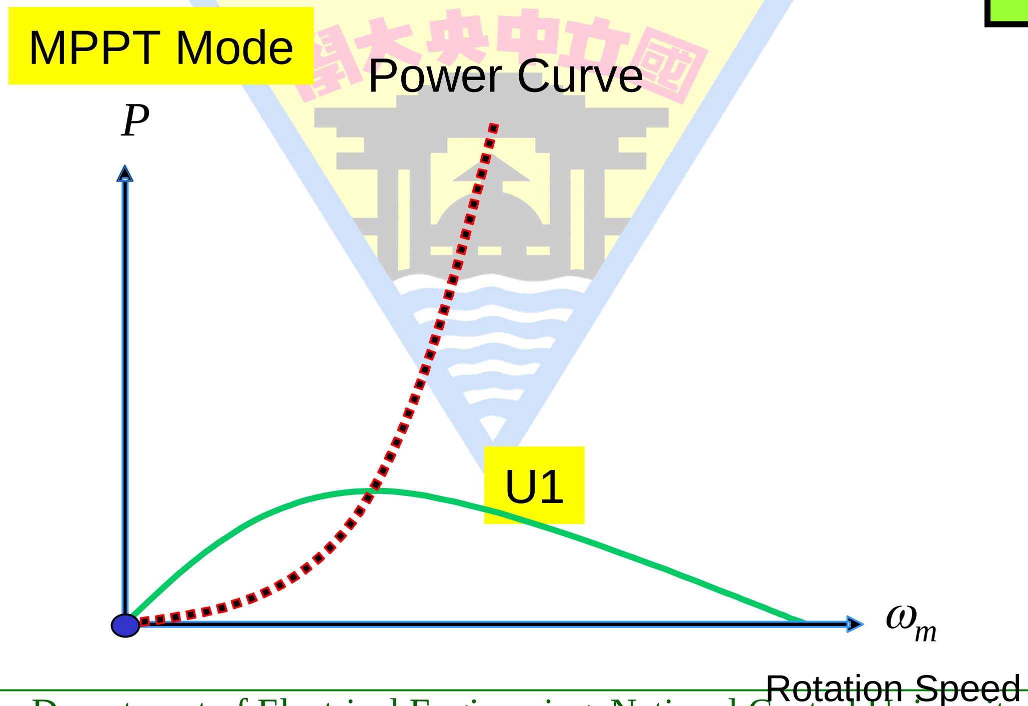
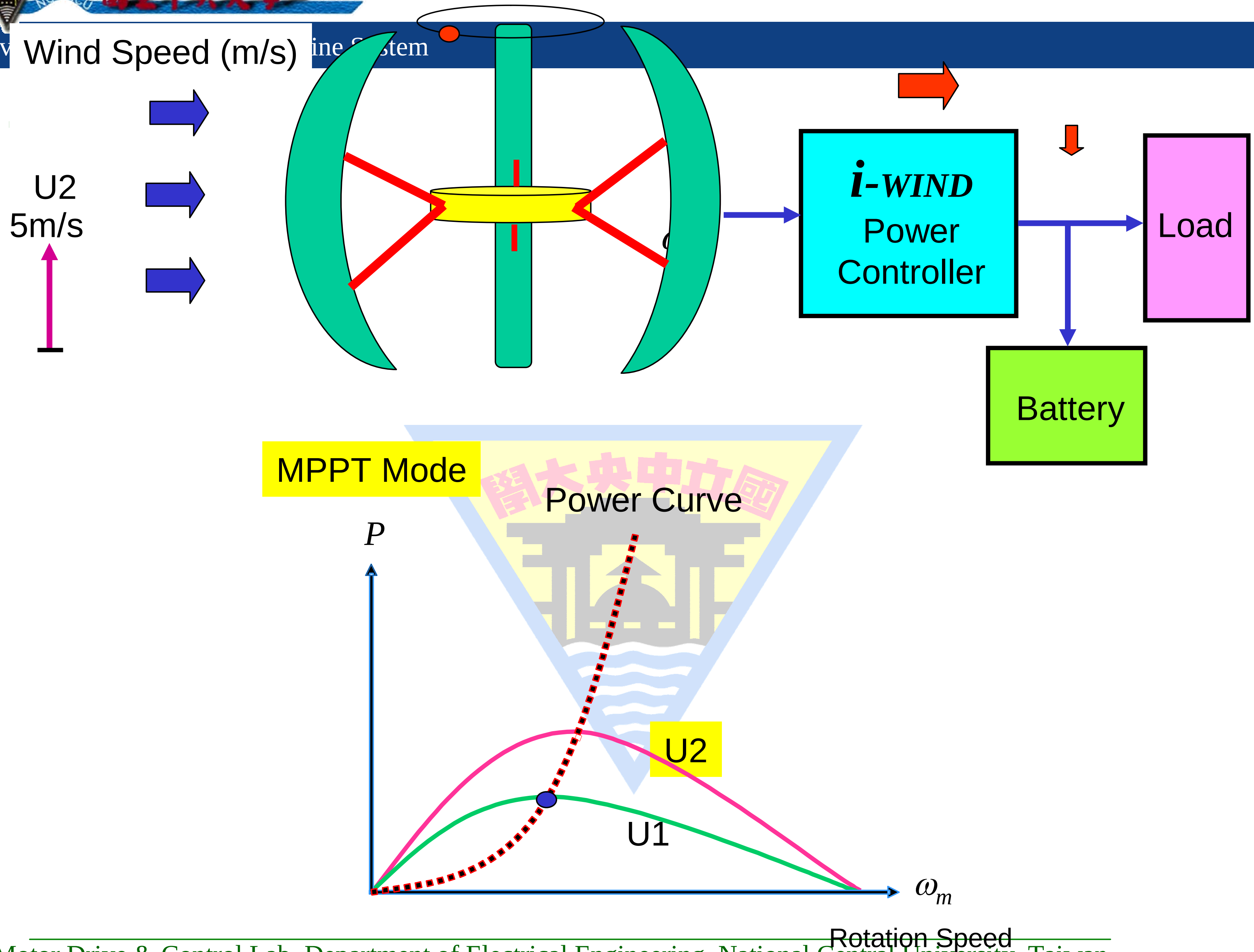


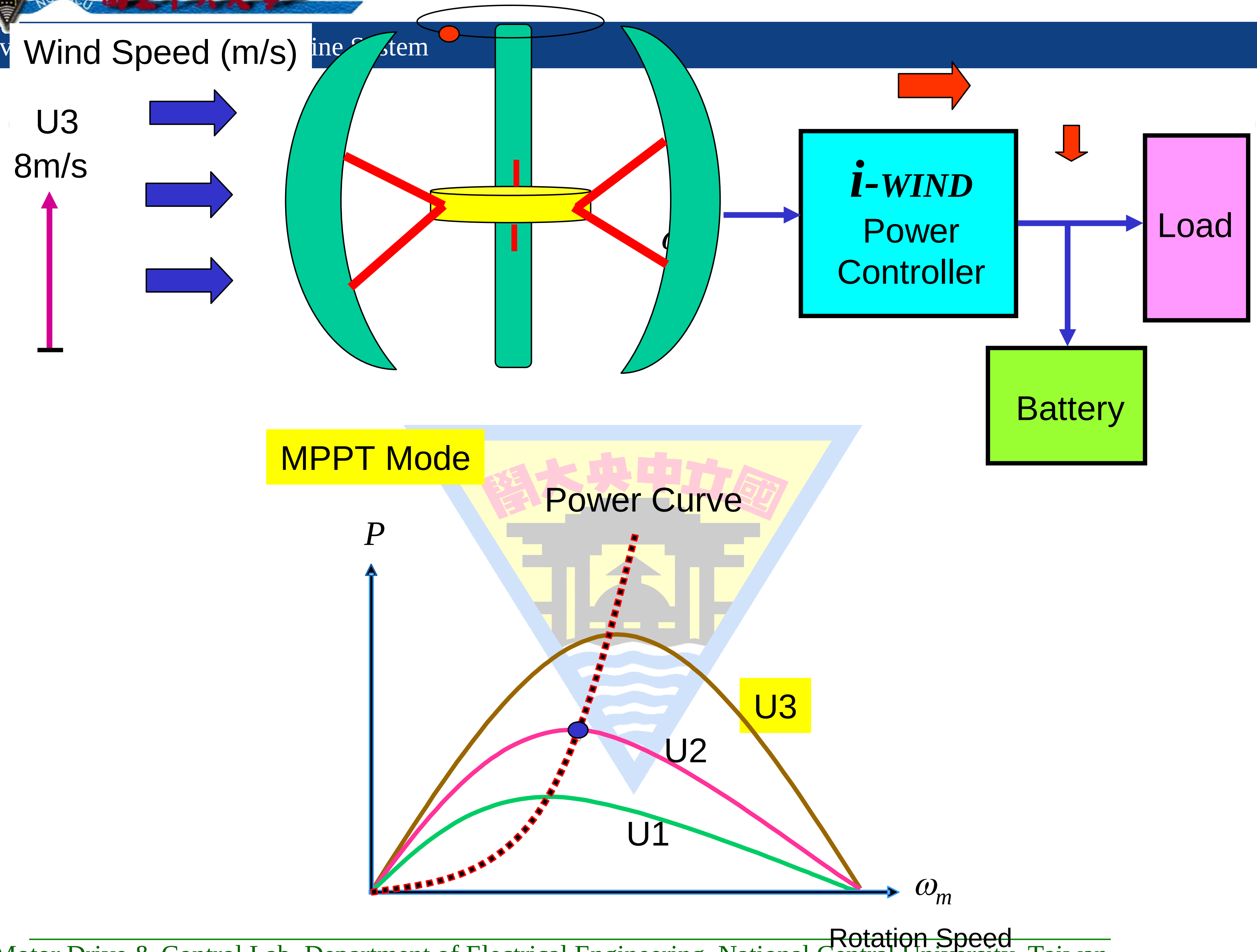
MPPT Controllers

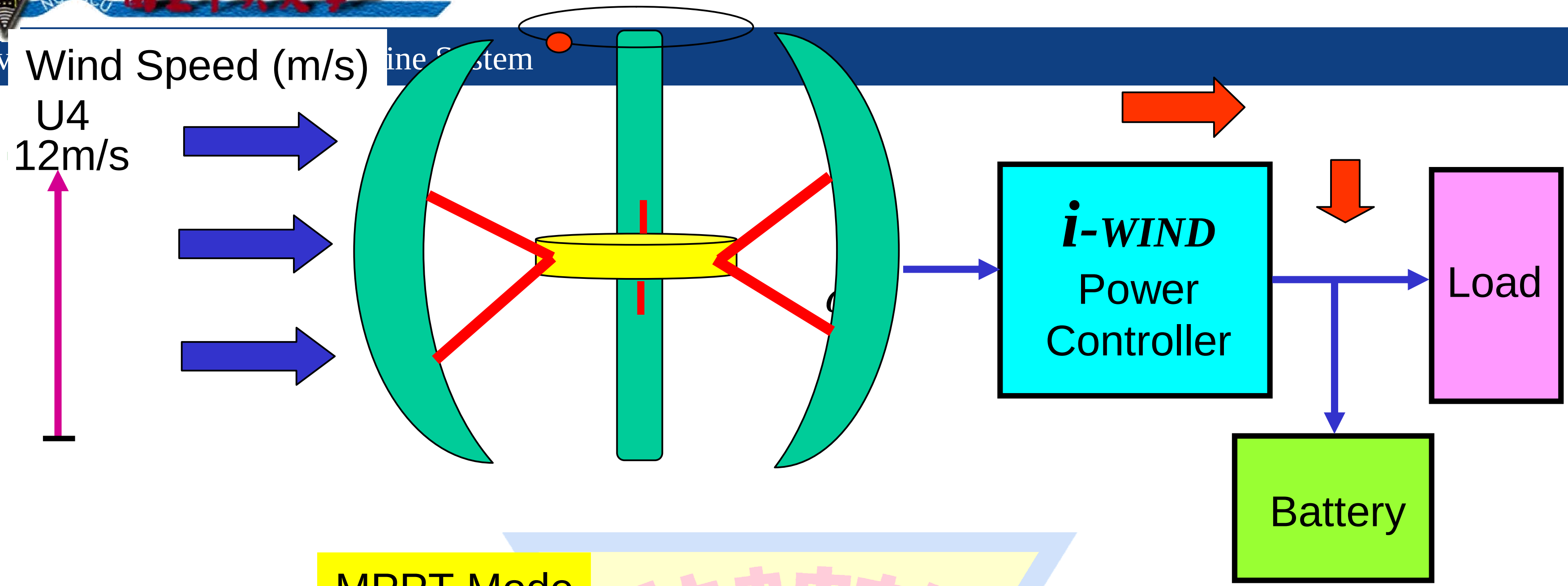
- Cell Power Controllers are featured with Intelligent Digital Signal Processing (DSP), Maximum Power Point Tracking (MPPT), Remote Control and Communication, Automatic Brake System (ABS) for over speed protection, compact, lightweight, super high efficiency, automatic electricity-balance control to extend battery life, etc.

