# State of Fuel Cell Power System Research and Applications


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July, 2010

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# 1. Introduction

- ✓ Fuel cell is an electrochemical device that converts chemical energy directly into electrical energy (DC power)

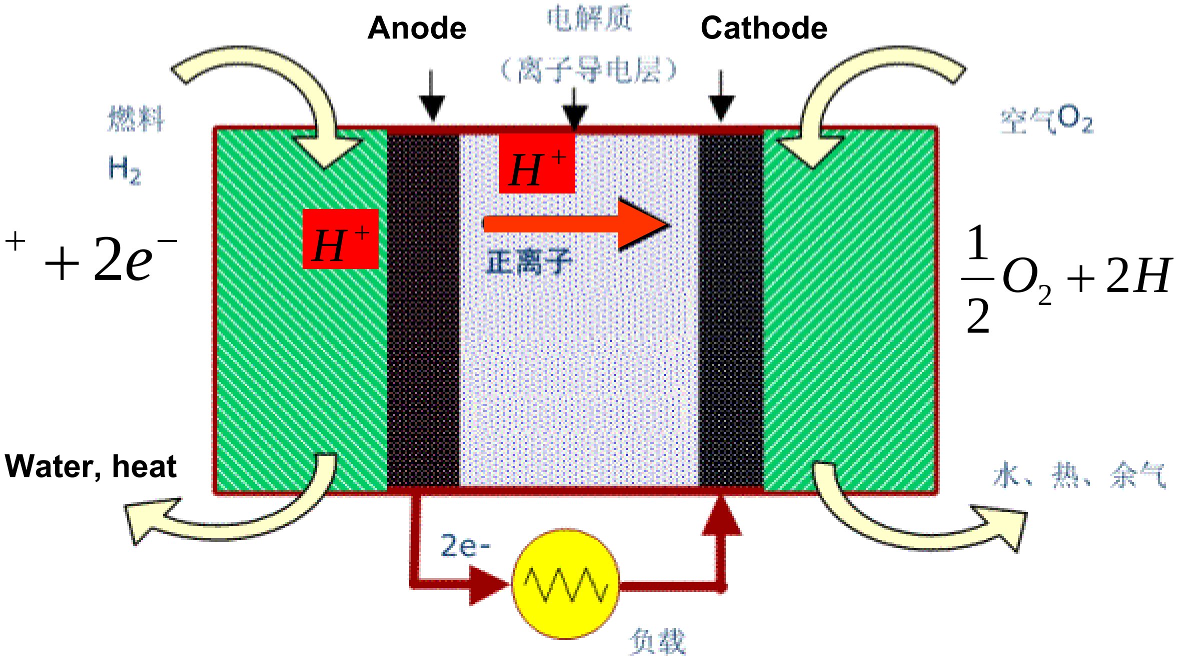
- ✓ Advantages
  - ✓ Low emission
  - ✓ High conversion efficiency(40%-60%)
  - ✓ Cogeneration for further increasing the energy usability
  - ✓ Potential to be more reliable and longer expectancy
  - ✓ Low noise( basically stationary equipment)
  - ✓ High power density

# Fuel cell types

- Proton exchange membrane fuel cell (PEMFC)
- Solid Oxide Fuel Cell (SOFC)
- Molten Carbonate Fuel Cell (MCFC)
- Phosphoric Acid Fuel Cell (PAFC)
- Alkaline

# Proton exchange membrane fuel cell (PEMFC)

$$H_2 \rightarrow 2H^+ + 2e^-$$

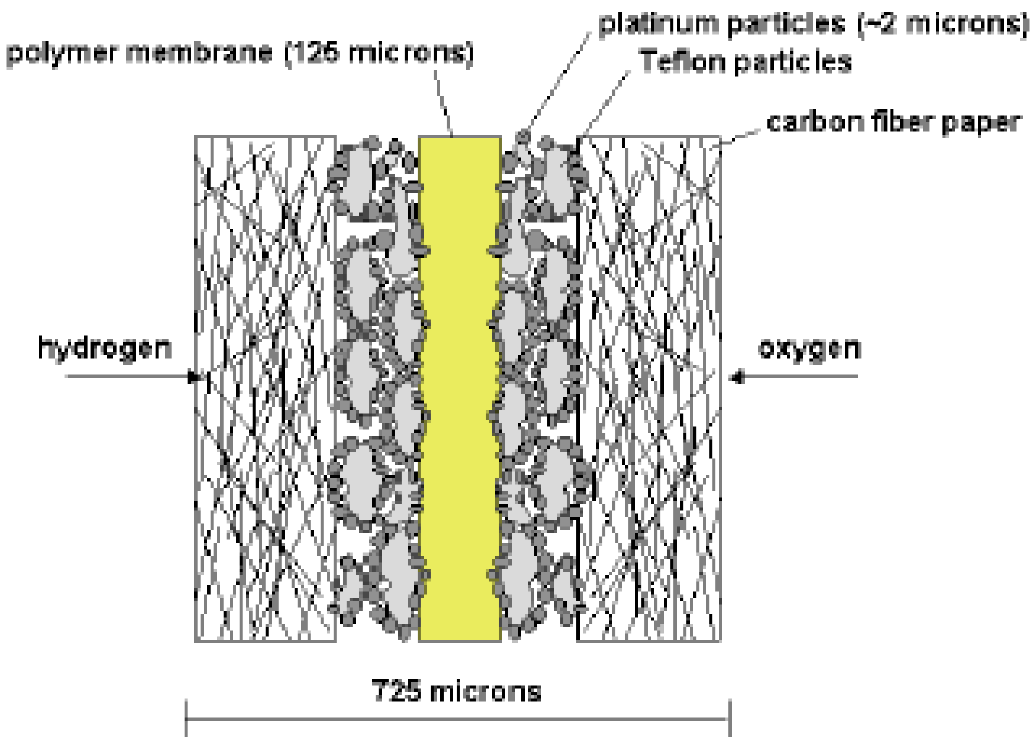



$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

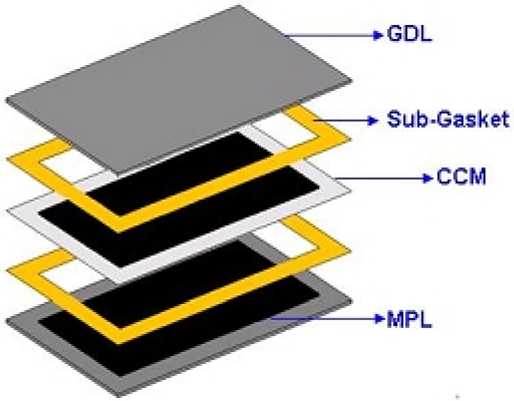
- Lower operating temperature(50-70°  )
- Higher power density
- Catalyst: Platinum，0.3 mg/cm2

# Structure of proton exchange membrane

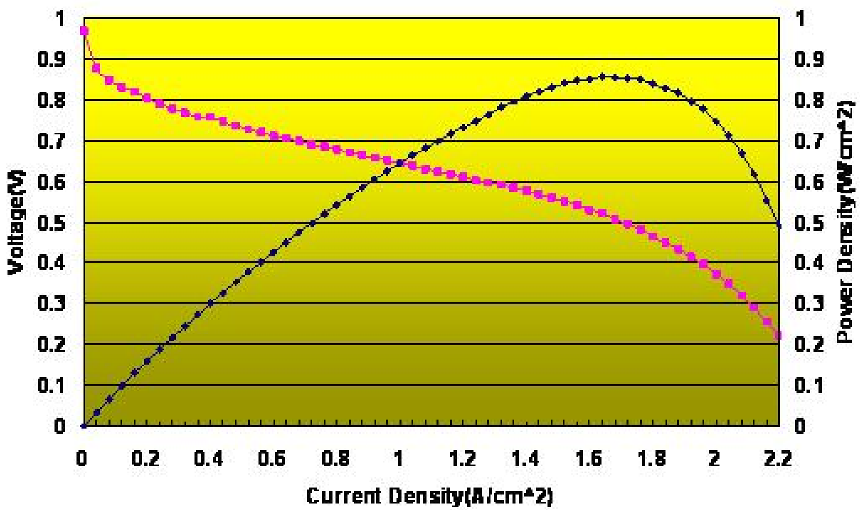



Only proton and water can pass the membrane

# Membrane electrode assembly (MEA) of PEMFC

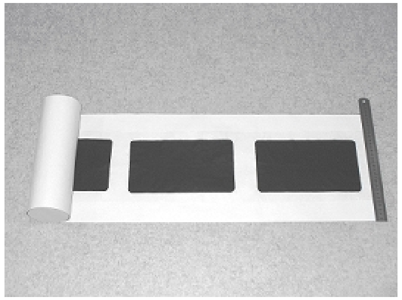



Sketch map




V vs. J and P vs. J

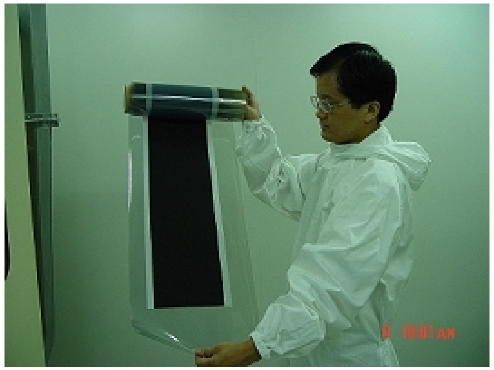
- ✓ Technology: Membrane electrode assembly (MEA) based on Catalyst Coated Membrane (CCM).
- ✓ The bonding strength of the catalyst layer and PEM are increased.
- ✓ Thickness of Catalyst layer <5um
- ✓ Pt density < 0.4 mg/$cm^2$