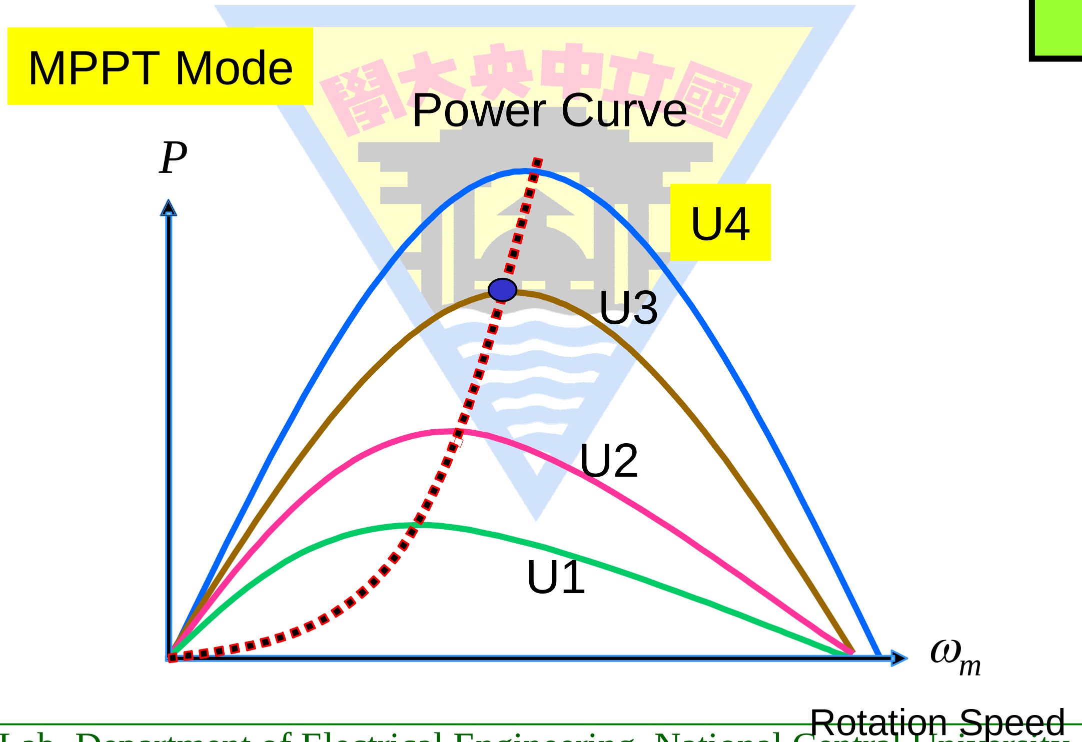

Wind Speed (m/s)
U1
2.5m/s
i-WIND
Power
Controller
Load
Battery

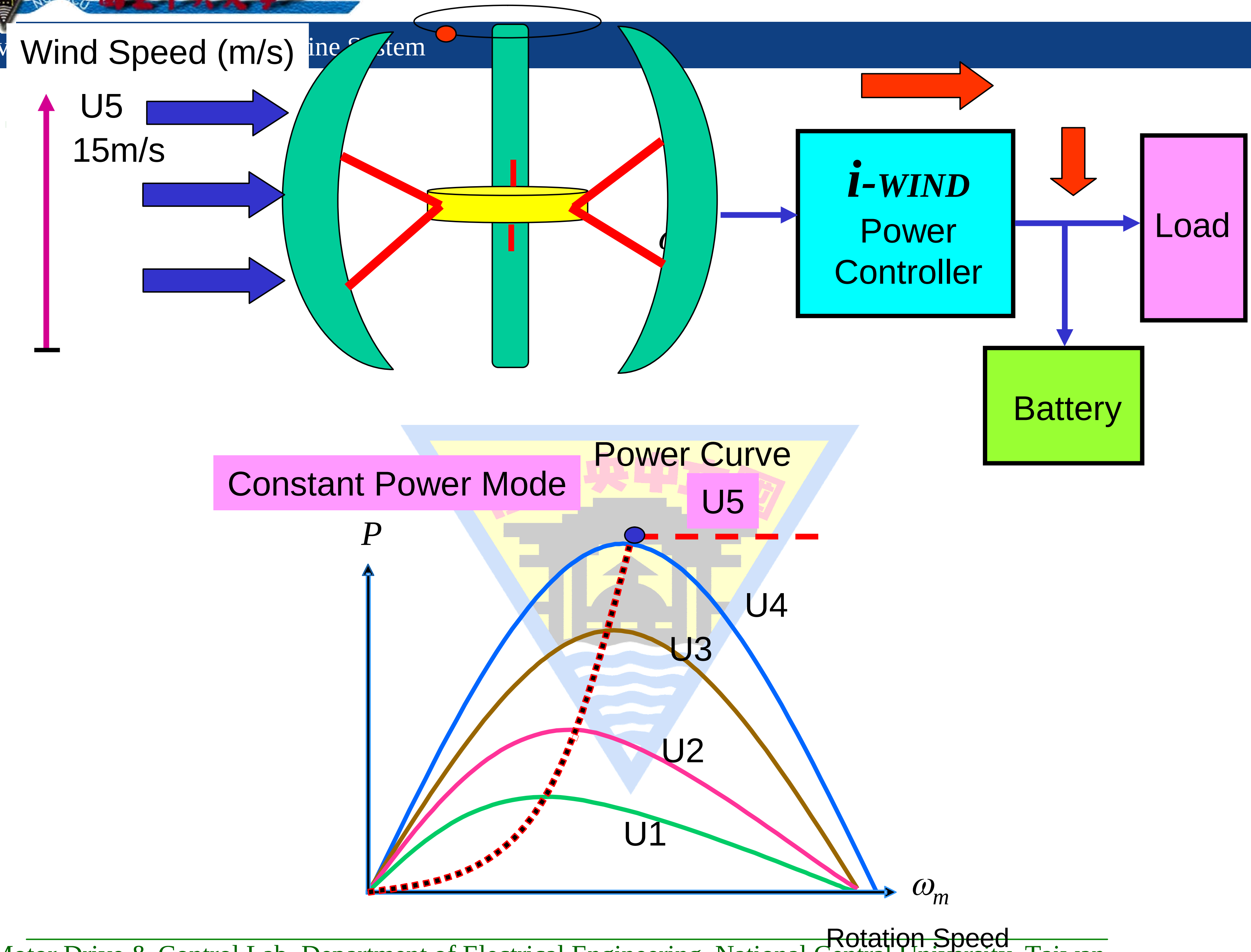

MPPT Mode
Power Curve
P
U1
ω_m
Rotation Speed

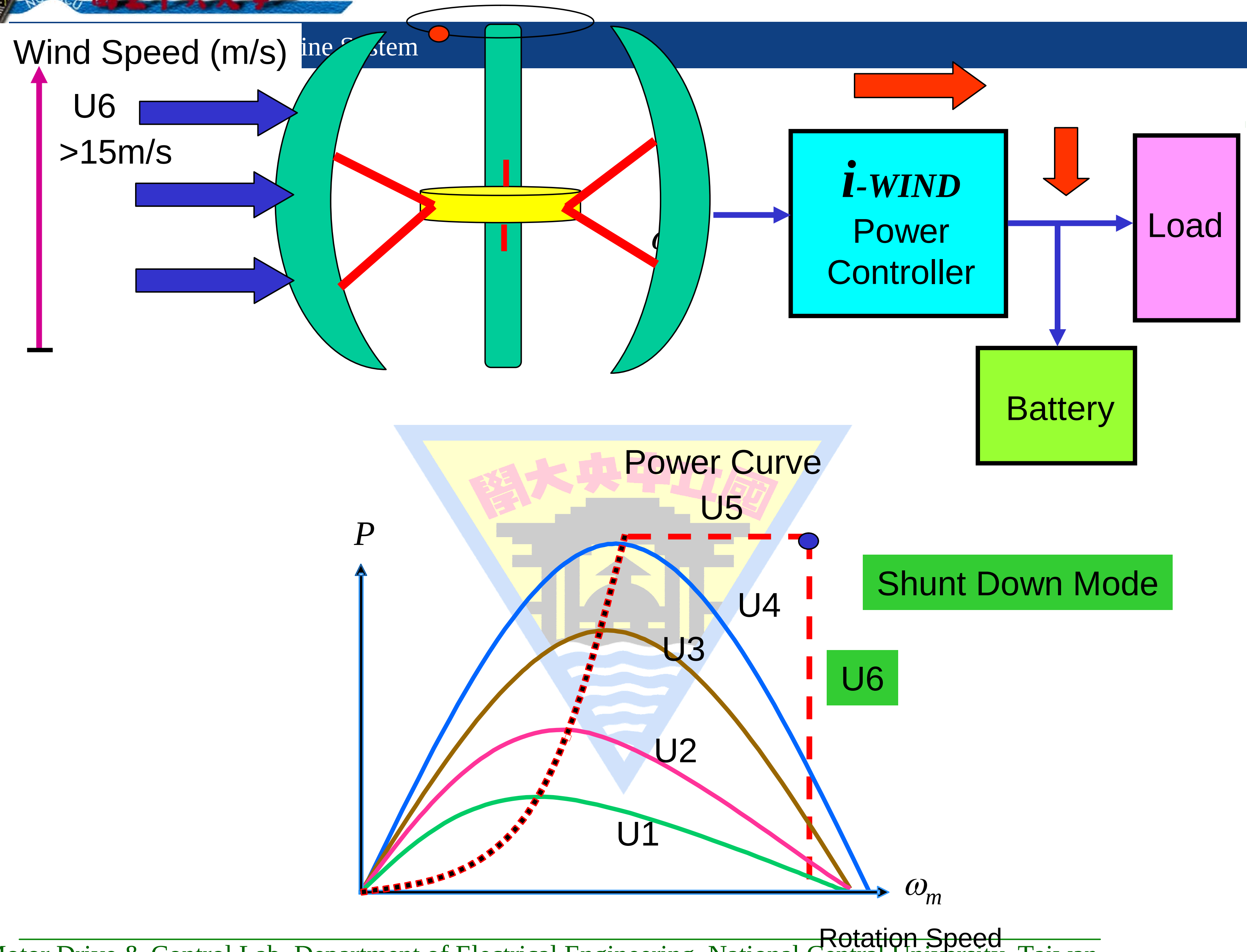

Wind Speed (m/s)
U2
5m/s
i-WIND
Power
Controller
Load
Battery
MPPT Mode
Power Curve
P
U2
U1
ωm
Rotation Speed

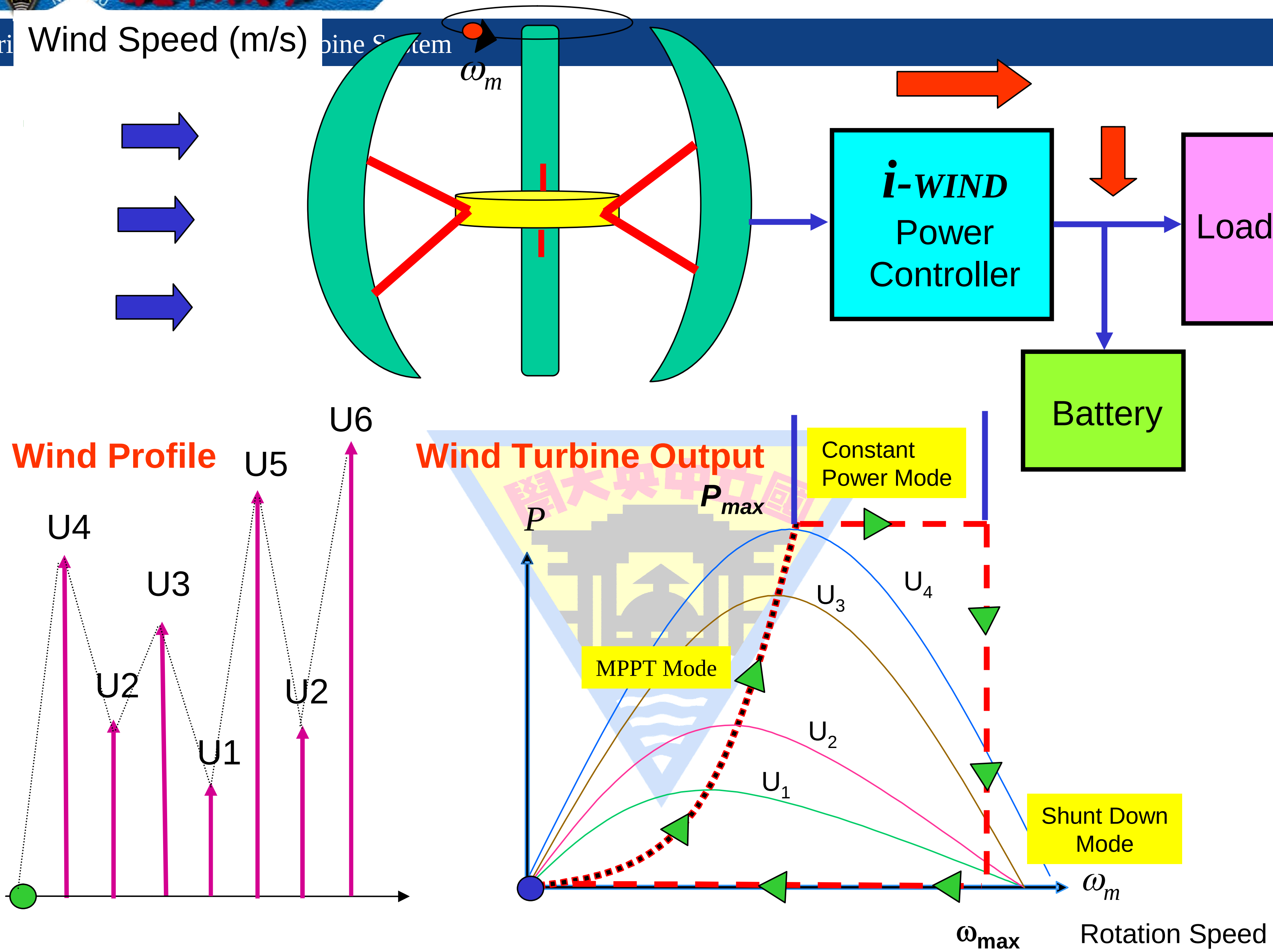

Wind Speed (m/s)
U3
8m/s
i-WIND
Power
Controller
Load
Battery
MPPT Mode
Power Curve
P
U3
U2
U1
ω_m
Rotation Speed


Wind Speed (m/s)
U4
12m/s
i-WIND
Power
Controller
Load
Battery


MPPT Mode
Power Curve
P
U4
U3
U2
U1
ωm
Rotation Speed


Wind Speed (m/s)
U5
15m/s
i-WIND
Power
Controller
Load
Battery
Constant Power Mode
Power Curve
U5
P
U4
U3
U2
U1
ω_m
Rotation Speed


Wind Speed (m/s)
U6
>15m/s
i-WIND
Power
Controller
Load
Battery
Power Curve
U5
P
U4
U3
U2
U1
Shunt Down Mode
U6
ω_m
Rotation Speed



Wind Speed (m/s)
ω_m
i-WIND
Power
Controller
Load
Battery
Wind Profile
U4
U3
U2
U1
U5
U2
U6
Wind Turbine Output
Constant
Power Mode
P_{max}
P
U_4
U_3
MPPT Mode
U_2
U_1
Shunt Down
Mode
ω_m
ω_{max}
Rotation Speed

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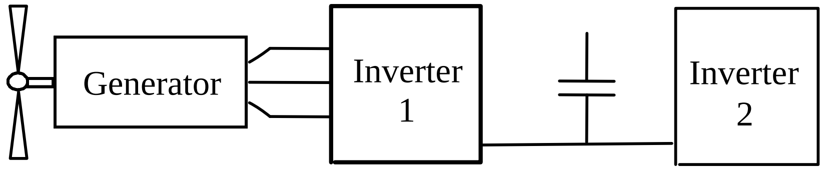
Design Case 1- Grid-Connected 10kW PMSG System



- **System Specification**
  - Wind Speed: 3m/s ~ 15m/s
  - Generator: 3-phase PMSG
  - Power: 10kW@12m/s
  - Grid: 3-phase 220V/60Hz

Wind Turbine Characteristic

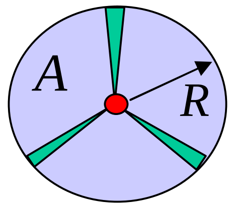
$$\lambda = \frac{\omega_t R}{U}$$

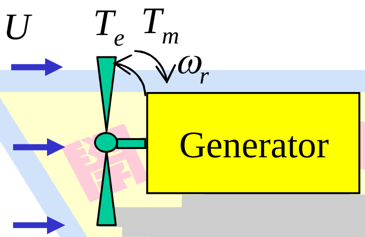
$$C_p(\lambda,\theta) = 0.22(\frac{116}{\lambda_i} - 0.4\theta - 5)e^{-12.5/\lambda_i}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\theta} - \frac{0.035}{\theta^3 + 1}$$

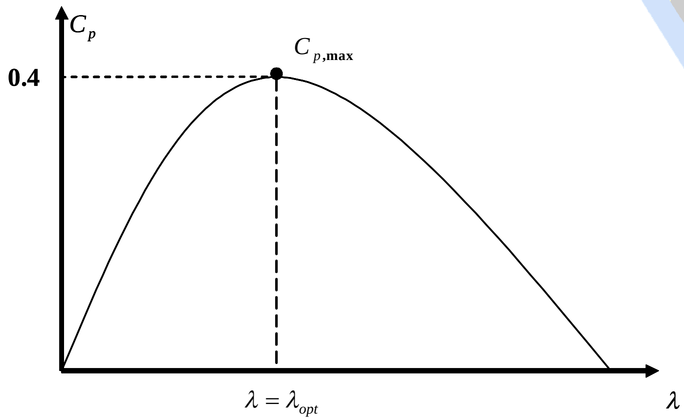
$$P_m = \frac{1}{2}\rho C_p A U^3 \qquad T_m = \frac{P_m}{\omega_r}$$

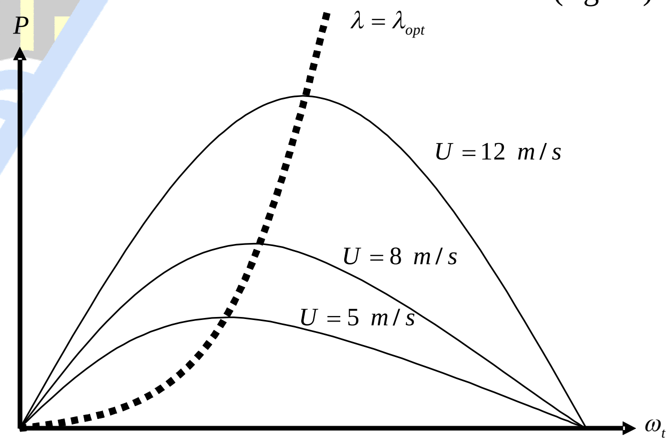
$$\frac{d\omega_r}{dt} = \frac{1}{J}(T_m - T_e) \qquad \omega_e = \frac{P}{2}\omega_r$$



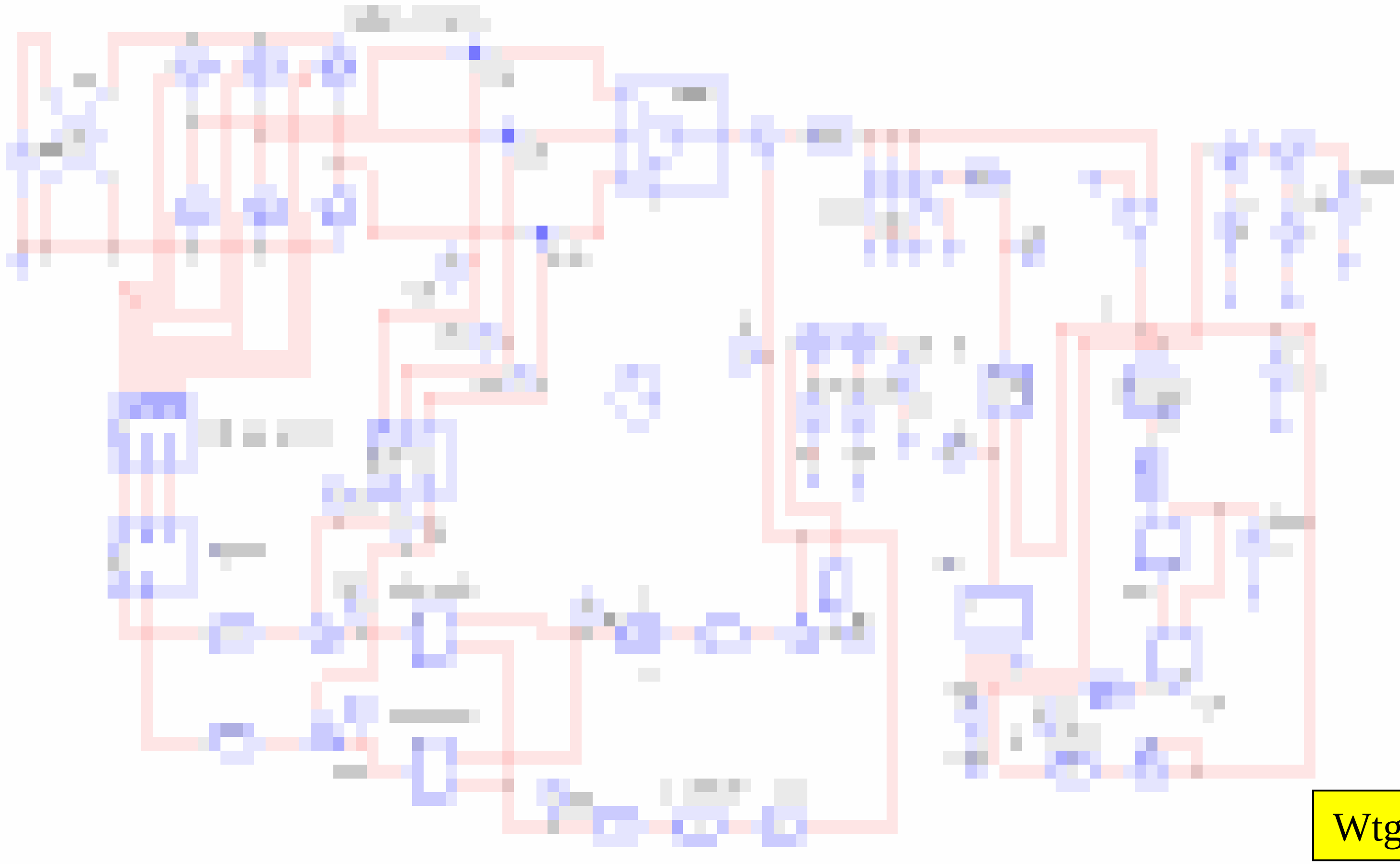


For the direct drive wind turbine system $\omega_t = \omega_r$
where:
P_m (W): Mechanical power in the wind turbine shaft
A (m^2): effective area covered by the turbine
U (m/s): wind speed
ρ (kg/m^3): air density
C_p: Power coefficient of the wind turbine
λ: Tip speed ratio
R (m): Radius of the blade
ω_t (rad/s): Wind turbine rotor speed
ω_r (rad/s): Generator rotor speed
ω_e (rad/s): Electric frequency of the generator
P: Pole number of the generator
θ (degree): Pitch angle of the blade
T_m (Nm): Mechanic torque
T_e(Nm): Electromagnetic torque
J: Moment of the machine inertia (kgm^2)





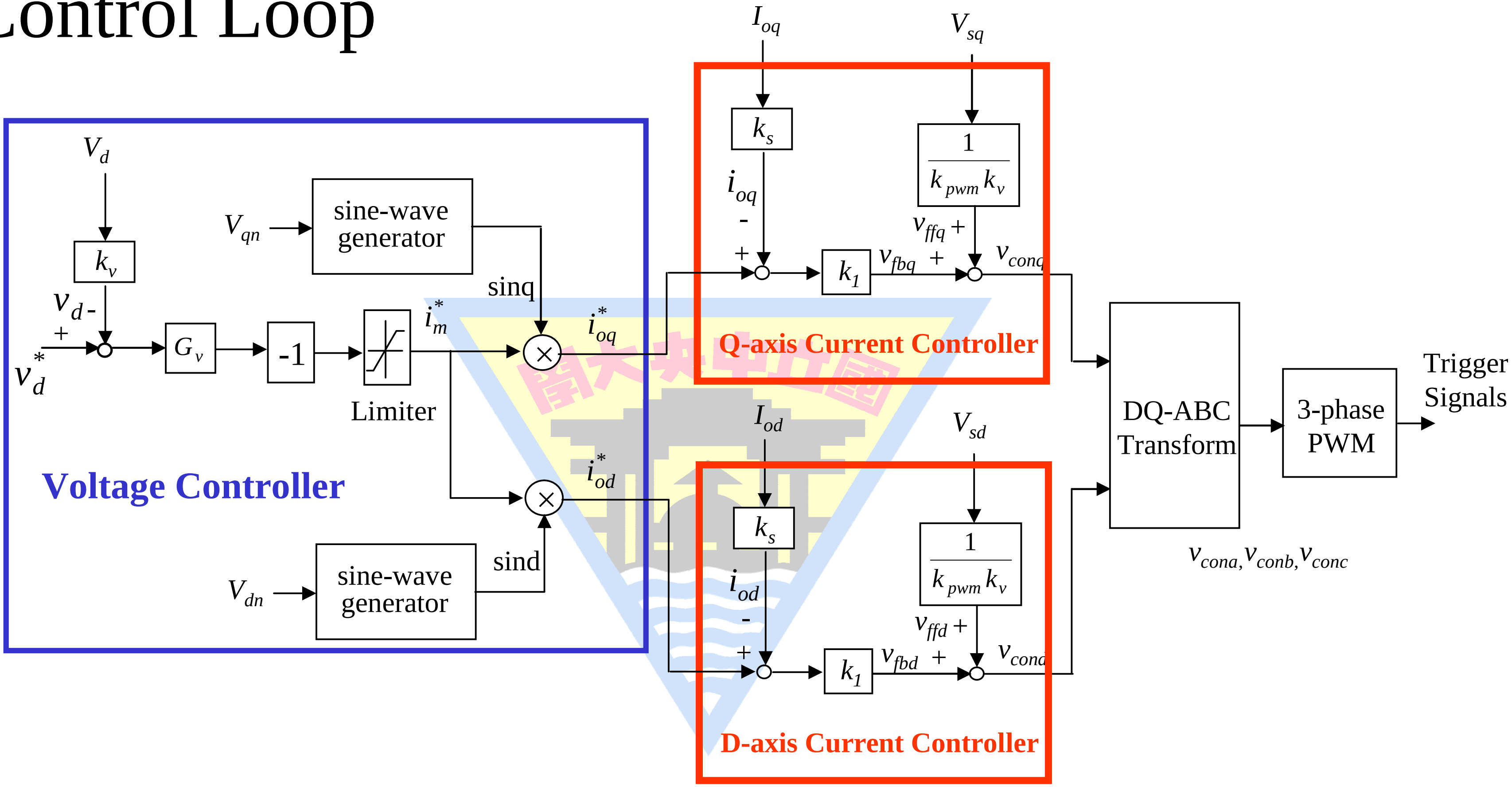
WTG + PMSG Drive (3m/s => 12m/s => 15m/s)



Wtg2.sch

Simulation Result (3m/s => 12m/s => 15m/s)

Control Loop

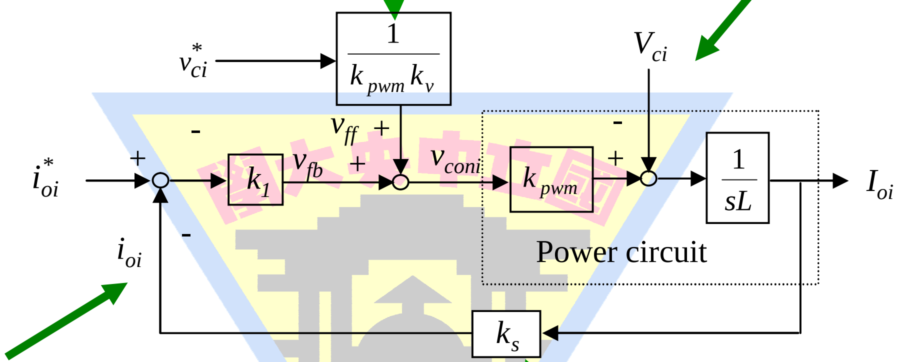


Voltage Control Outer Loop Plus Current Control Inner Loop

Inner Current Control Loop

Feedforward Control

$$L\frac{dI_{oi}}{dt}=k_{pwm}v_{coni}-V_{ci}, i=d,q$$



Feedback Control

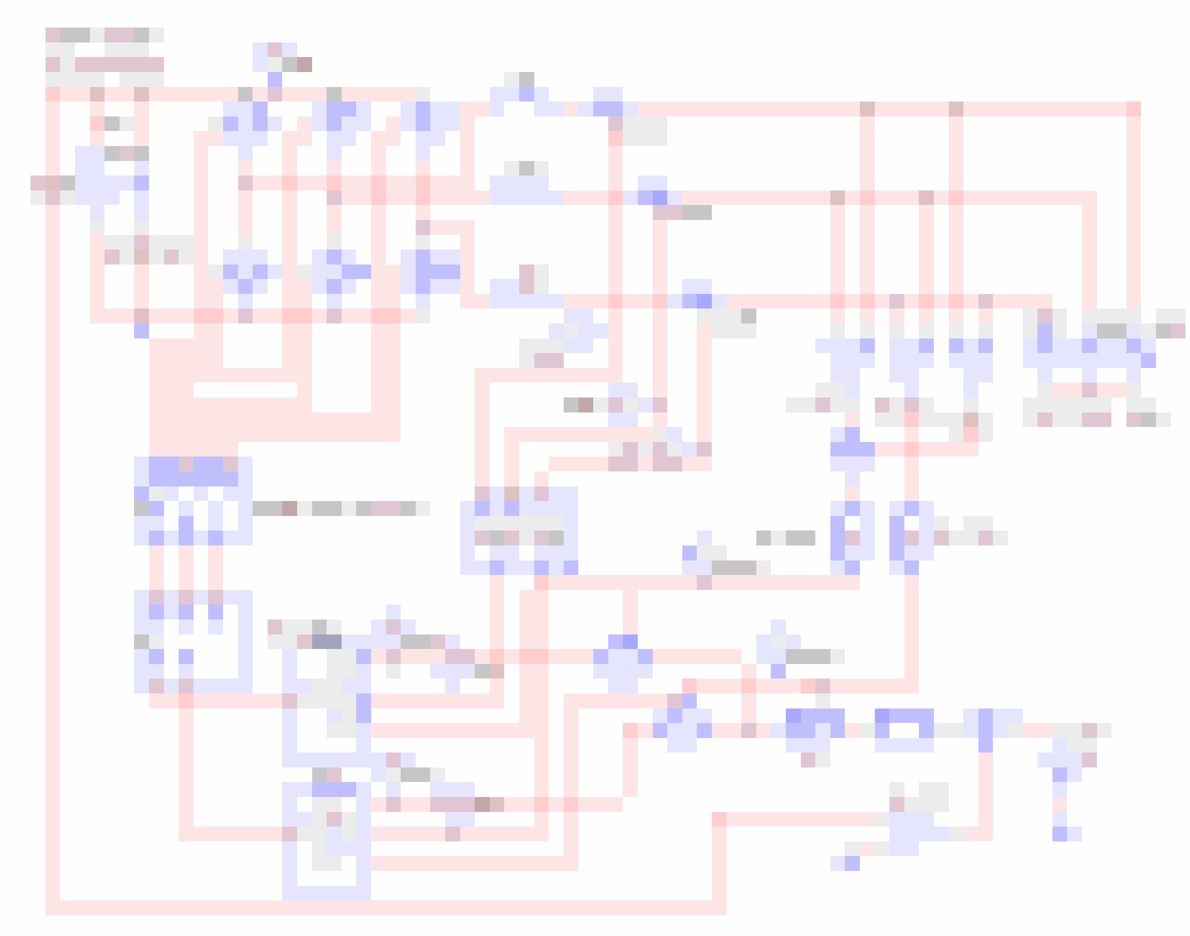
k_s: Hall sensor gain (V/A)

$$\frac{i_{oi}}{i_{oi}^*}=\frac{\frac{k_1k_sk_{pwm}}{L}}{s+\frac{k_1k_sk_{pwm}}{L}}=\frac{u_i}{s+u_i}$$

$$u_i=\frac{k_1k_sk_{pwm}}{L}$$

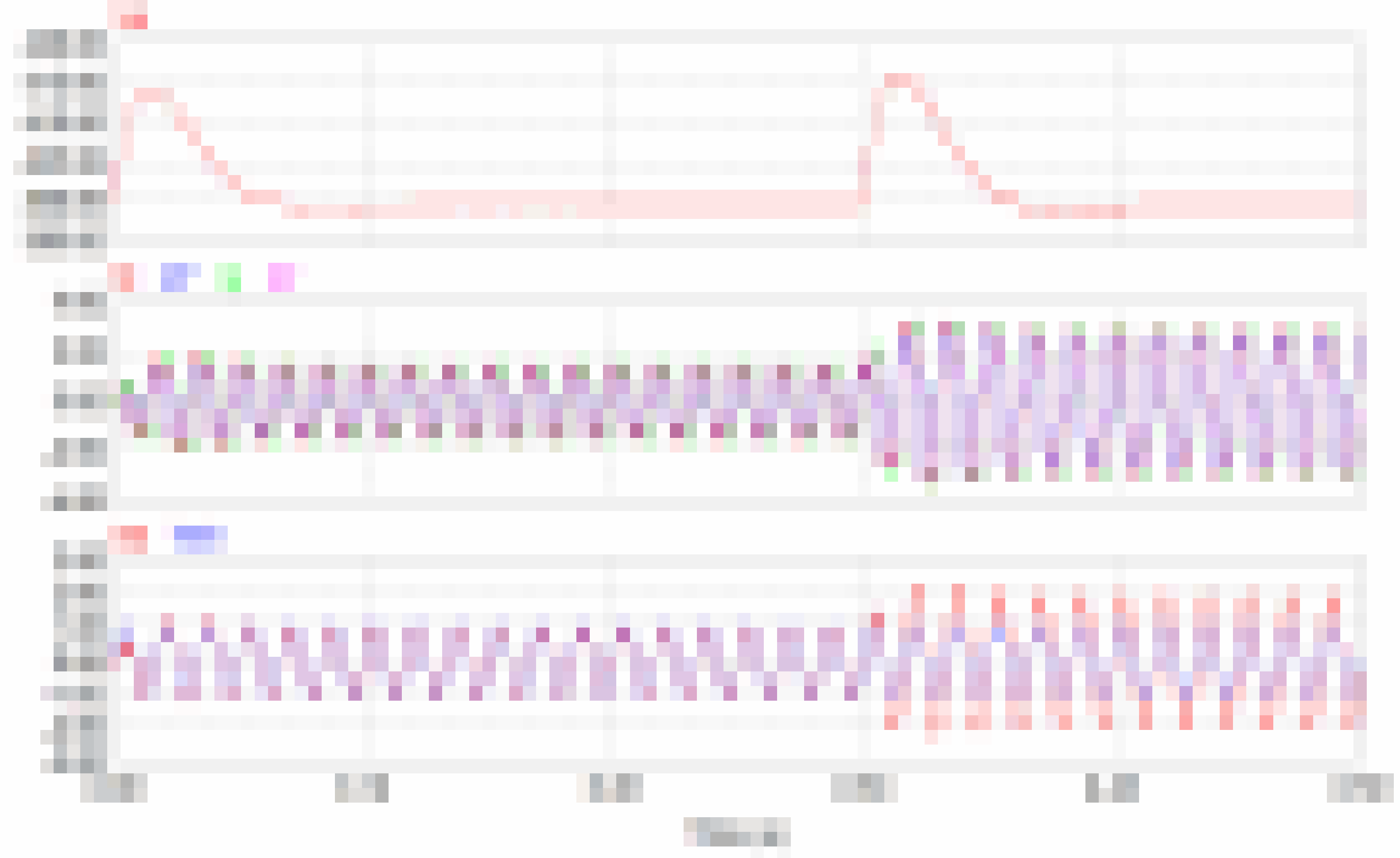
u_i : Current loop bandwidth can be set by k_1