TEST CONDITION

- Cell Temp:70℃
- Ambient Pressure
- 100%RH An and Ca
- $H_2$/Air Stoich:1.5/2.5
- Single Serpentine

MEA based CCM



•by WUT New Energy Co., Ltd

# PEMFC stack


@Shanghai Shen-Li High Tech Co., Ltd

| | |
|---|---|
| **Performance** | Net power Output: 55kW<br>Maximum stable Power Output: 60kW<br>Voltage★: 380-530V<br>Current★: 0-160A<br>Efficiency: >50%(Fuel to DC power) |
| **Operating Environment** | Environment Temperature: 0-55℃<br>Working Temperature: 60-80℃<br>Pressure: Ambient air and low pressure |
| **Physical** | Dimensions( L × W × H): 1000mm×950mm×130mm<br>Weight: 244Kg |
| **Emission** | Emission Noise: ≤60dB |
| **Fuel Type:** | Gaseous Hydrogen<br>Storage options: Compressed gas cylinders |

| | |
|---|---|
| **Maximum power Output** | Net : 110kW |
| **Maximum current Output** | 500 A |
| **Rating voltage output** | 360 V |
| **Stack Dimensions ( L × W × H):** | 890mm×580mm×680mm |
| **Released by** | Xinyuan Dynamic Co., Ltd & Dalian Institute of Chemical Physics, China Academy of Science |
| **Application** | Fuel cell city bus |
| **Release data** | 2003 |

# SOFC planar and tubular cell

Planar Cell

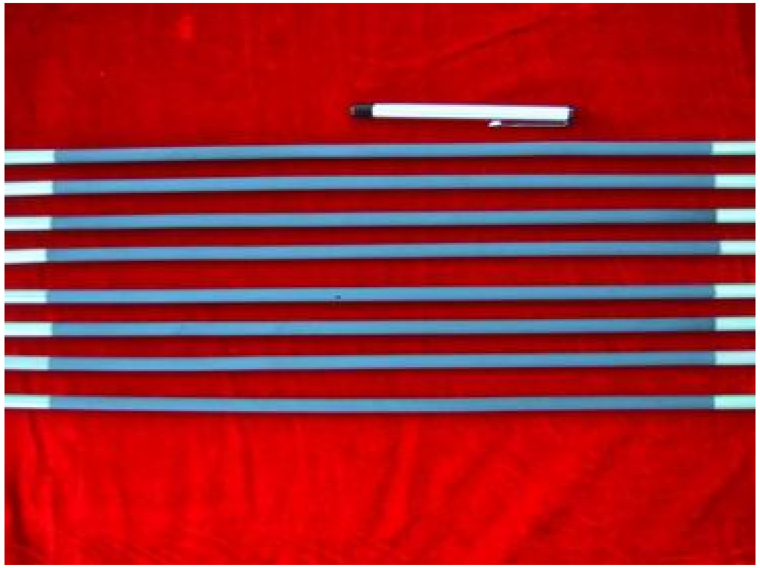
- ✓ Effective area: 10cm×10cm

Planar cell stack

- ✓ Maximum output power: 616W
- ✓ Power density: >500mW/cm$^2$

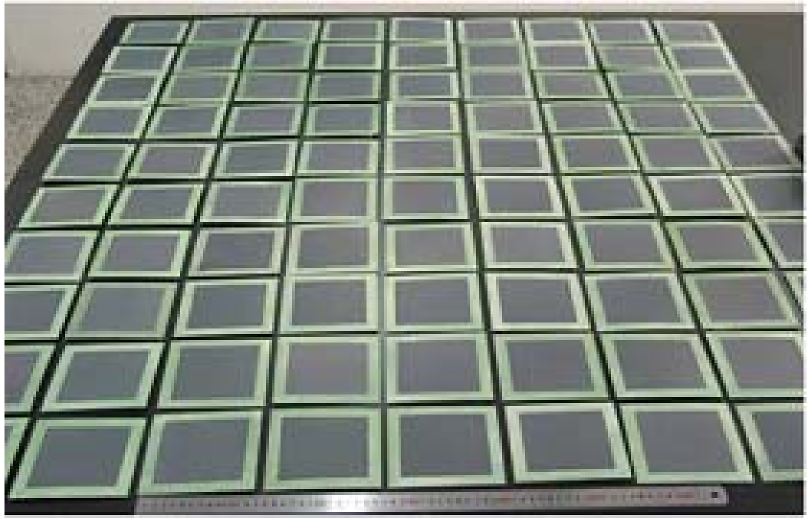
Tubular Cell

- ✓ Dimension: Φ8mm×500mm
- ✓ Maximum output power : >25W@800 ℃
- ✓ Fuel efficiency : 60%-70%



@Developed by Dalian Institute of Chem. Phys. , Chinese Academy of Science

# SOFC cell production line

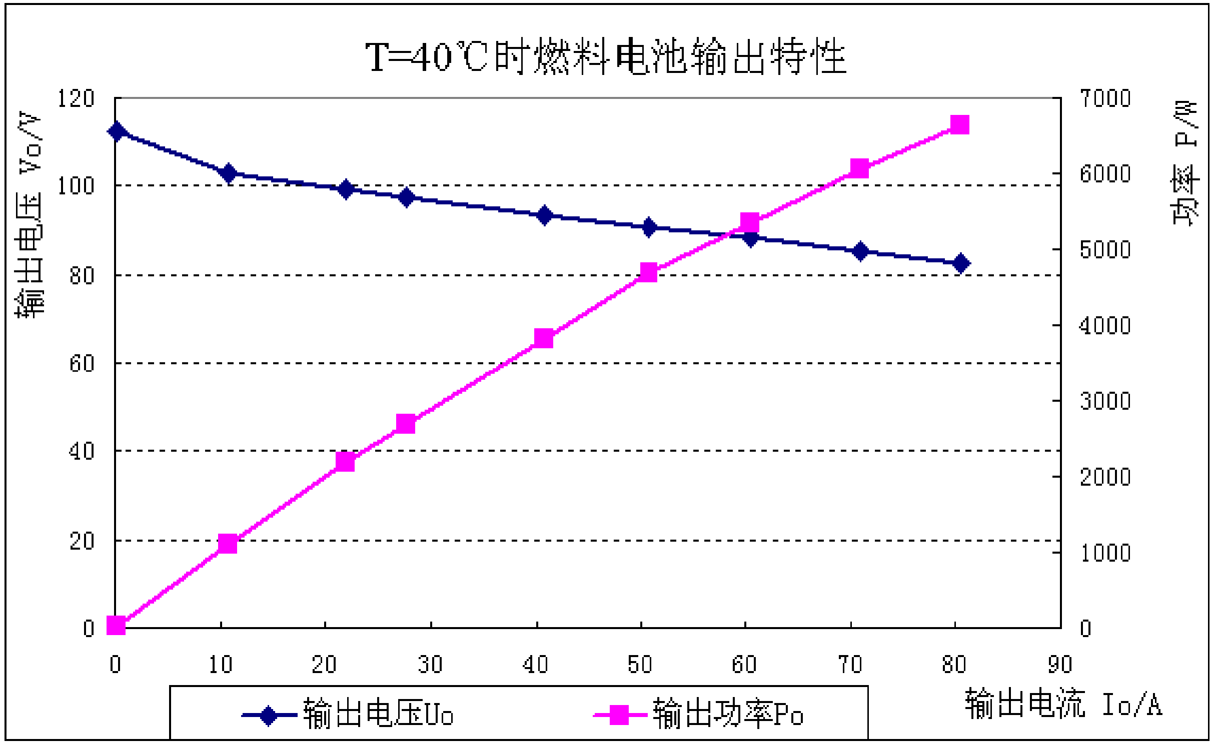


- ✓ Annual production capacity of 20,000 pcs.
- ✓ News released on 2009-3-11

# Players of SOFC

| Institute | Location | Prototype | Comments |
|---|---|---|---|
| Dalian Institute of Chem. Phys. , Chinese Academy of Science | Dalian | SOFC cell | Both Planar cell and Tubular Cell |
| Ningbo Institute of Material Tech. & Engineering, Chinese Academy of Science | Ningbo | SOFC cell | First planar SOFC cell production line in China |
| Shanghai Institute of Ceramics, Chinese Academy of Science | Shanghai | SOFC cell and stack | Planar cell and stack |

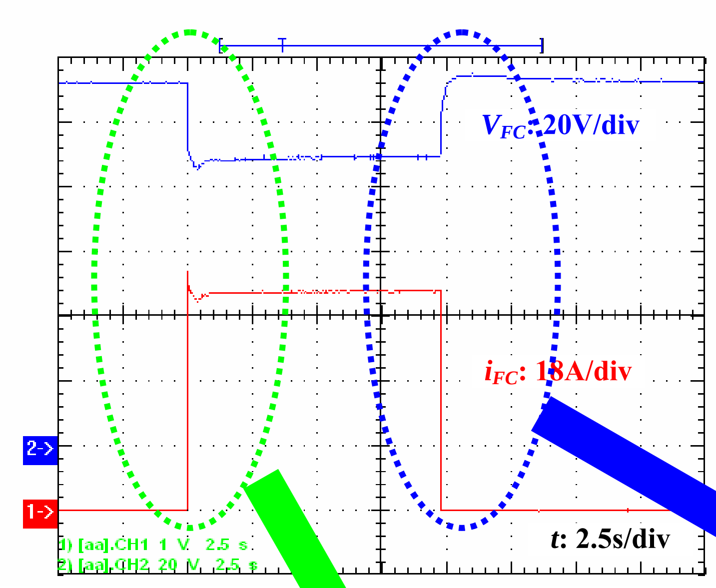
# 2. PEMFC Output characteristics (static)




**Specifications:**
**10kW rated power**
**Rated voltage:100V**
**Rated current:100A**
**Stack has 132 cells**

- **PEM Fuel cell stack is composed of a large number of fuel cells**
- **Output voltage varies with the increase of load**
- **Post regulator is required in applications**

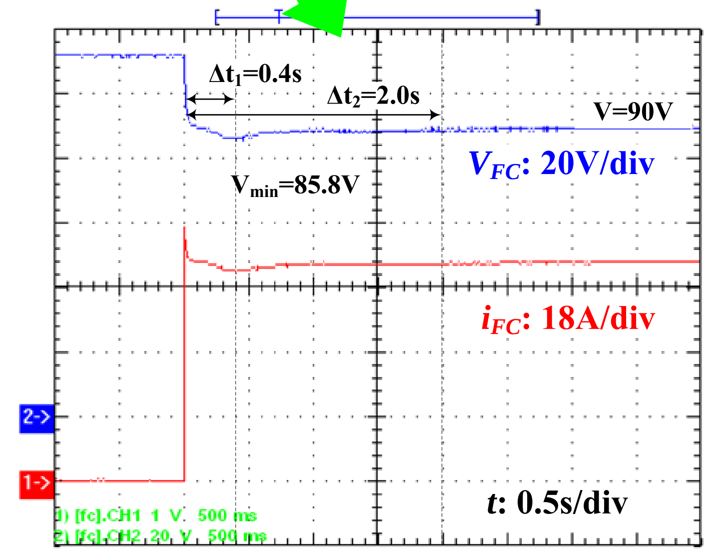
# PEMFC Output characteristics (dynamics)



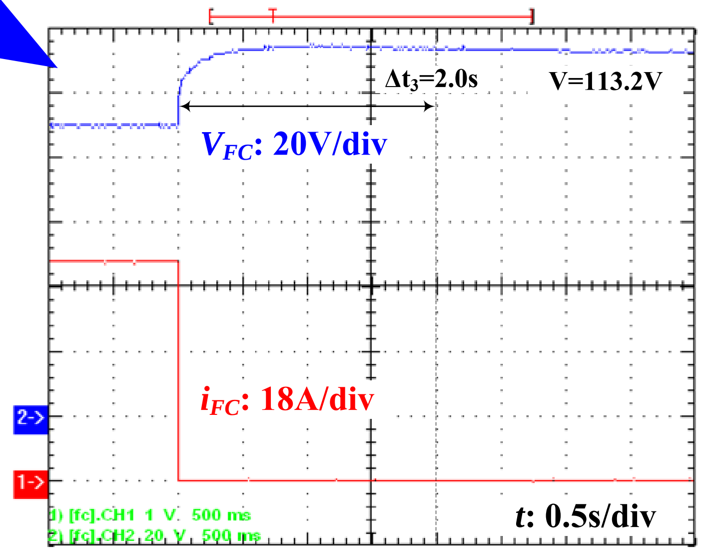

（0→5kW→0）

Load step up or step down:

- ✓ Voltage settle time: 2s




**time constant: $\tau_{FC}=\Delta t_2/3=0.67s$**



# PEMFC characteristics and Power management

**PEMFC poor output characteristics**

- Terminal V-A static characteristics is soft. Output voltage varies in a larger range
- Delay exists due to the chemical reaction process and mechanical actuator such as fans

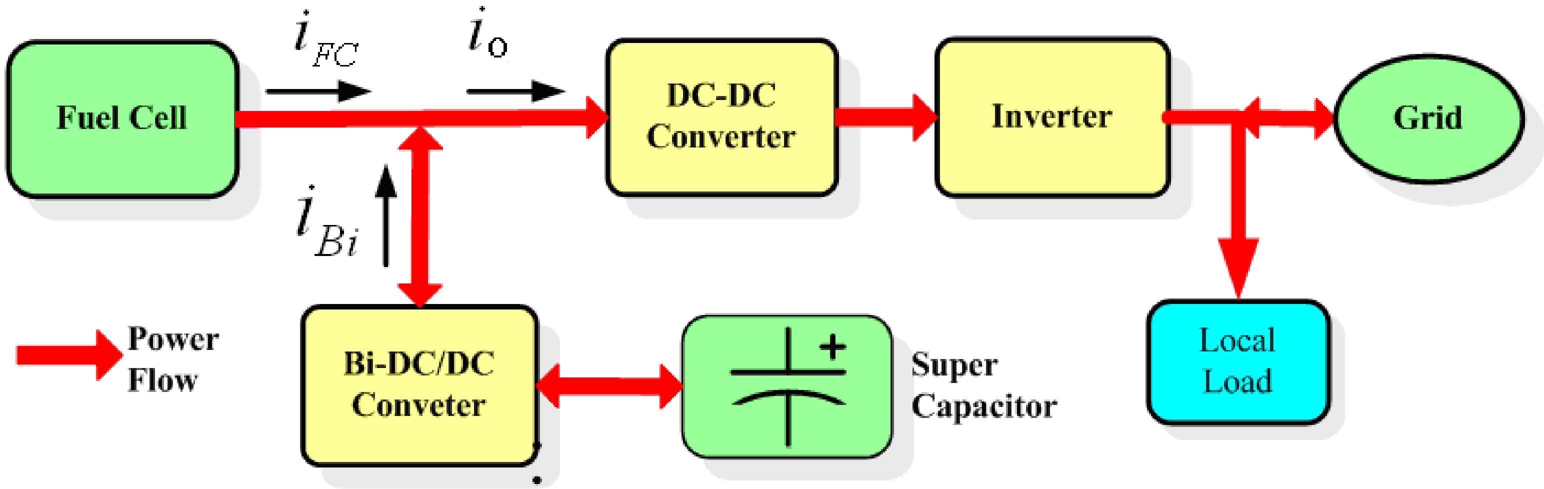
**Safety requirement to PEMFC stack**

- Frequently load variation will shorten expectancy of the mechanical actuators
- Fast load variation may cause the operation parameters such temperature and humidity deviate away from limited range, which may damage the membrane.

FC output characteristics is not compatible to the load requirement

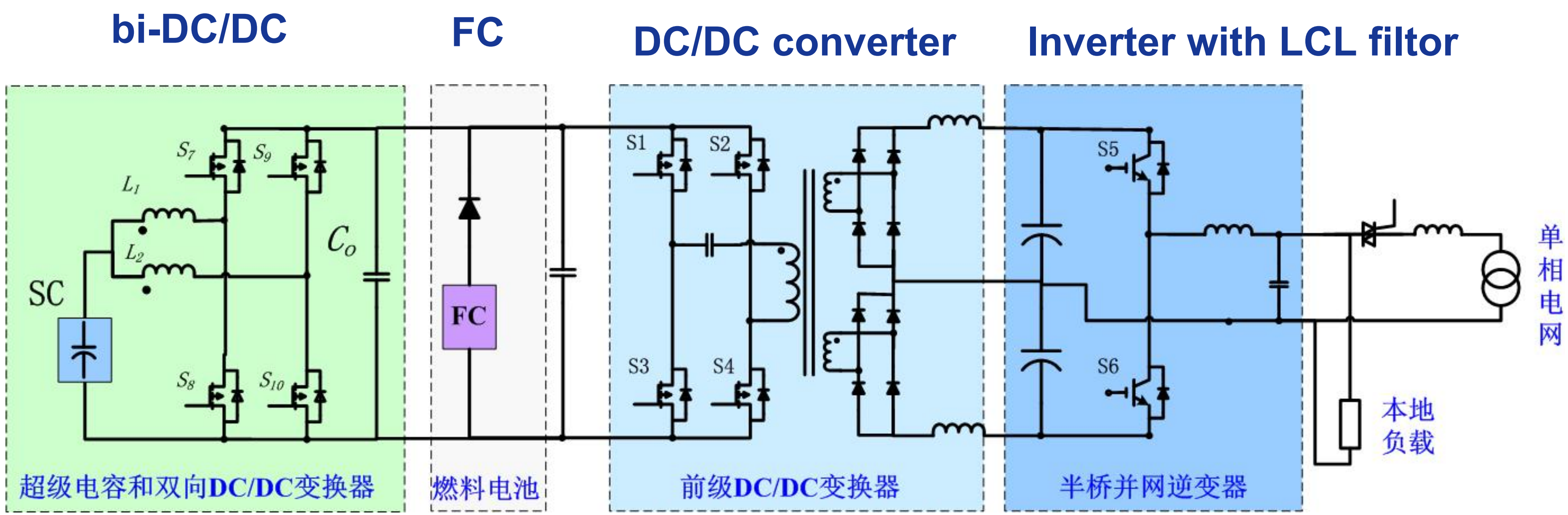
Power management is needed to meet both the PEMFC and load requirements