Simulation of 3-phase Grid-Connected Inverter (5kW => 10kW)



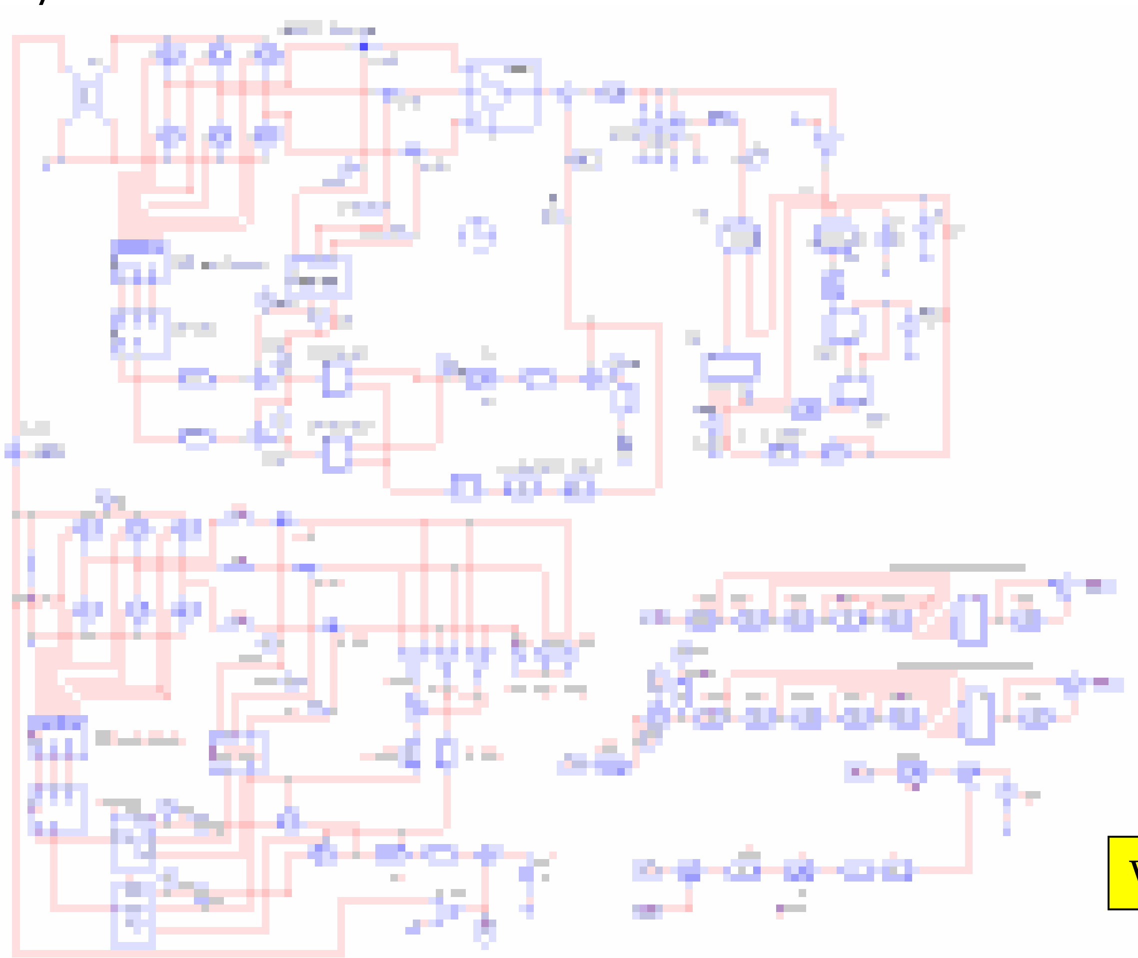
Wtg3.sch

Simulation Result (5kW => 10kW)



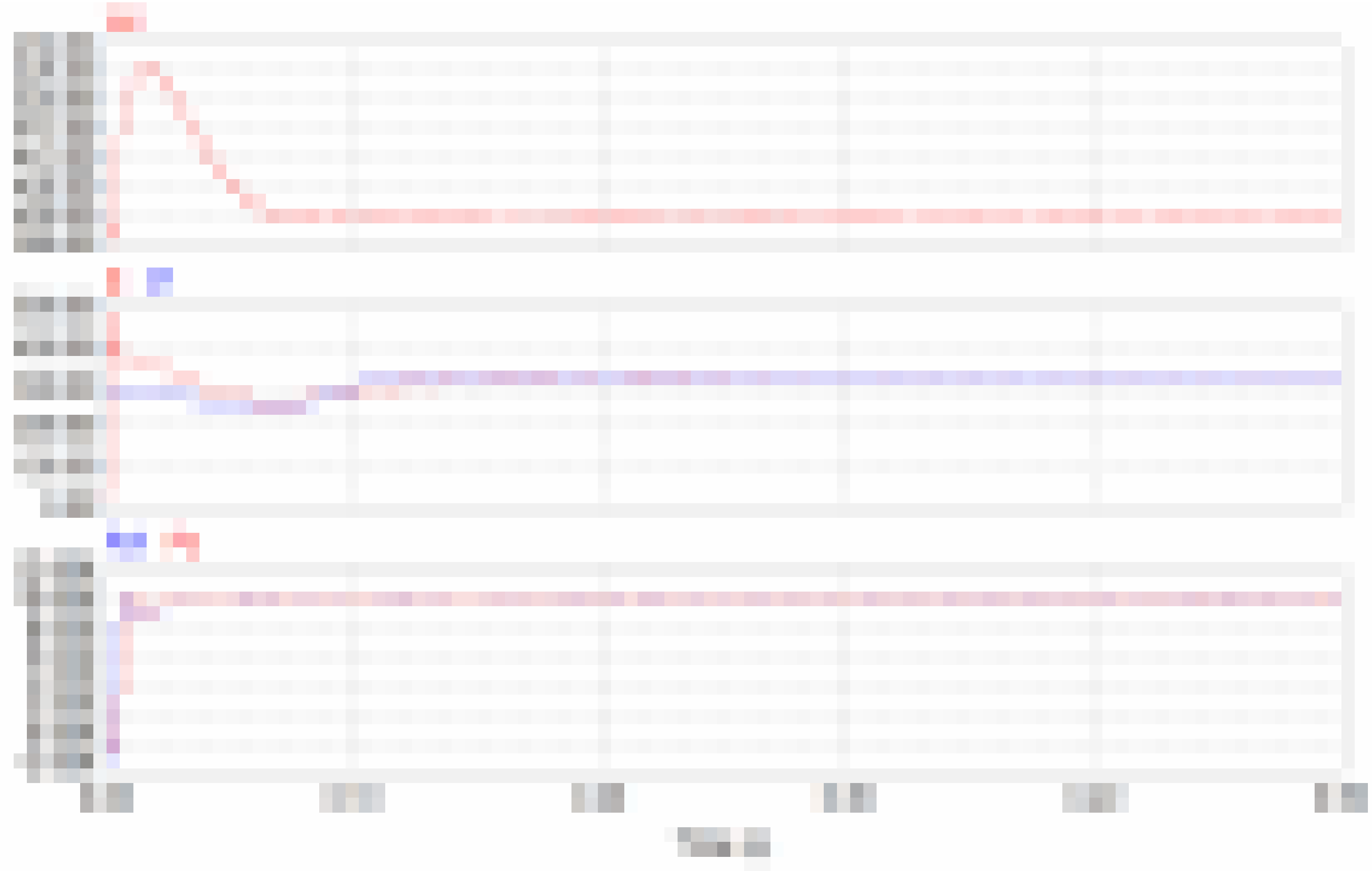
The Whole System

WTG
+
PMSG Drive
+
Grid-Connected Inverter
+
MPPT



Wtg5.sch

Simulation Result of the Whole System (U=12m/s)



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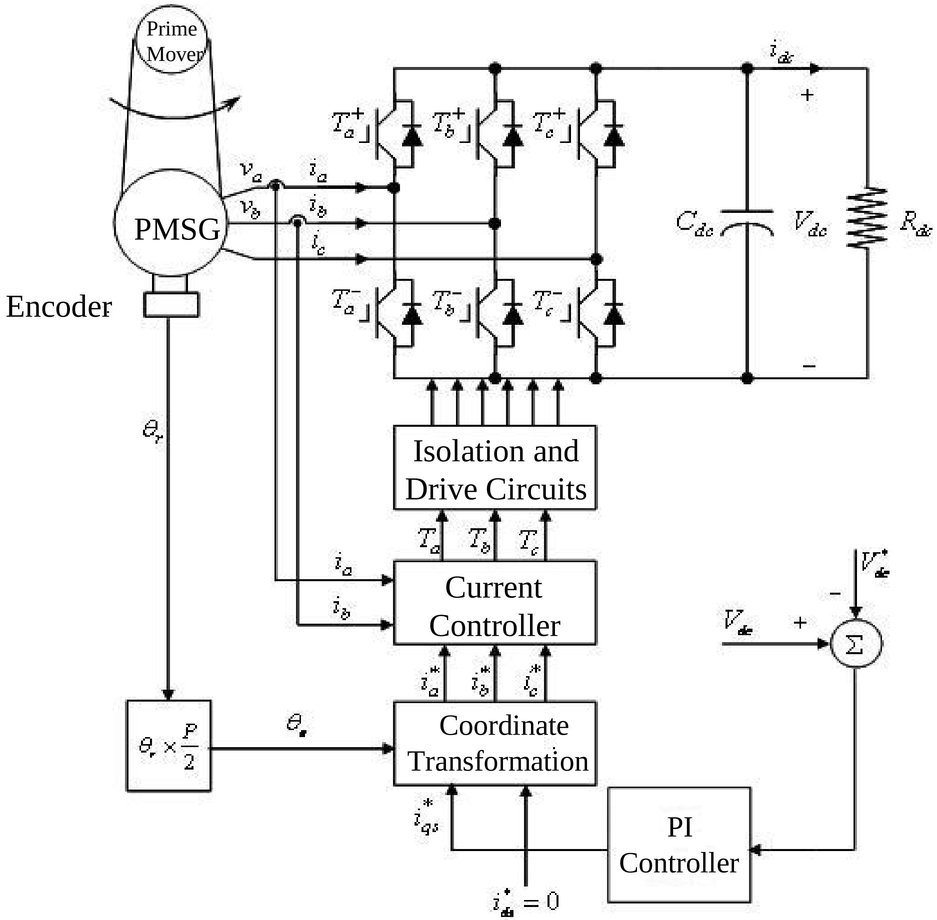
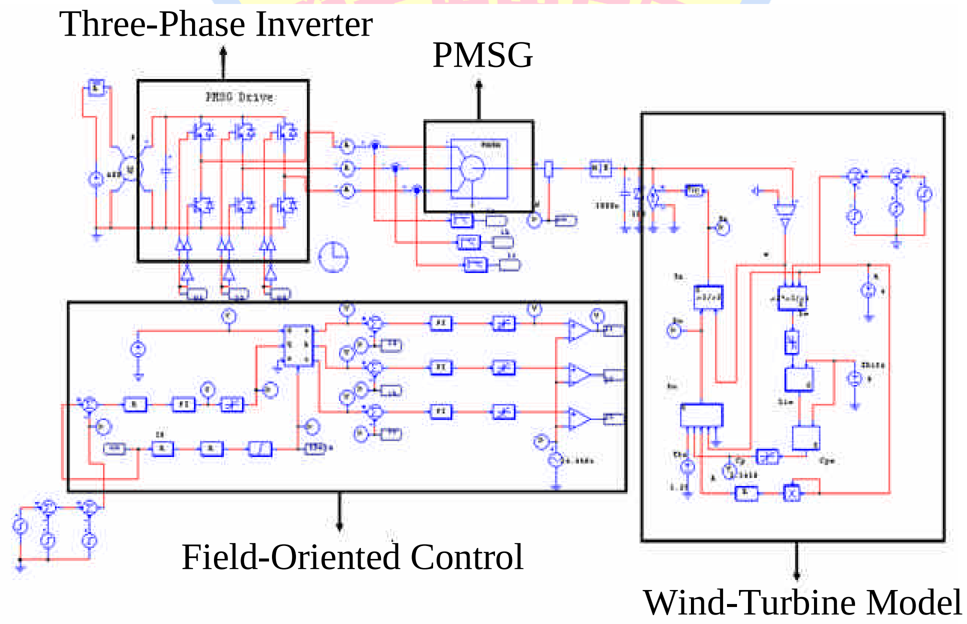
Design Case 2 - Field-Oriented Controlled PMSG System with DC Load



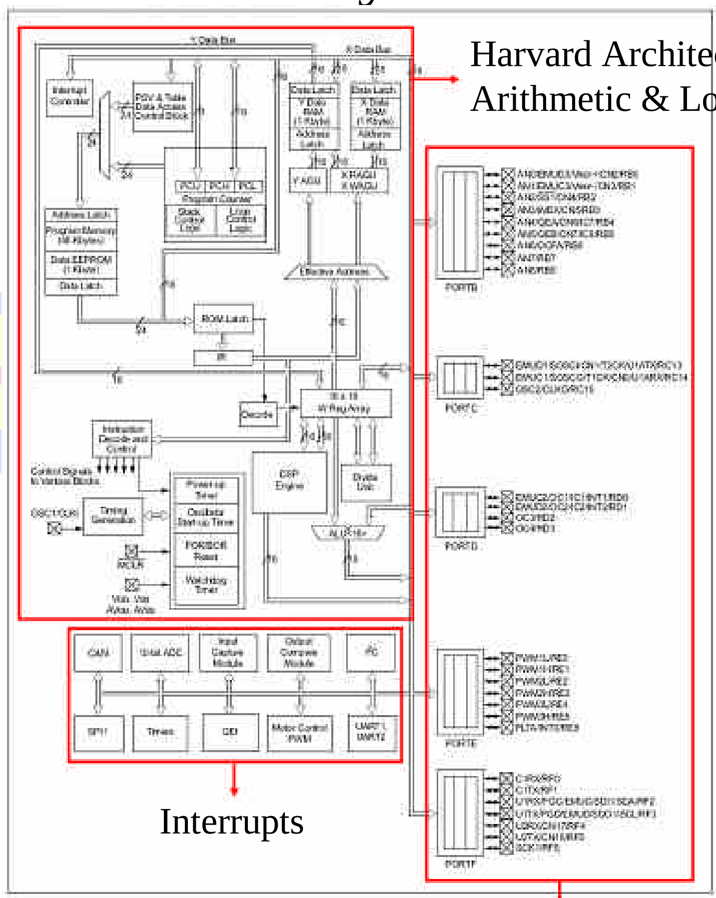
Field-Oriented Controlled PMSG System with DC Load

- PSIM package is adopted to simulate the drive system
  - 5kW、60 pole, rated speed 150rpm
  - Test Cases: 30rpm、45rpm and 60rpm with DC-link 140V、190V and 240V at 38Ω and 25Ω DC load.



Field-Oriented Controlled PMSG System with DC Load

- Control Block of dsPIC30F4011



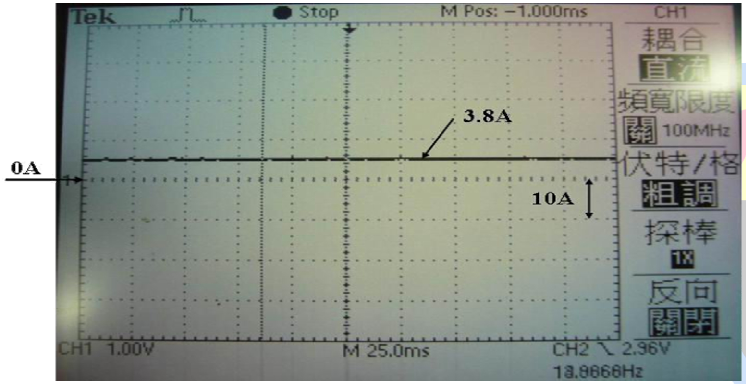
Harvard Architecture
Arithmetic & Logic Unit, ALU

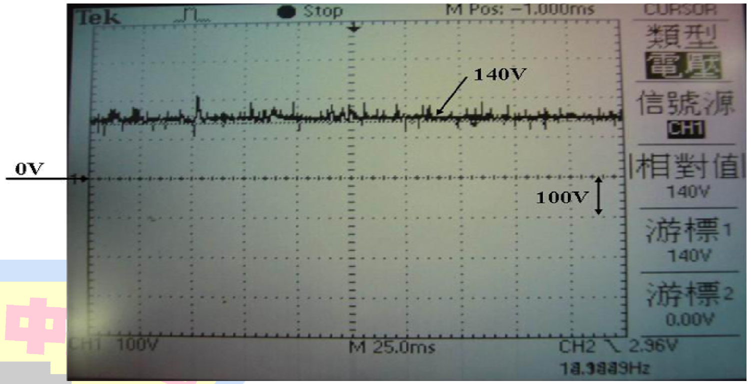
Interrupts

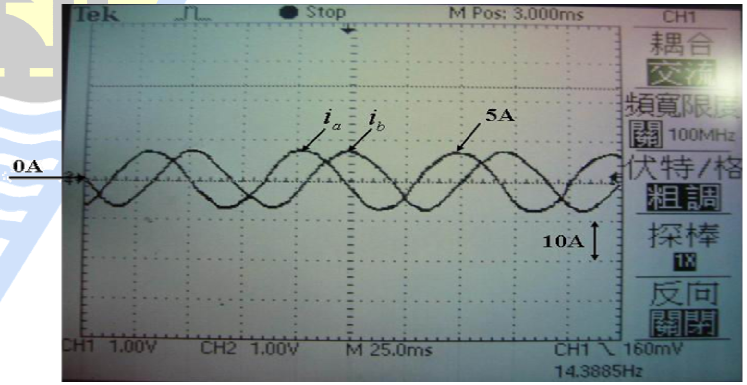
Input/Output Module

Experimentation

- 30rpm with load 38Ω

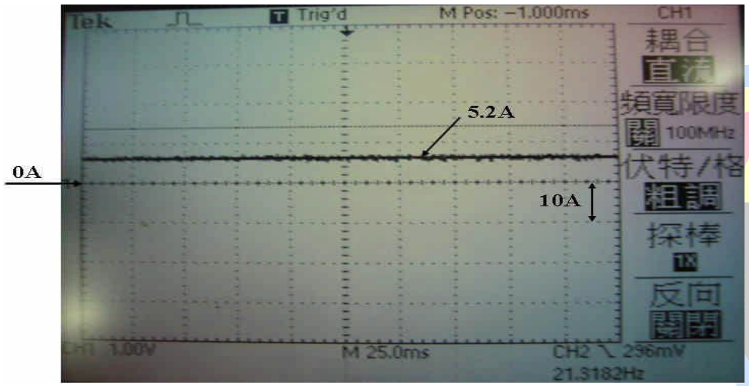


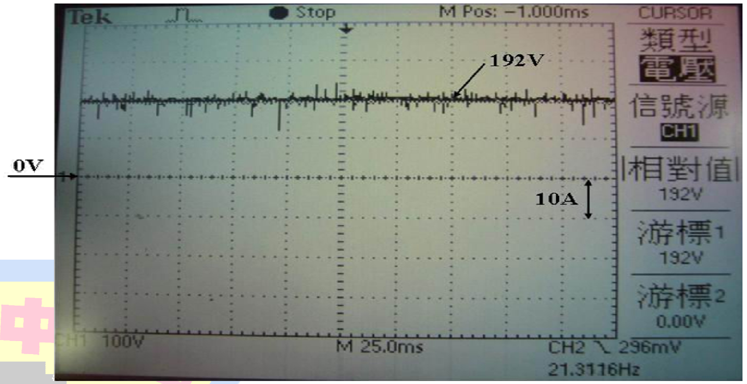


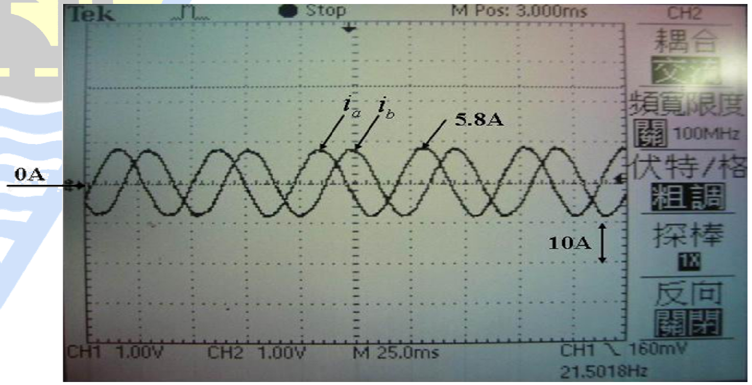


Experimentation

- 45rpm with load 38Ω

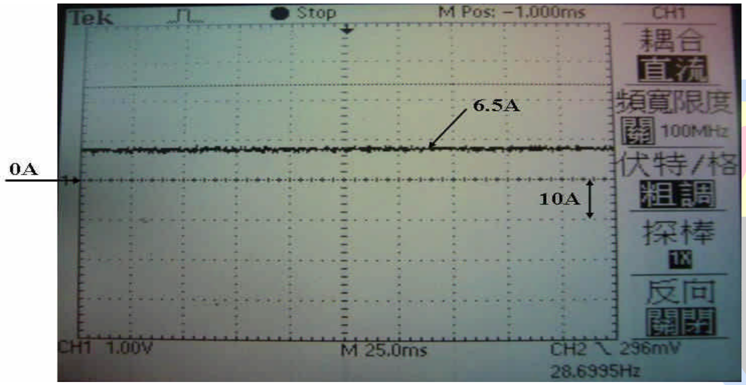


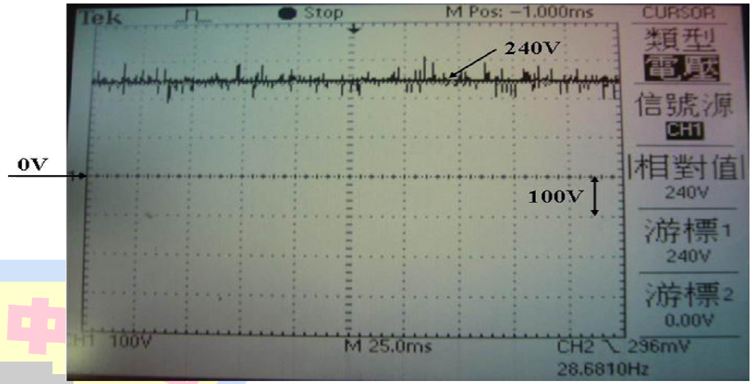


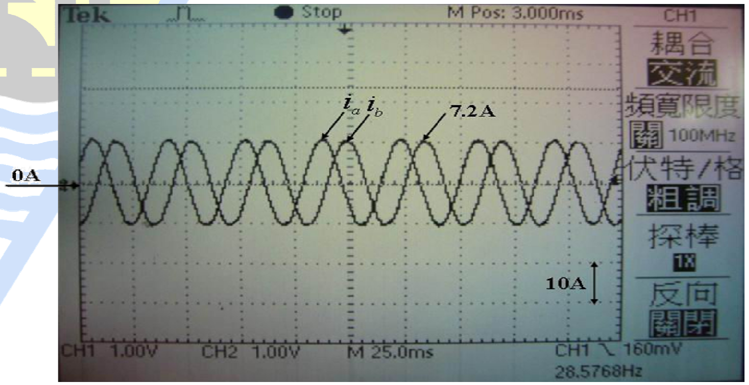


Experimentation

- 60rpm with load 38Ω

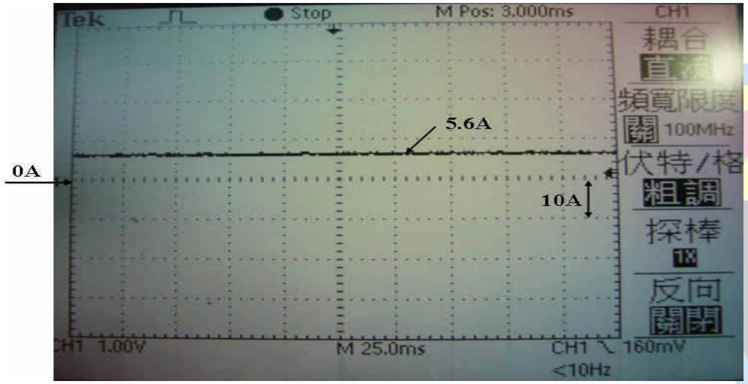


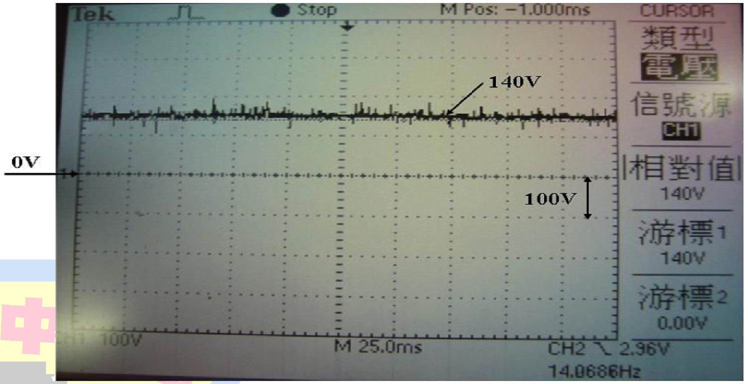


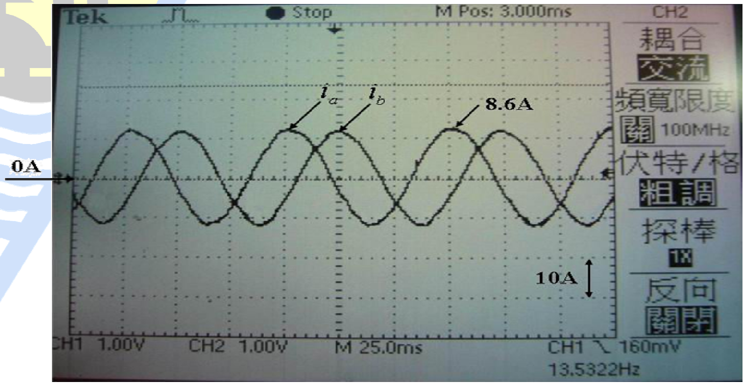


Experimentation

- 30rpm with load 25Ω

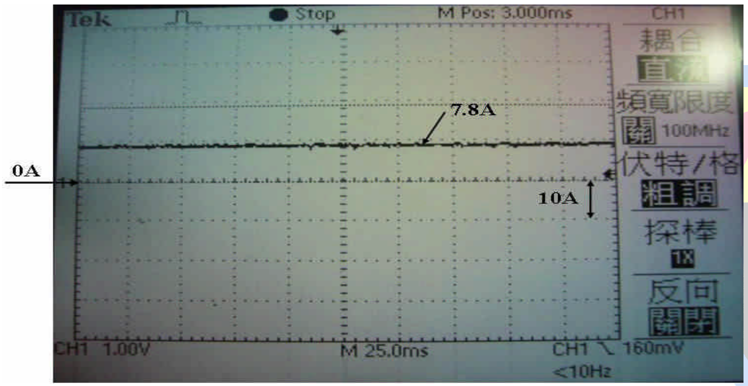


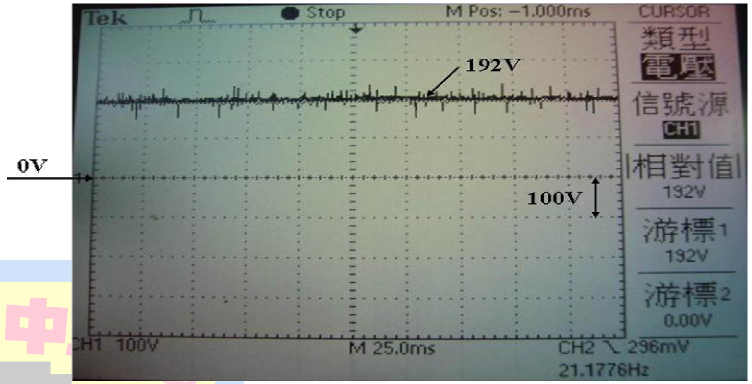


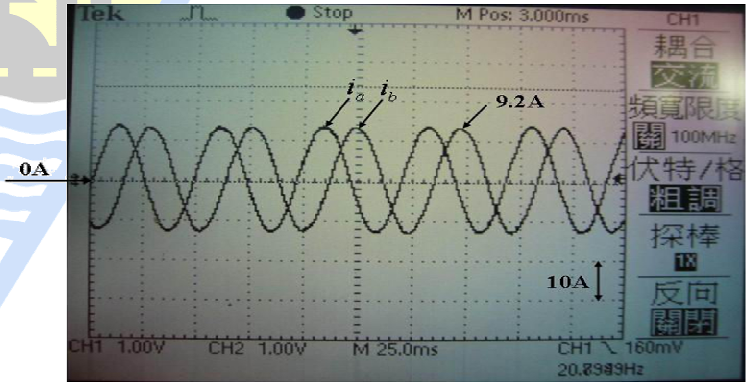


Experimentation

- 45rpm with load 25Ω

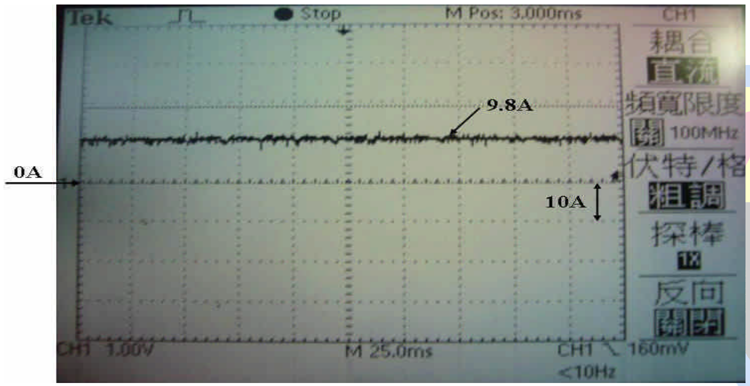


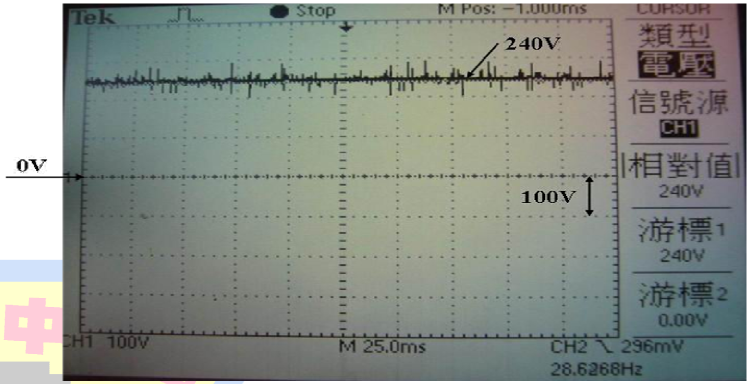


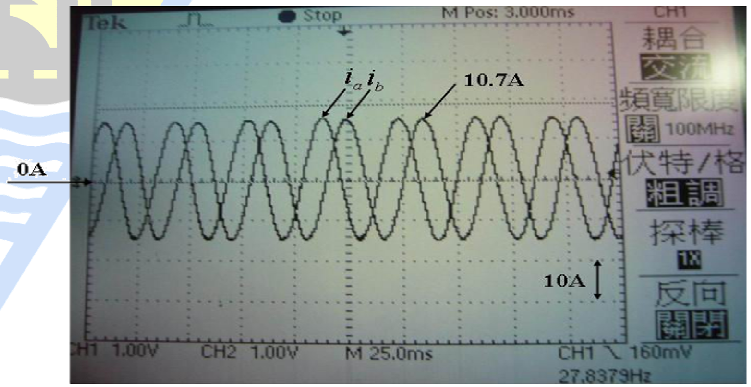


Experimentation

- 60rpm with load 25Ω







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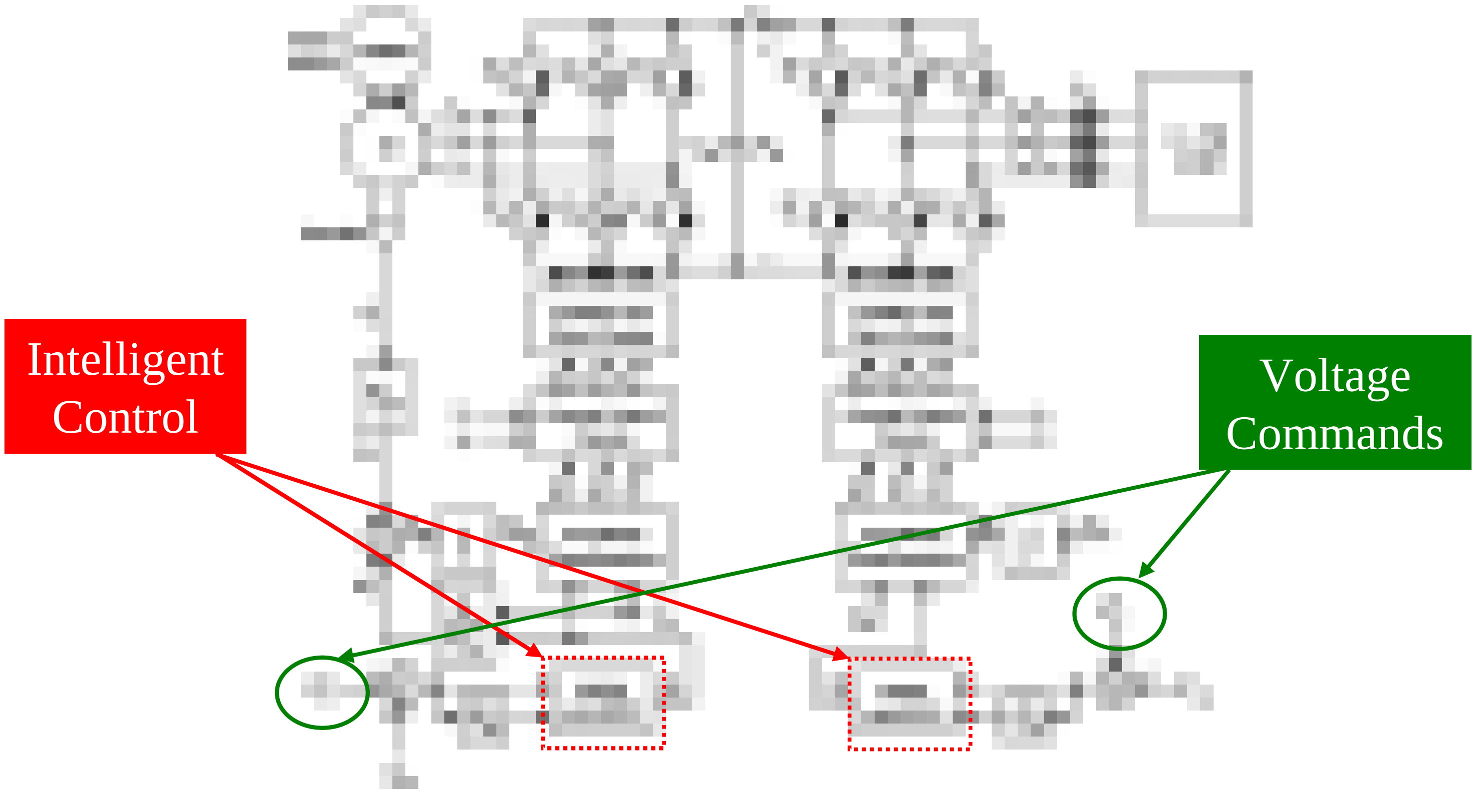
Design Case 3 - Intelligent Control for Induction Generator System

- Indirect field-oriented control induction generator system



Why Use Intelligent Control to Replace Traditional Control?

- Do not require mathematical models and have the ability to approximate nonlinear systems.
- Supply on-line ability to turn the parameters efficiently.
- Radial Basis Function Network
  - Based on the biological receptive fields, the RBFN employs local receptive fields to perform function mappings.
  - The RBFN has a similar feature to the fuzzy system:
  - First, the output value is calculated using the weighted sum method.
  - Second, the number of nodes in the hidden layer of the RBFN is the same as the number of if-then rules in the fuzzy system.
  - Finally, the receptive field functions of the RBFN are similar to the membership functions of the premise part in the fuzzy system.
- Therefore, the RBFN is very useful to be applied to control the dynamic systems.

Radial Basis Function Network

- Structure of RBFN
  - *Layer 1: Input layer*

$$net_i^1(N) = x_i^1(N)$$

$$y_i^1(N) = f_i^1(net_i^1(N)) = net_i^1(N), \quad i = 1, 2$$

  - *Layer 2: Hidden layer*

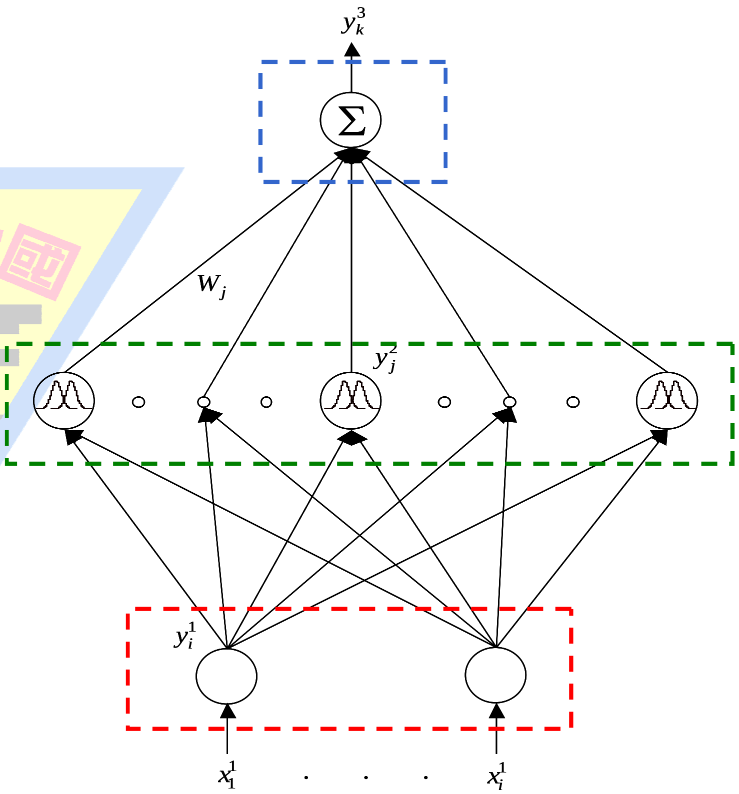
$$net_j^2(N) = -(\boldsymbol{X} - \boldsymbol{M}_j)^T \sum_j (\boldsymbol{X} - \boldsymbol{M}_j)$$

$$y_j^2(N) = f_j^2(net_j^2(N)) = \exp(net_j^2(N)), \quad j = 1, \ldots, 9$$