# 3. PEMFC power conversion system



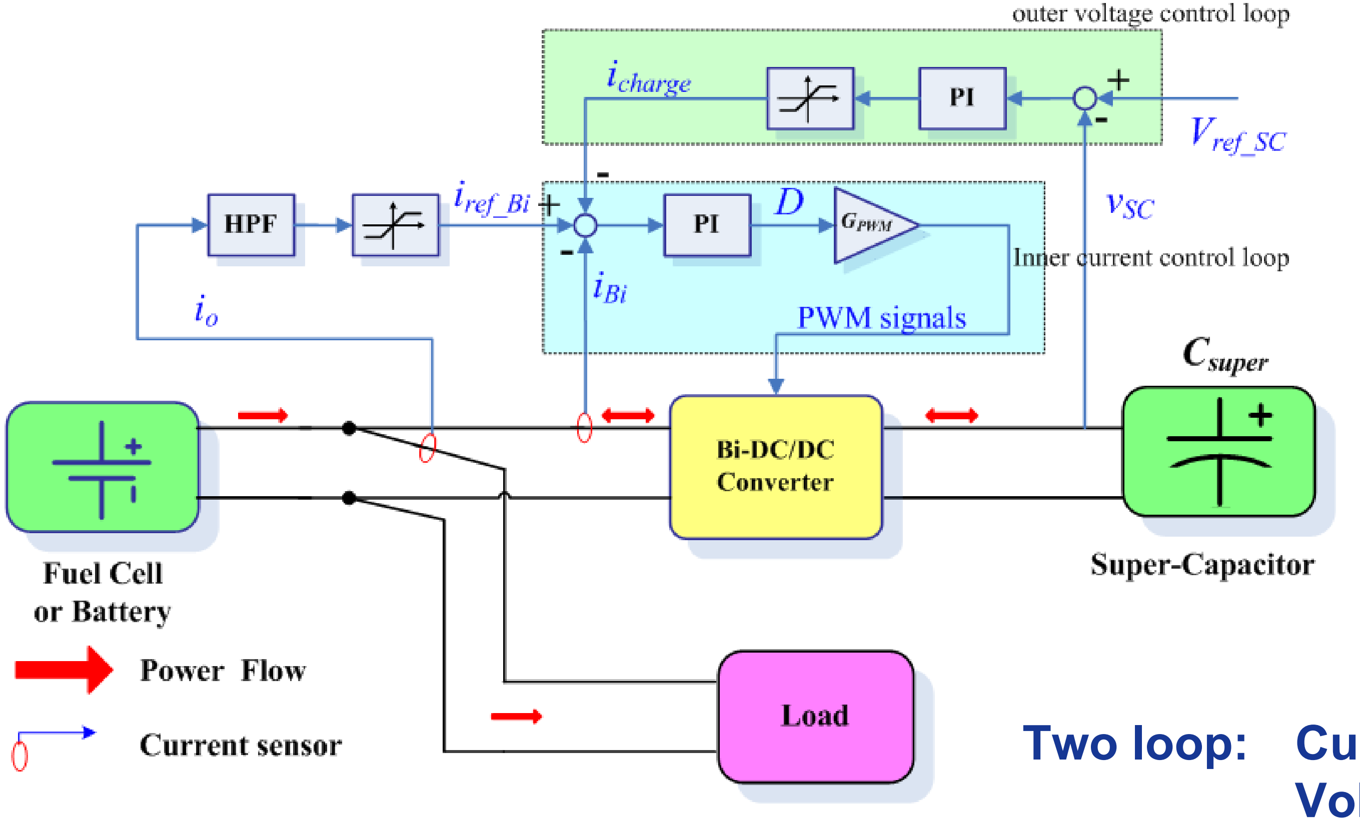

- ✓ Two stages
- ✓ Front end DC/DC converter: voltage step up/down, high frequency isolation
- ✓ Inverter and Gird interface control
- ✓ Bi-directional DC/DC converter with ultra-capacitor for power management: pulse power source or sink
- ✓ On-grid or stand-alone

# 5kW PEMFC power system structure




- ✓ Front end DC/DC converter: ZVS Full bridge phase shifting converter
- ✓ Inverter with LCL filter
- ✓ Interleaving bi-directional DC/DC converter

# 4. Energy management



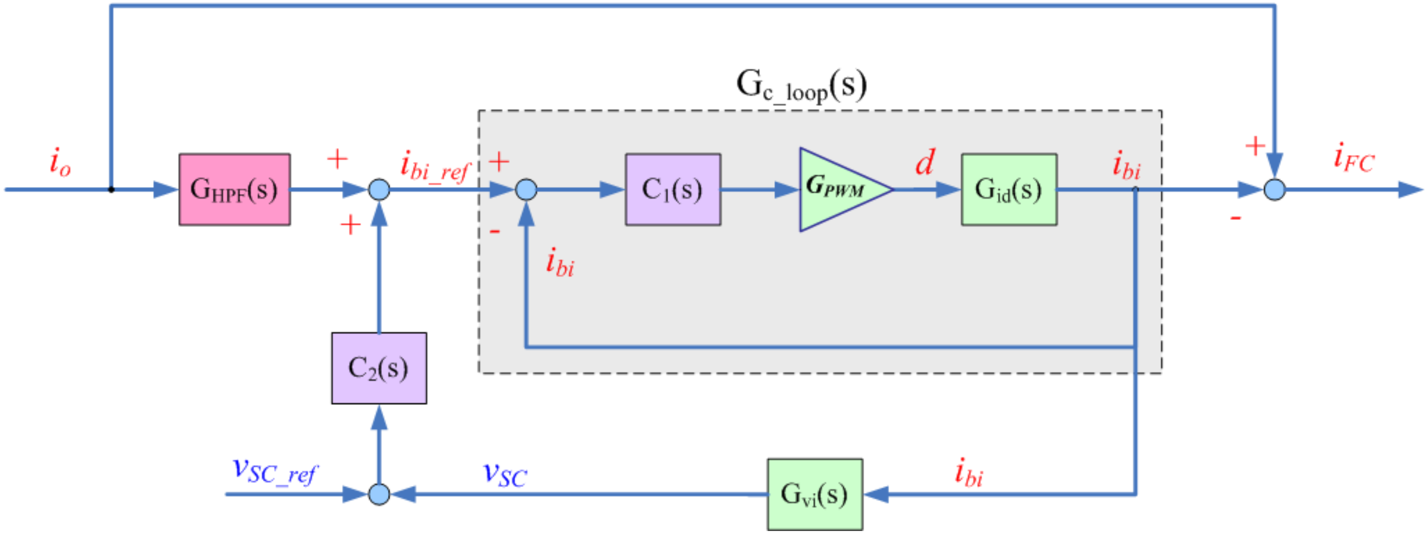

**Two loop: Current loop**
**Voltage loop**

Function of the energy management:

① Power management: supply pulsed power to satisfy load dynamic requirement

② Energy management: control ultra-capacitor to keep its stored energy in the state which is ready for charging or discharging

# Control diagram




- ✓ $G_{HPF}(s)$ : high pass filter
- ✓ $C_1(s)$ : current controller
- ✓ $G_{PWM}$ : gain of PWM modulator
- ✓ $G_{id}(s)$ : D to bi-directinal DC/DC converter output current transfer function
- ✓ $G_{c\_loop}(s)$ : current loop transfer function
- ✓ $G_{vi}(s)$ : bi-directinal DC/DC converter output current to ultra-cap voltage transfer function
- ✓ $C_2(s)$ : voltage controller