  - *Layer 3: Output layer*

$$net_k^3(N) = \sum_j W_j y_j^2(N),$$

$$y_k^3(N) = f_k^3(net_k^3(N)) = net_k^3(N), \quad k = 1$$



Radial Basis Function Network

- On-Line learning algorithm of RBFN
  - *Update law for weight*

$$\Delta W_j = -\eta_W \frac{\partial E}{\partial W_j} = -\eta_W \frac{\partial E}{\partial y_k^3}\frac{\partial y_k^3}{\partial net_k^3}\frac{\partial net_k^3}{\partial W_j} = \eta_W \delta_k y_j^2$$

$$W_j(N+1) = W_j(N) + \Delta W_j(N)$$

  - *Update law for mean*

$$\Delta m_{ij} = -\eta_m \frac{\partial E}{\partial m_{ij}} = -\eta_m \frac{\partial E}{\partial net_k^3}\frac{\partial net_k^3}{\partial y_j^2}\frac{\partial y_j^2}{\partial m_{ij}} = \eta_m \delta_k W_j y_j^2 \frac{2(x_i^1 - m_{ij})}{(\sigma_{ij})^2}$$

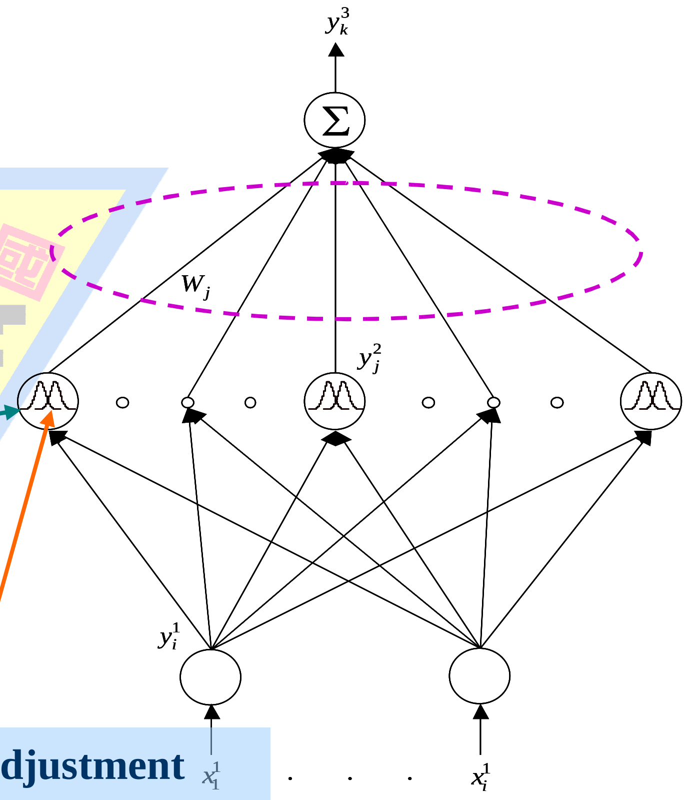
$$m_{ij}(N+1) = m_{ij}(N) + \Delta m_{ij}(N)$$

  - *Update law for standard deviation*

$$\Delta \sigma_{ij} = -\eta_\sigma \frac{\partial E}{\partial m_{ij}} = -\eta_\sigma \frac{\partial E}{\partial net_k^3}\frac{\partial net_k^3}{\partial y_j^2}\frac{\partial y_j^2}{\partial \sigma_{ij}} = \eta_\sigma \delta_k W_j y_j^2 \frac{2(x_i^1 - m_{ij})^2}{(\sigma_{ij})^3}$$

$$\sigma_{ij}(N+1) = \sigma_{ij}(N) + \Delta \sigma_{ij}(N)$$

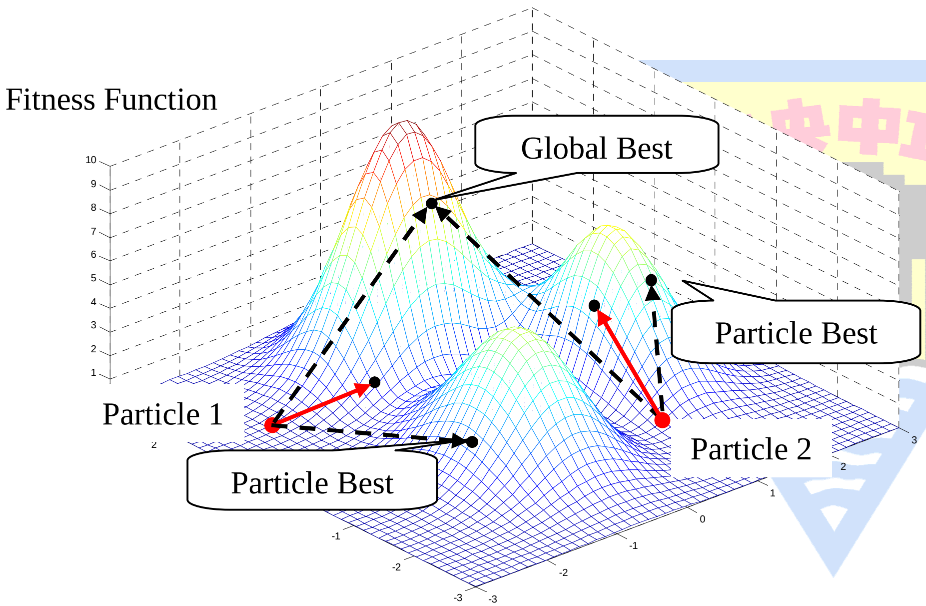
Learning Rates Adjustment Using IPSO

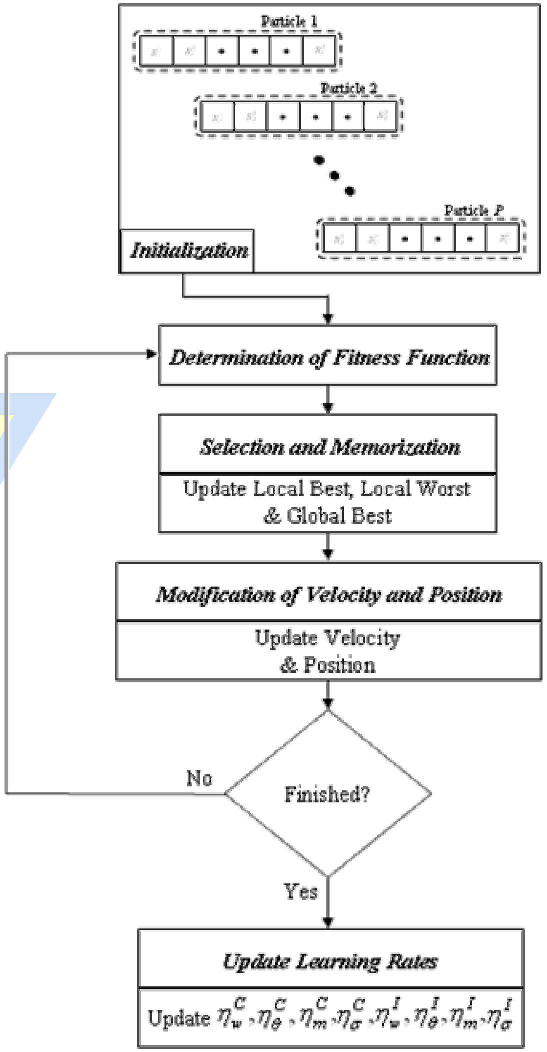


Improved Particle Swarm Optimization Algorithm (IPSO)

- PSO is an algorithm based on a school of flying birds to simulate the behavior of a swarm as a simplified social system.
- In the PSO, the individuals are evolved by cooperation and competition among the individuals through generations instead of using genetic operators.
- Each individual is named as a "particle" which represents a potential solution to a problem. Each particle is treated as a point in a D-dimensional space.
- The IPSO is adopted to adapt the learning rates in the backpropagation process of the RBFNs to improve the learning capability.

The Procedure of IPSO Algorithm





Learning Rates Adjustment Using IPSO

1) *Initialization*

Randomly generates the initial trial vectors $R^d_i(N)$, which indicates the possible solutions for the learning.

2) *Determination of Fitness Function*

For each trial vector, a fitness value should be assigned and evaluated.

$$FIT = \frac{1}{0.1 + abs(V_{dc} - V_{dc}^*) + abs(V_{uv} - V_{uv}^*)}$$

3) *Selection and Memorization*

Each particle memorizes its own fitness value and chooses the maximum one that is the best so far as $Pbest^d_i$. The particle with the best fitness value among *Pbest* is set to be the global best *Gbest*.