- ✓ Load to fuel cell terminal current transfer function

$$G_C(s) = \frac{i_{FC}(s)}{i_o(s)} = 1 - G_{HPF}(s)$$

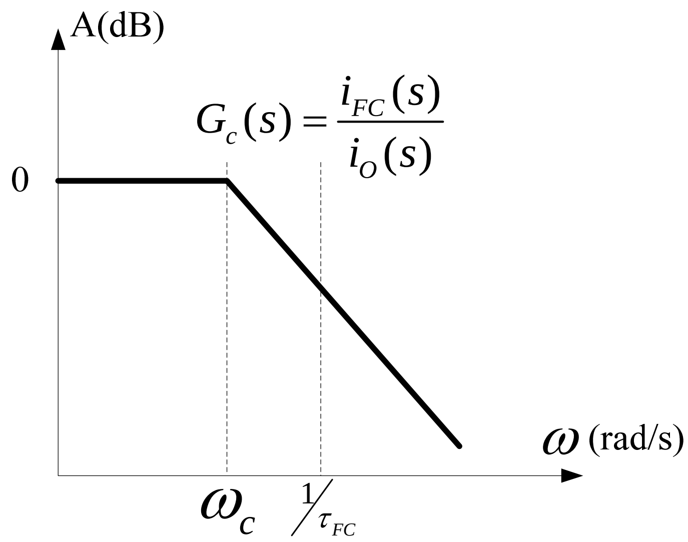
- ✓ Low pass characteristics is expected so that FC only output low frequency current

# $G_c(s)$的设计

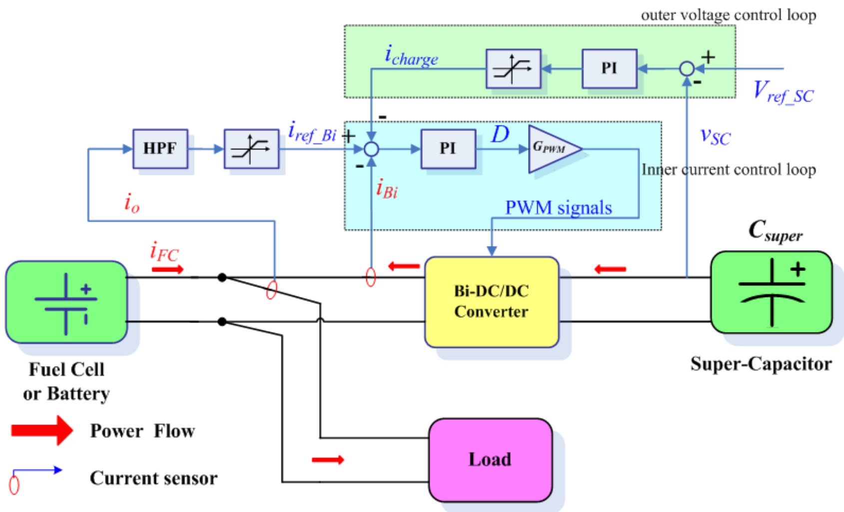
$$G_C(s) = \frac{i_{FC}(s)}{i_o(s)}$$

- ✓ 0dB gain at low frq band
- ✓ high attenuation in higher frq
- ✓ Corner freq.: $\omega_c < 1/\tau_{FC}$

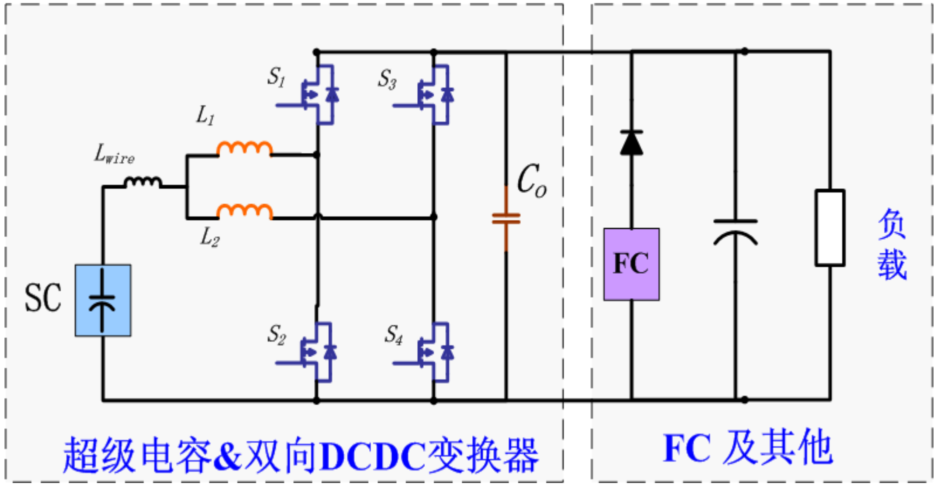
$\tau_{FC}$ :time constant of FC




Expected freq. characteristics



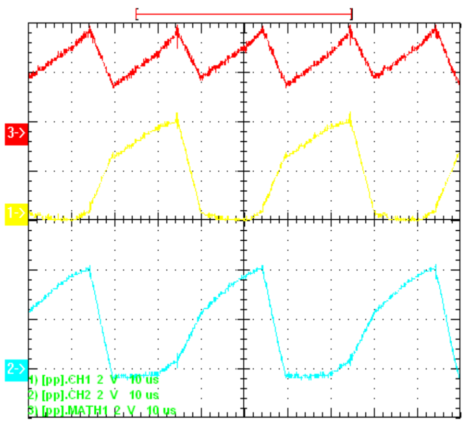
# Bi-DC/DC converter

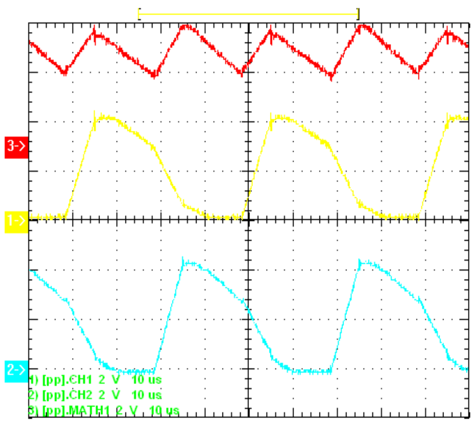



- ✓ DCM mode to reduce diode reverse recovery
- ✓ Interleaving structure to reduce ripples

**parameters：**

- ✓ $L_1$=$L_2$=4.5 uH　　$L_{wire}$=2.75 uH　　$C_O$=60 uF
- ✓ $V_{SC}$= 60～85 V　$V_{FC}$= 85~110 V
- ✓ $P_O$= -5 kW～+5 kW　　$f_s$=25 kHz





- ✓ left：SC charging state
- ✓ right：SC discharging state

CH1－$L_1$ current:-40A/div（left)，40A/div（right）

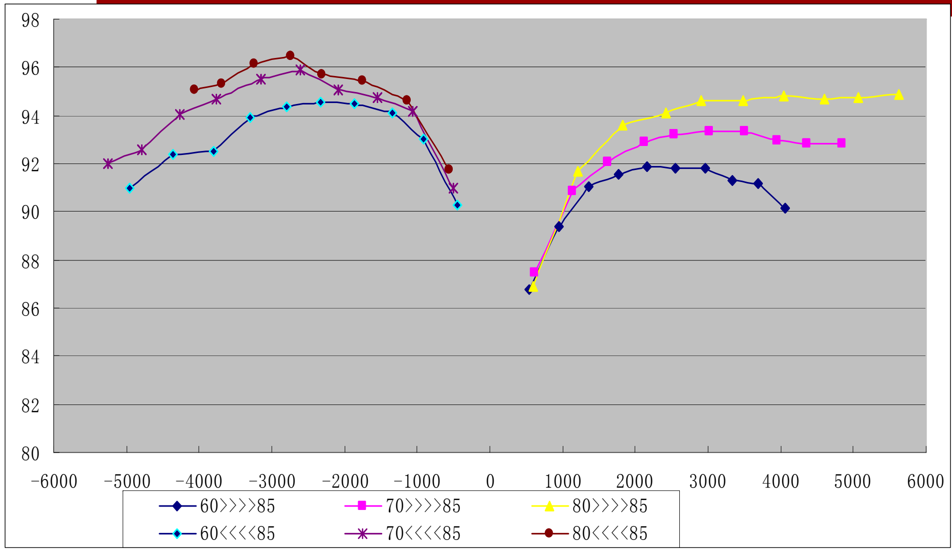
CH1－L2 current:-40A/div（left)，40A/div（right）

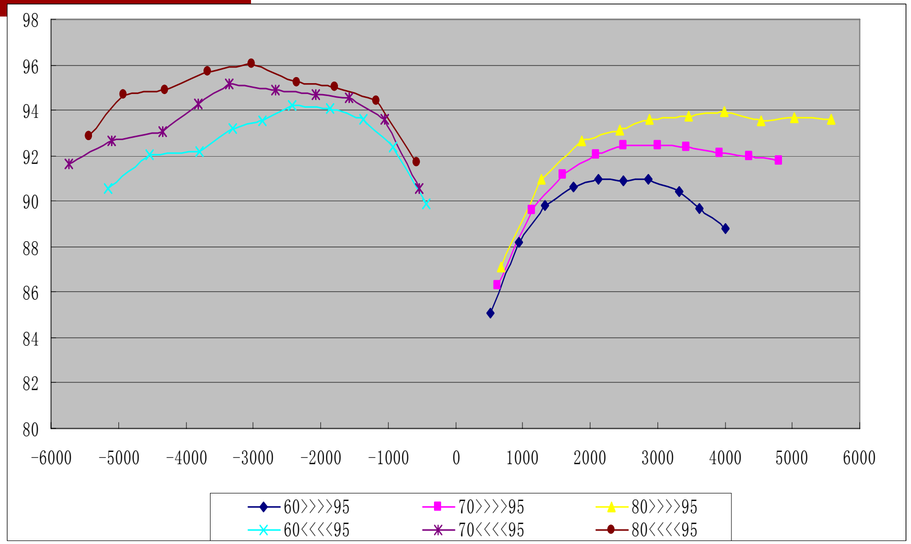
CH2－total current:-40A/div（left)，40A/div（right）

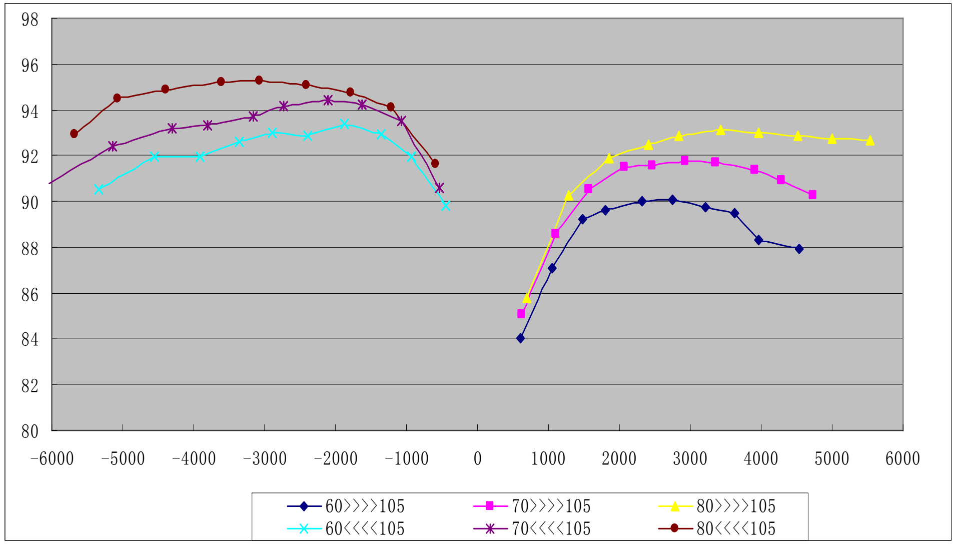
time：10 us/div

| Po= -5000 W （buck） | Po= +5000 W （boost） |
|---|---|
| SC charging state | SC discharging state |

# Bi-DC/DC converter efficiency

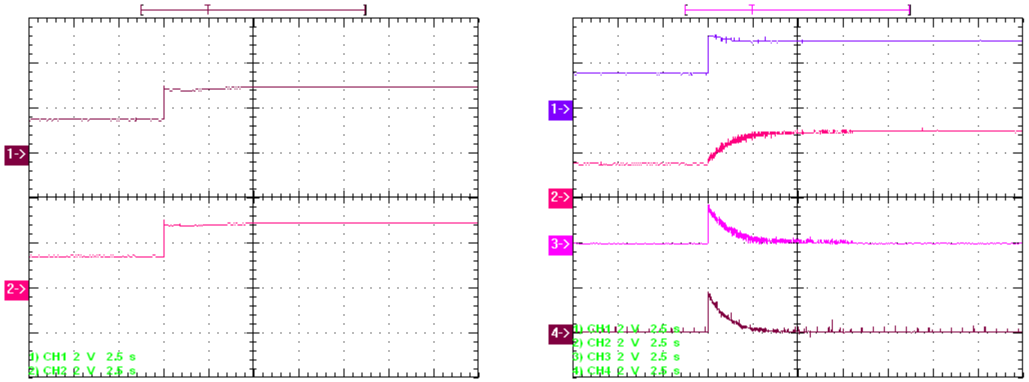


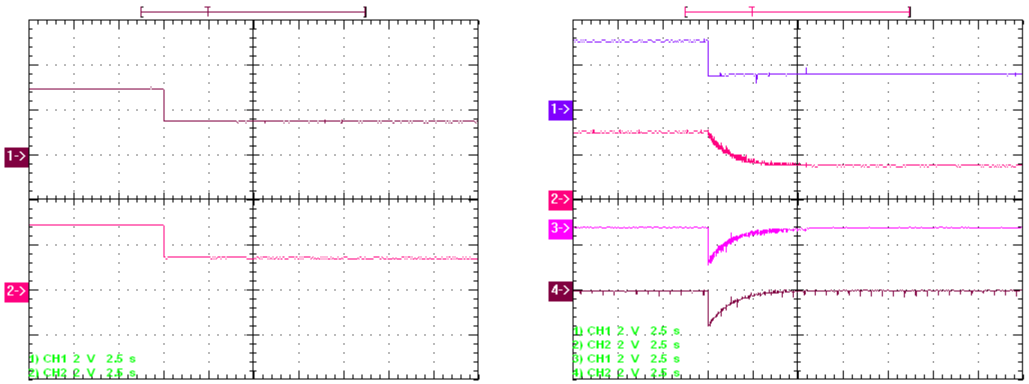




- ✓ SC cap side DC voltage：60V， 70V，80V
- ✓ FC side DC voltage：85V，95V，105V
- ✓ Power range：-5kW～5kW

# Energy management experiment（1）



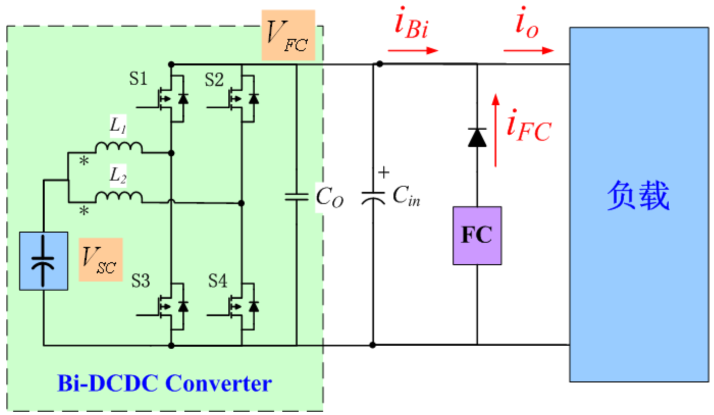
Load steps from half load to rated load



Load steps from rated load to half load

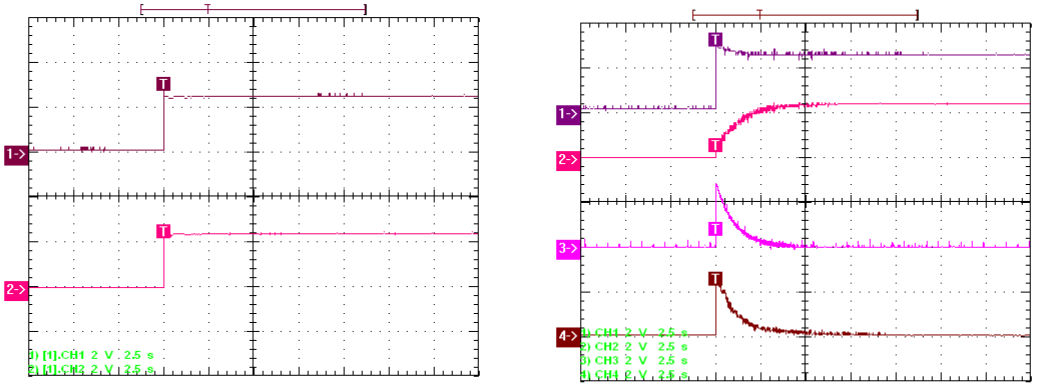
CH1: load *io:* 40 A/div
CH2:*:* FC output *iFC:* 40 A/div
time：2.5 s/div

CH1: load *io:* 40 A/div
CH2:*:* FC output *iFC:* 40 A/div
CH3: Bi-DC/DC *iBi*：40A/div
CH4: *iref_Bi*：40A/div

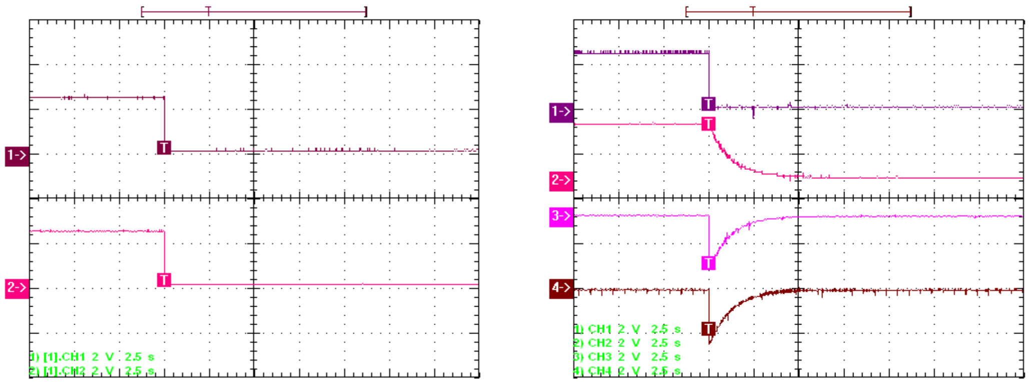



FC only outputs low frequency component due to the energy management!