4) *Modification of Velocity and Position*

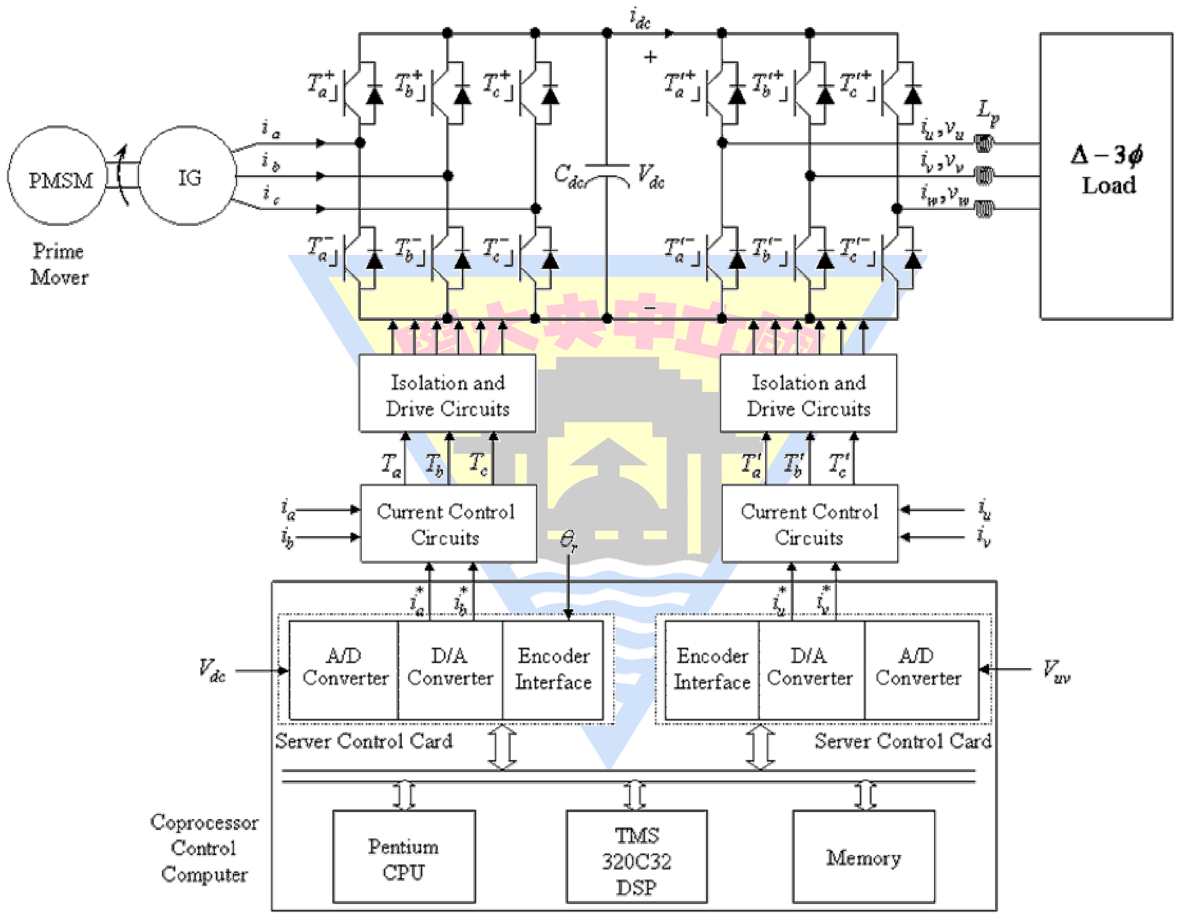
$$v_i^d(N+1) = wv_i^d(N) + c_1 \times rand() \times (Pbest_i^d - R_i^d(N)) + c_2 \times rand() \times (Gbest^d - R_i^d(N))$$

$$R_i^d(N+1) = R_i^d(N) + v_i^d(N+1)$$

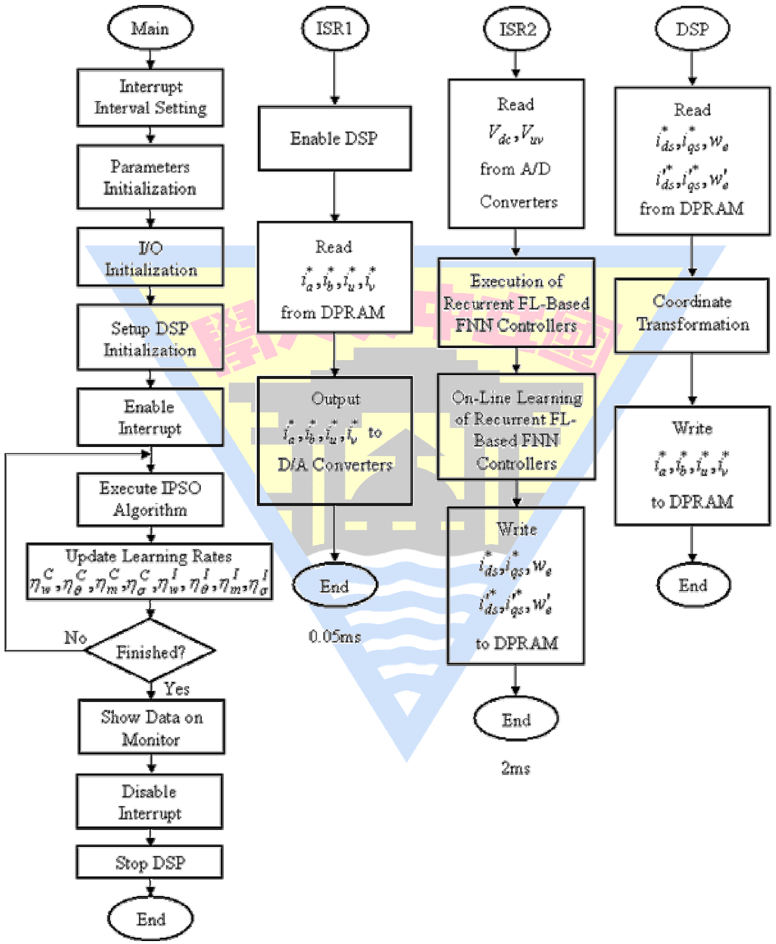
5) *Stopping Rule*

Repeat step 1) to 4) until the best fitness value for the *Gbest* is obviously improved or a set count of the generation is reached. The $R^d_i(N)$ with the best fitness value among *Pbest* is set to be the global best *Gbest*.

Coprocessor Control Computer for RBFN Controlled IG System



Flowcharts of RBFN Controlled IG System



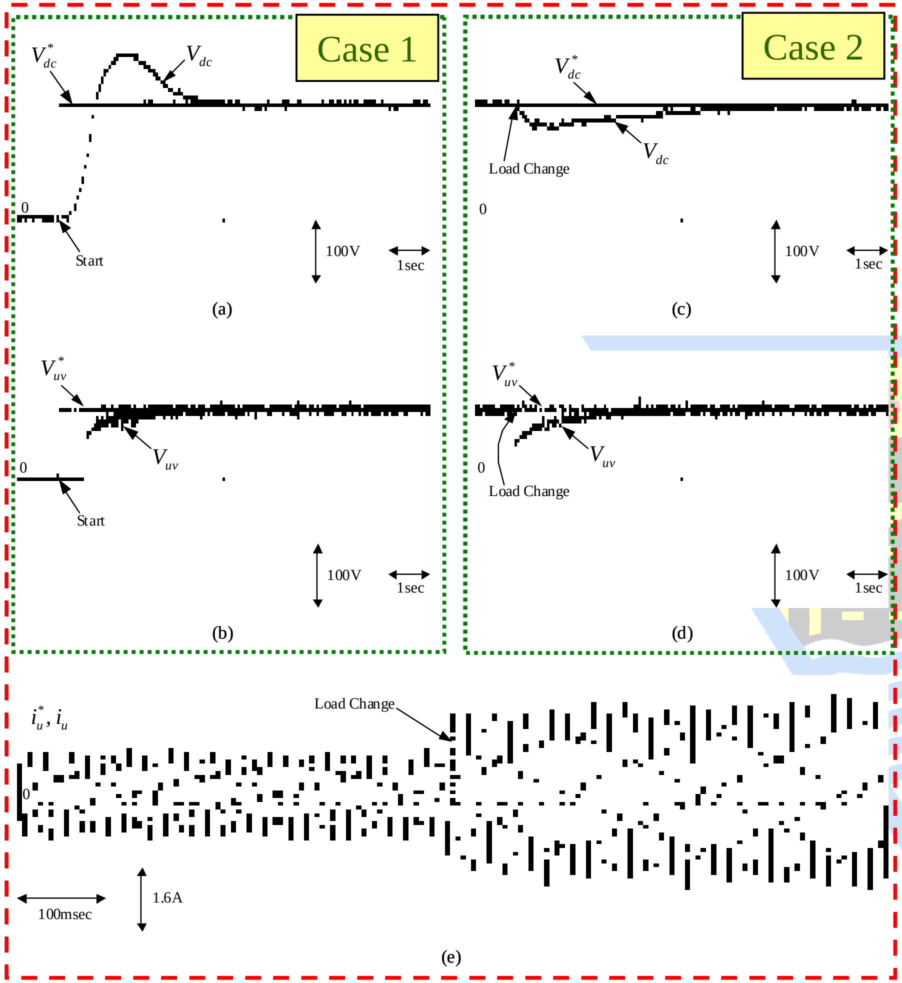
Experimental Setup

- In order to verify the control performance of the proposed RBFN controller with IPSO, four cases are tested to demonstrate the control performance.

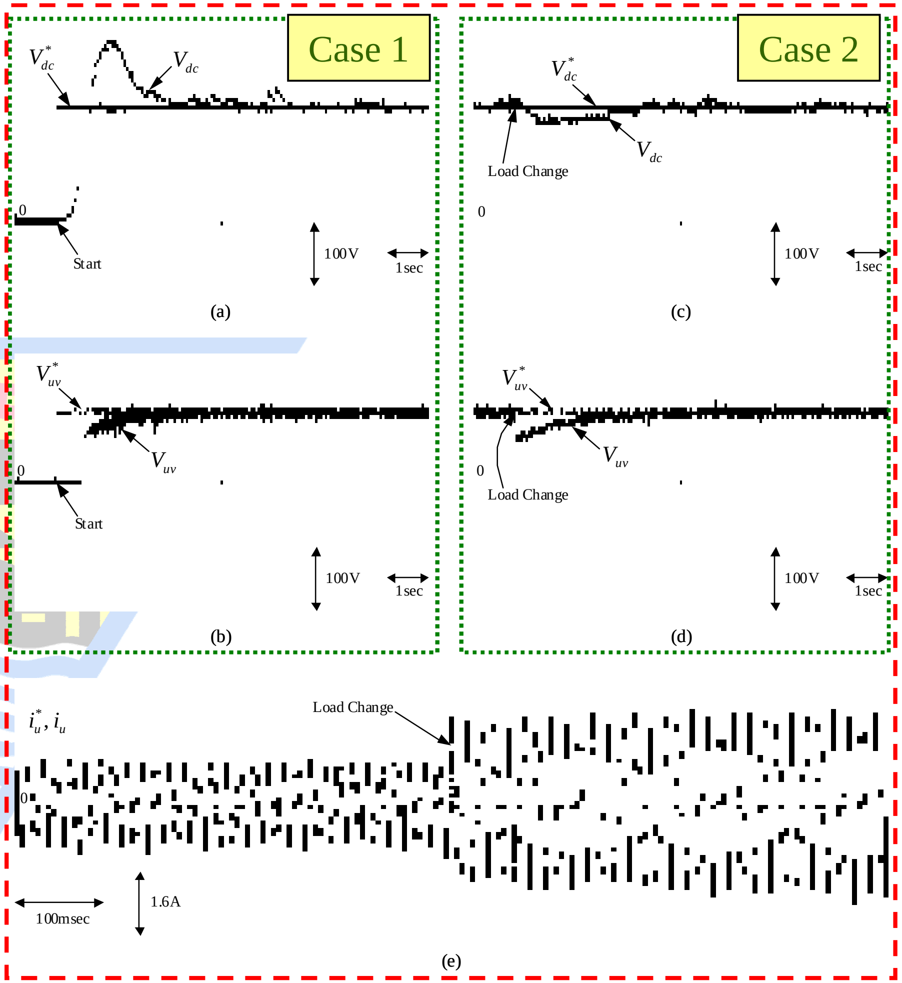
	Wind speed ω_m^*	△ connection three-phase load	V_{dc}^*	V_{uv}^*
Case 1	Fixed (1200rpm or 1600rpm)	66.6Ω	180V	110V
Case 2	Fixed (1200rpm or 1600rpm)	After both voltage commands are reached at Case 1, change 66.6Ω→22.2Ω.	180V	110V
Case 3	Varied (1200rpm → 1600rpm)	22.2Ω or 66.6Ω	180V	110V
Case 4	Varied (1600rpm → 1200rpm)	22.2Ω or 66.6Ω	180V	110V

- The integral-proportional (IP) controlled IG system are also discussed for the comparison of the control performance.