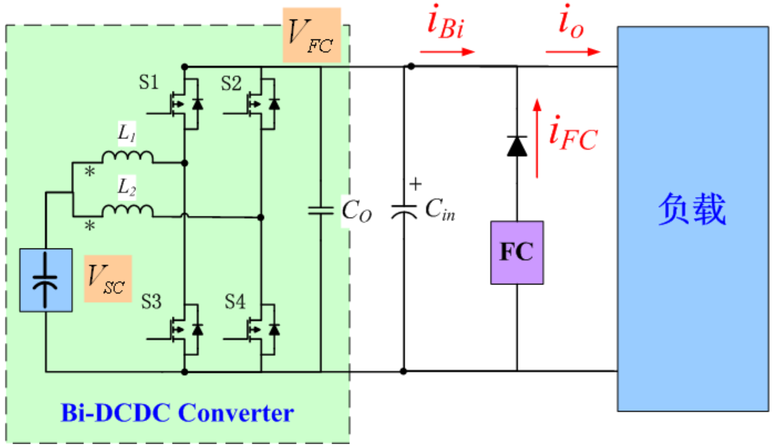
# Energy management experiment（2）



steps from no load to rated load



steps from rated load to no load

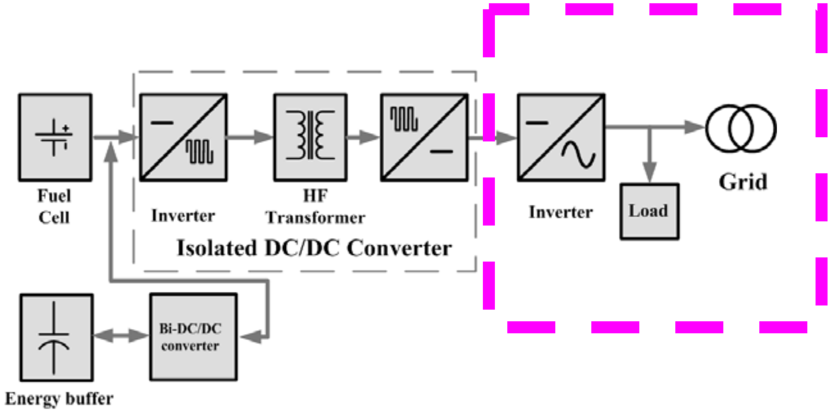


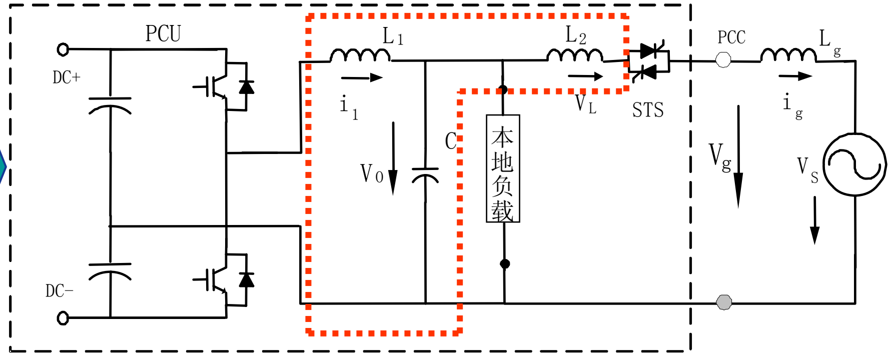

**FC only outputs low frequency component due to the energy management!**

**CH1: load *$i_o$*: 40 A/div**
**CH2:: FC output *$i_{FC}$*: 40 A/div**
**time：2.5 s/div**

**CH1: load *$i_o$*: 40 A/div**
**CH2:: FC output *$i_{FC}$*: 40 A/div**
**CH3: Bi-DC/DC *$i_{Bi}$*：40A/div**
**CH4: *$i_{ref\_Bi}$*：40A/div**

# 5. Gird interface control




IEEE STD 1547-2003 standard: THD<5.0%

**LCL filter is used**

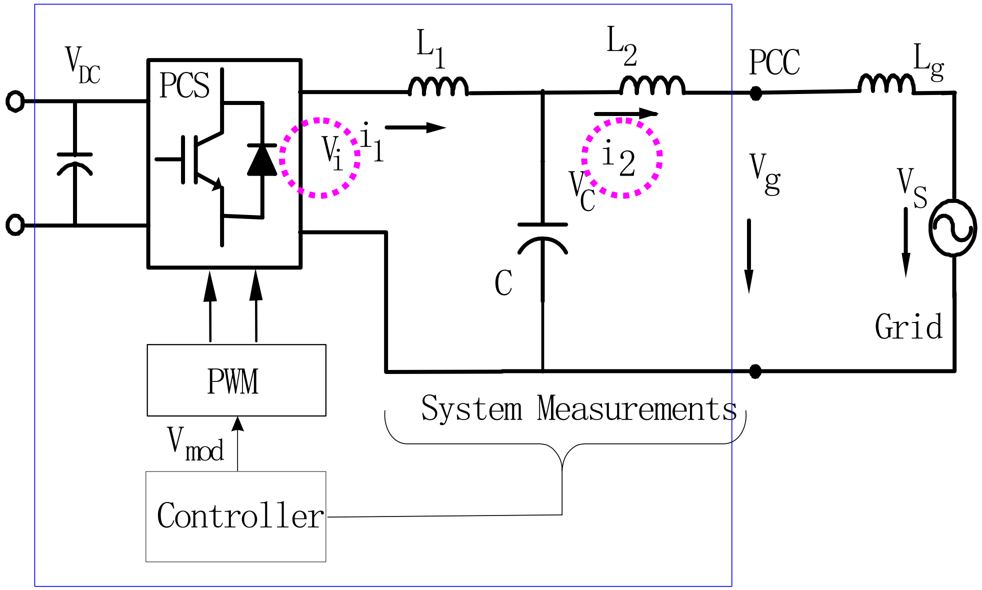
Advantages

- ✓ Higher attenuation to current harmonics
- ✓ Small Filter size
- ✓ Satisfy both on-gird and stand-alone modes

Disadvantage

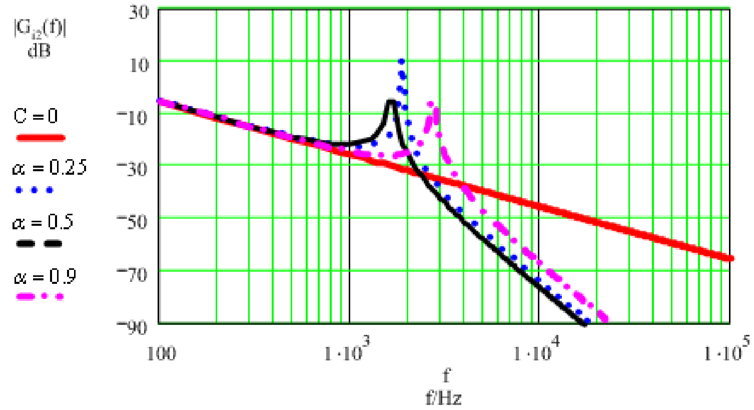
✓The 3rd order system and not easy for control