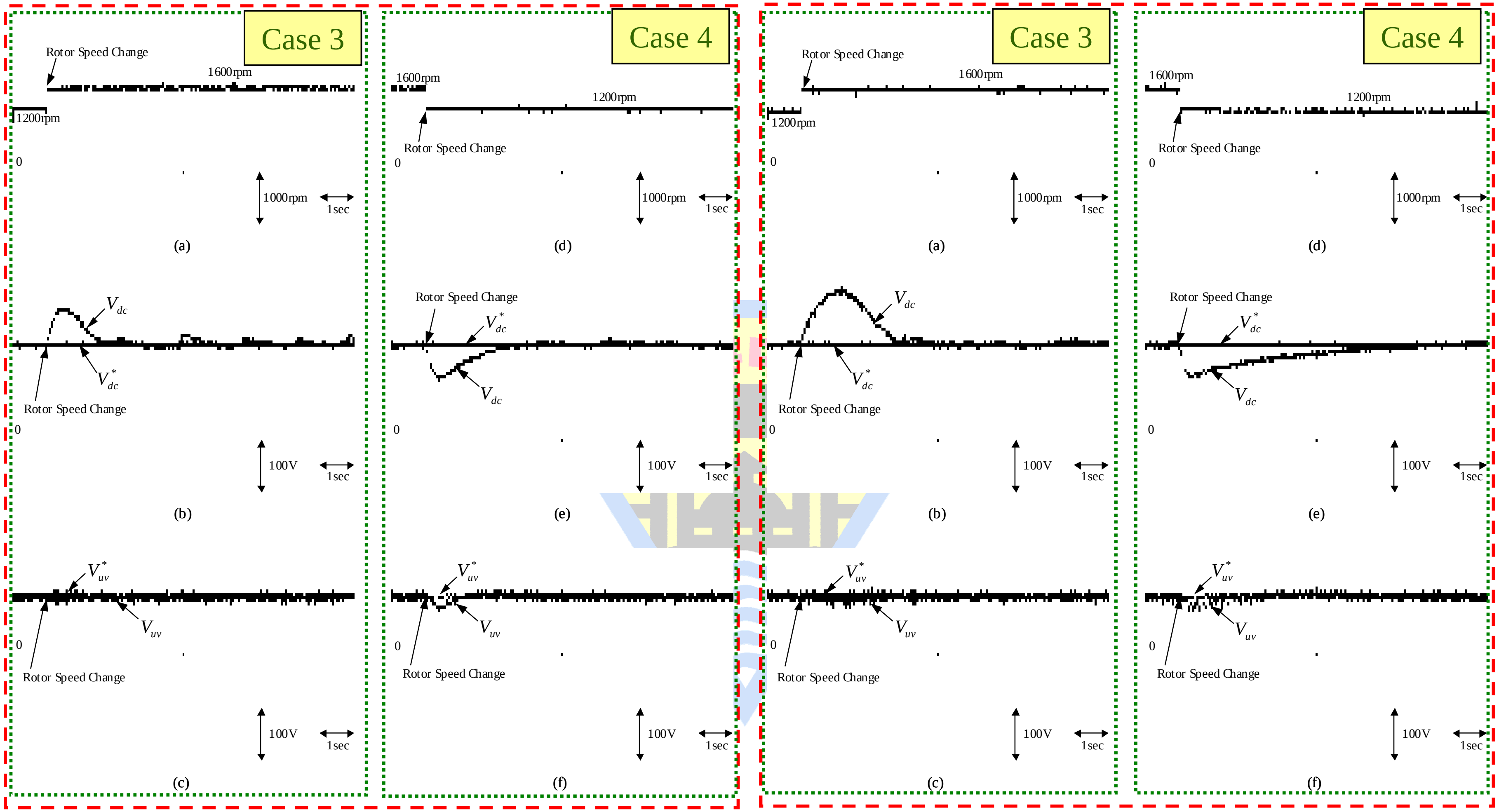
Experimental Results of IP Controller



1200rpm



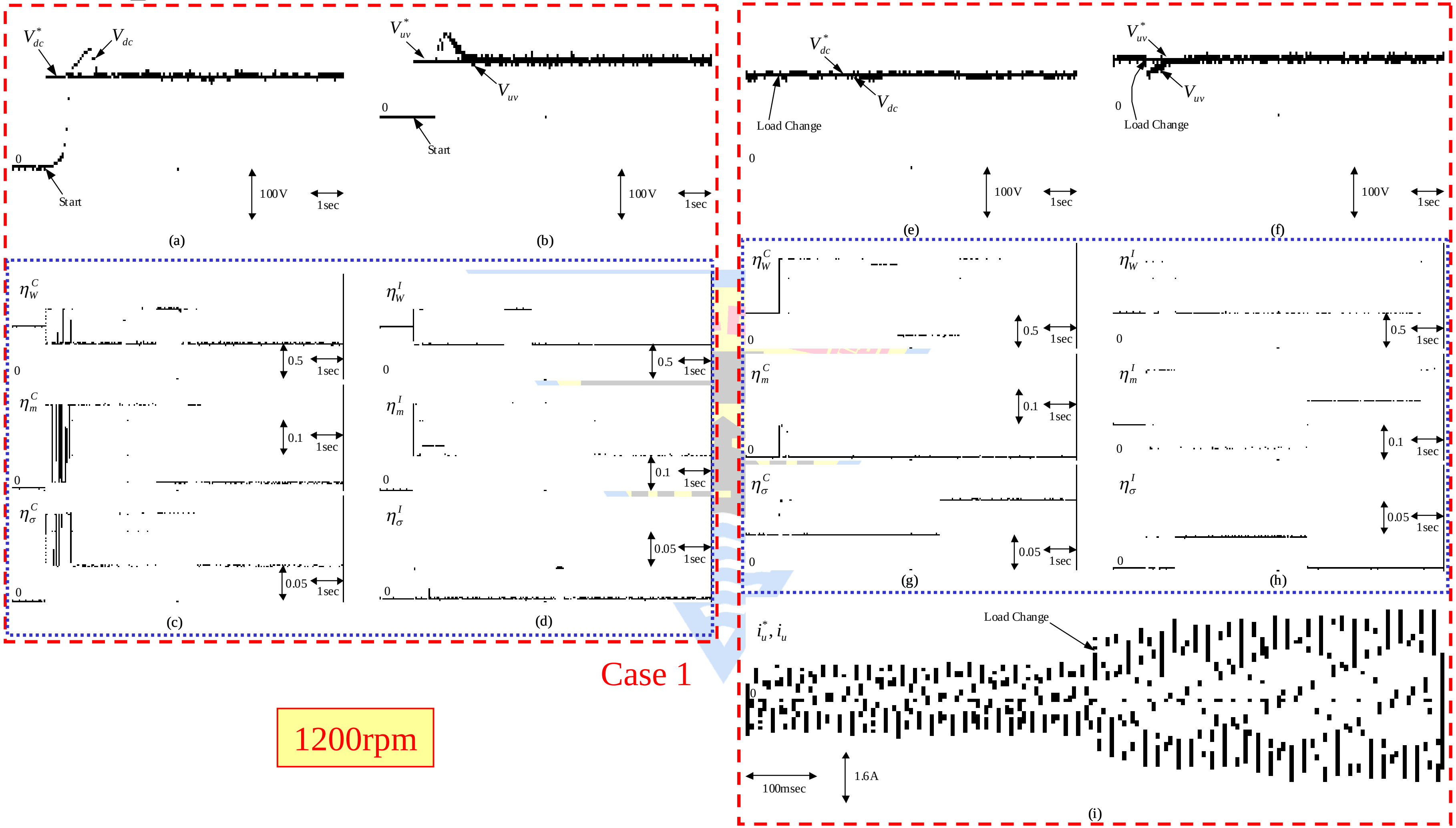
1600rpm


Case 3
Rotor Speed Change
1600rpm
1200rpm
0
1000rpm
1sec
(a)
V_{dc}
V_{dc}^*
Rotor Speed Change
100V
(b)
V_{uv}^*
V_{uv}
(c)
Case 4
1600rpm
1200rpm
Rotor Speed Change
(d)
(e)
(f)
Case 3
Case 4

66.6 Ω

22.2 Ω

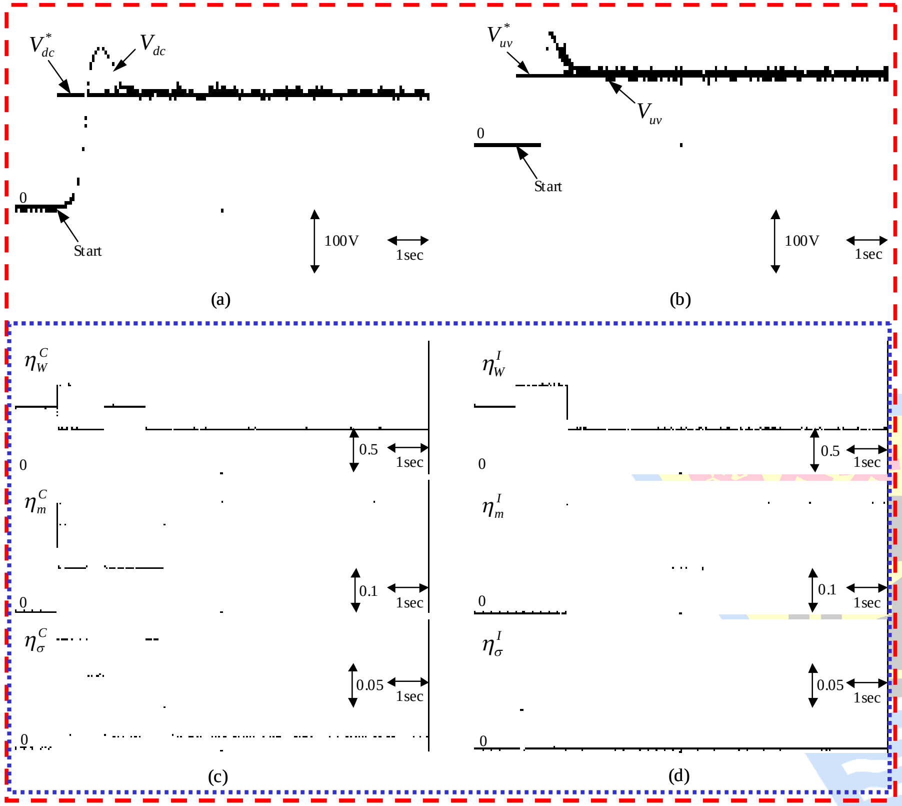
Experimental Results of RBFN Controller



Case 1

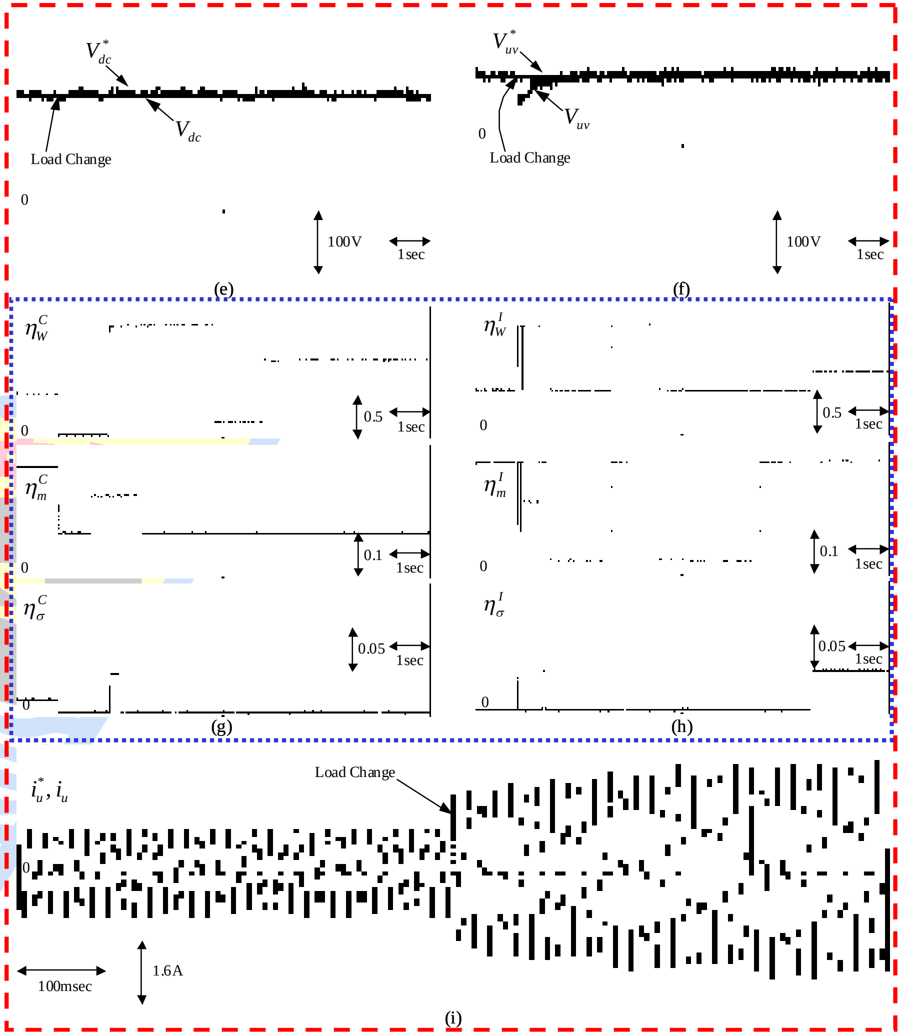
1200rpm

Case 2

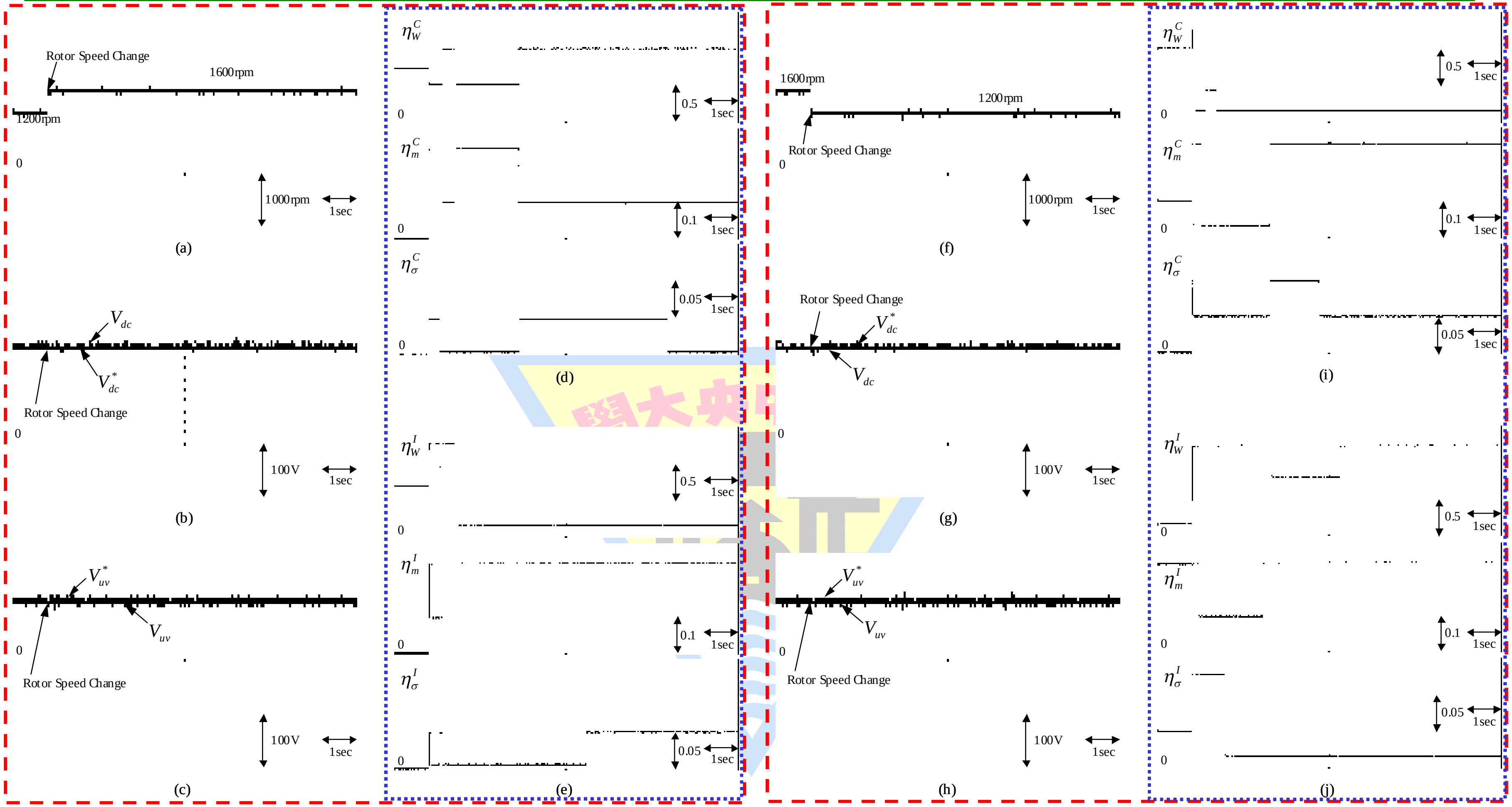


Case 1

1600rpm



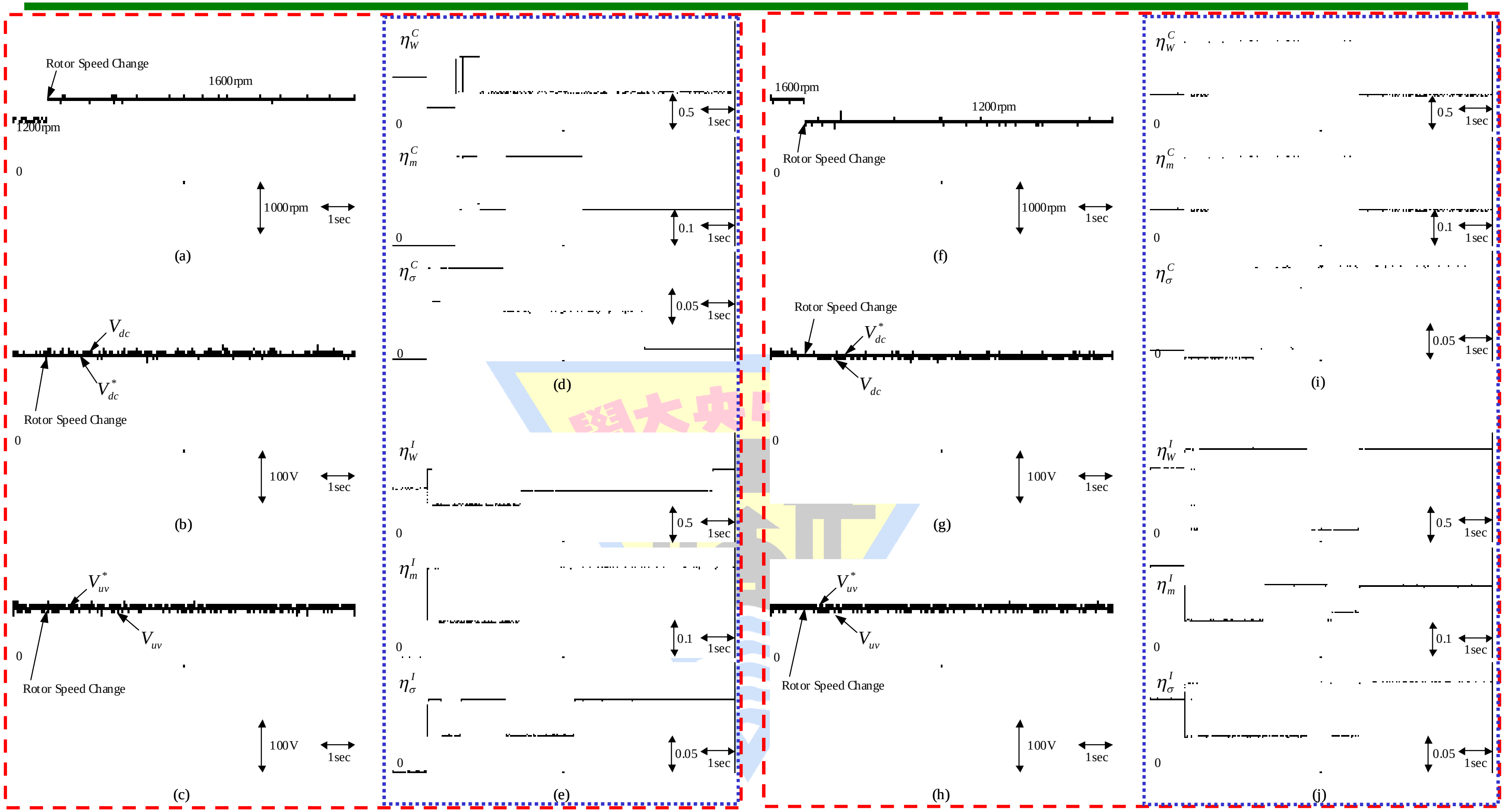
Case 2



Case 3

Case 4

66.6 Ω



Case 3

Case 4

22.2 Ω

Thanks for your attention!

Any question?