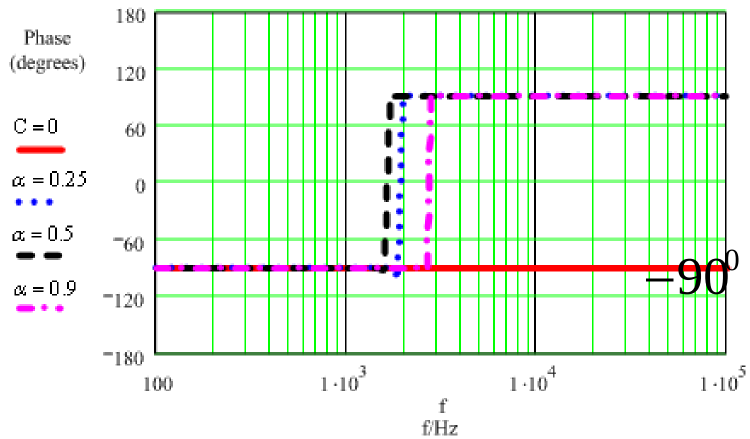
# Inverter with LCL filter




$$G_{i_2}(s) = \frac{I_2(s)}{V_i(s)} = \frac{1}{\alpha(1-\alpha)L^2Cs^3 + Ls}$$

$$\alpha = \frac{L_1}{L_1 + L_2}, \qquad L = L_1 + L_2$$



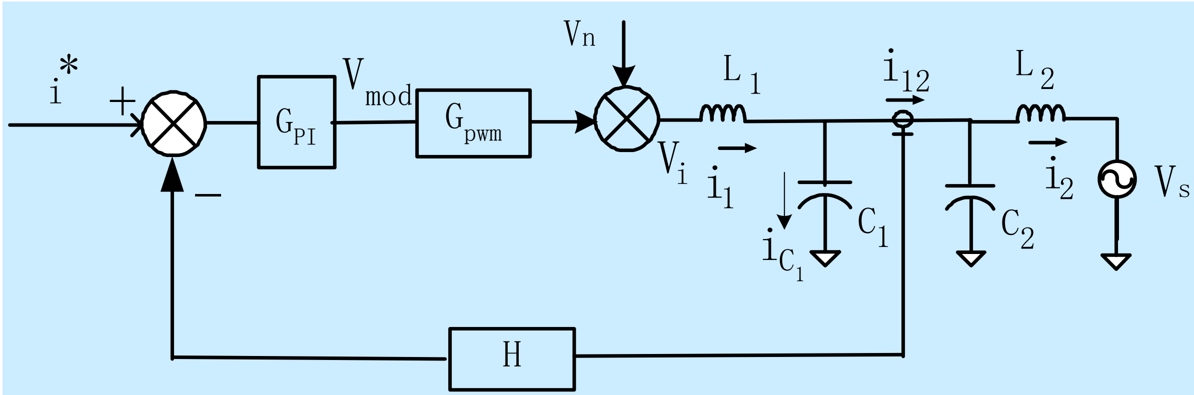




•3rd order system and not easy for control design

# Weighted current feedback control (WCFC)

$$\alpha = \frac{L_1}{L_1 + L_2}, \quad L = L_1 + L_2$$

$$\beta = \frac{C_1}{C_1 + C_2}, \quad C = C_1 + C_2$$




$$i_{12} = (1-\beta)i_1 + \beta i_2$$

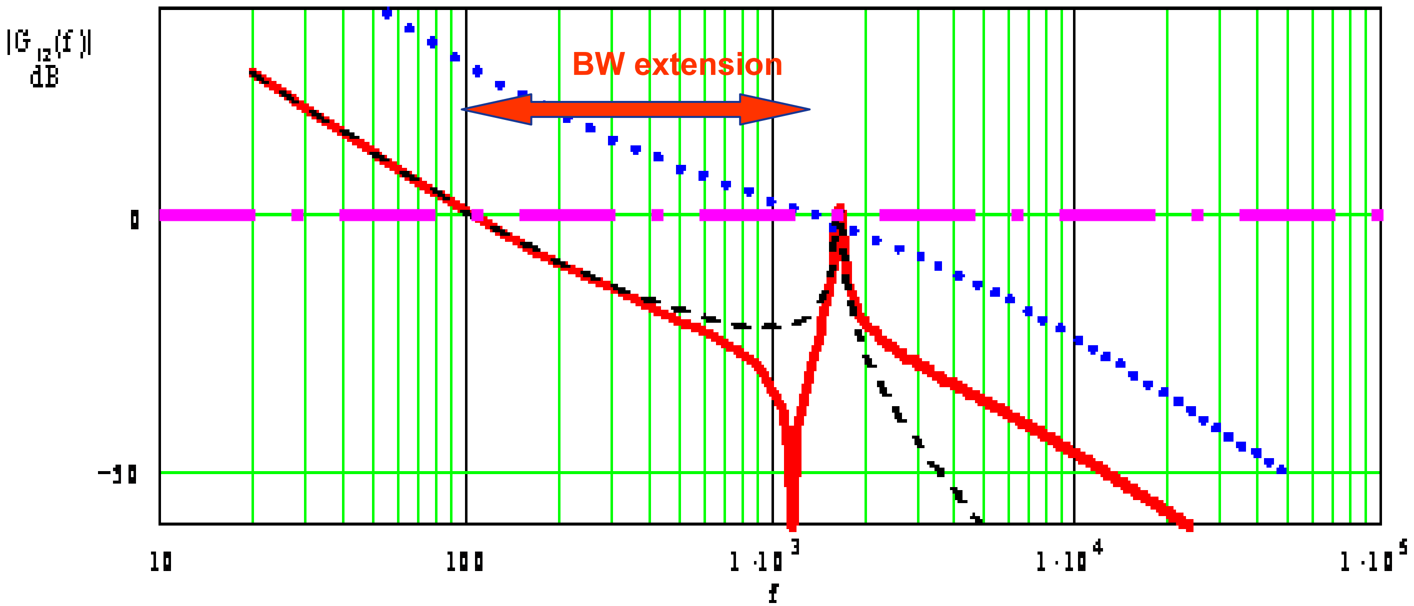
$$G_{i_{12}}(s) = \frac{I_{12}(s)}{V_i(s)} = \frac{(1-\beta)(1-\alpha)LCs^2 + 1}{\alpha(1-\alpha)L^2Cs^3 + Ls}$$

$$\beta = 1 - \alpha$$

$$G_{i_{12}}(s) = \frac{I_{12}(s)}{V_i(s)} = \frac{1}{Ls}$$

- Degenerate into an integrator due to canceling two poles

# WCFC vs. PI control



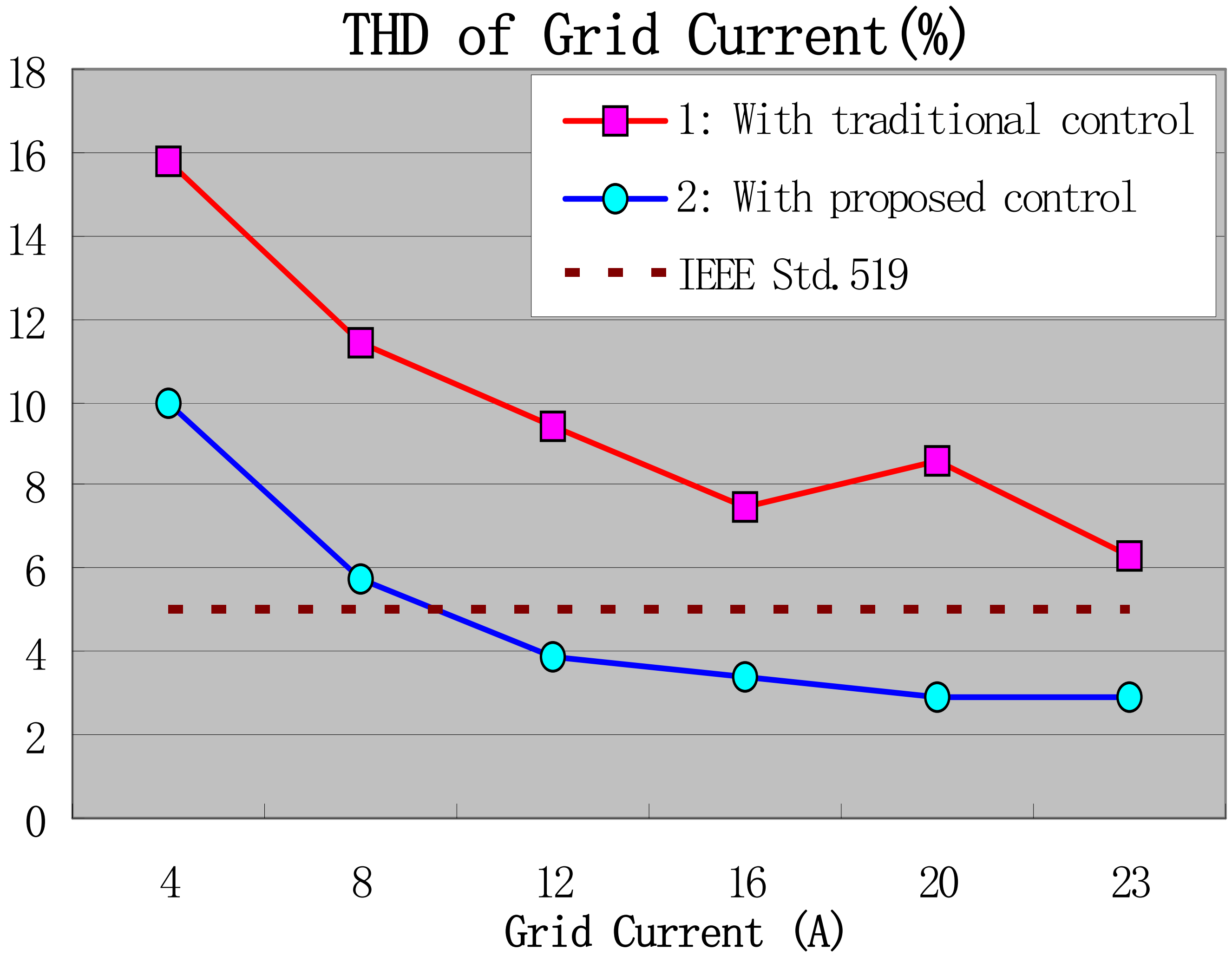

$I_1$ PI w/ inverter output current feedback（red line）

$I_2$ PI w/ gird current feedback（black doted line）

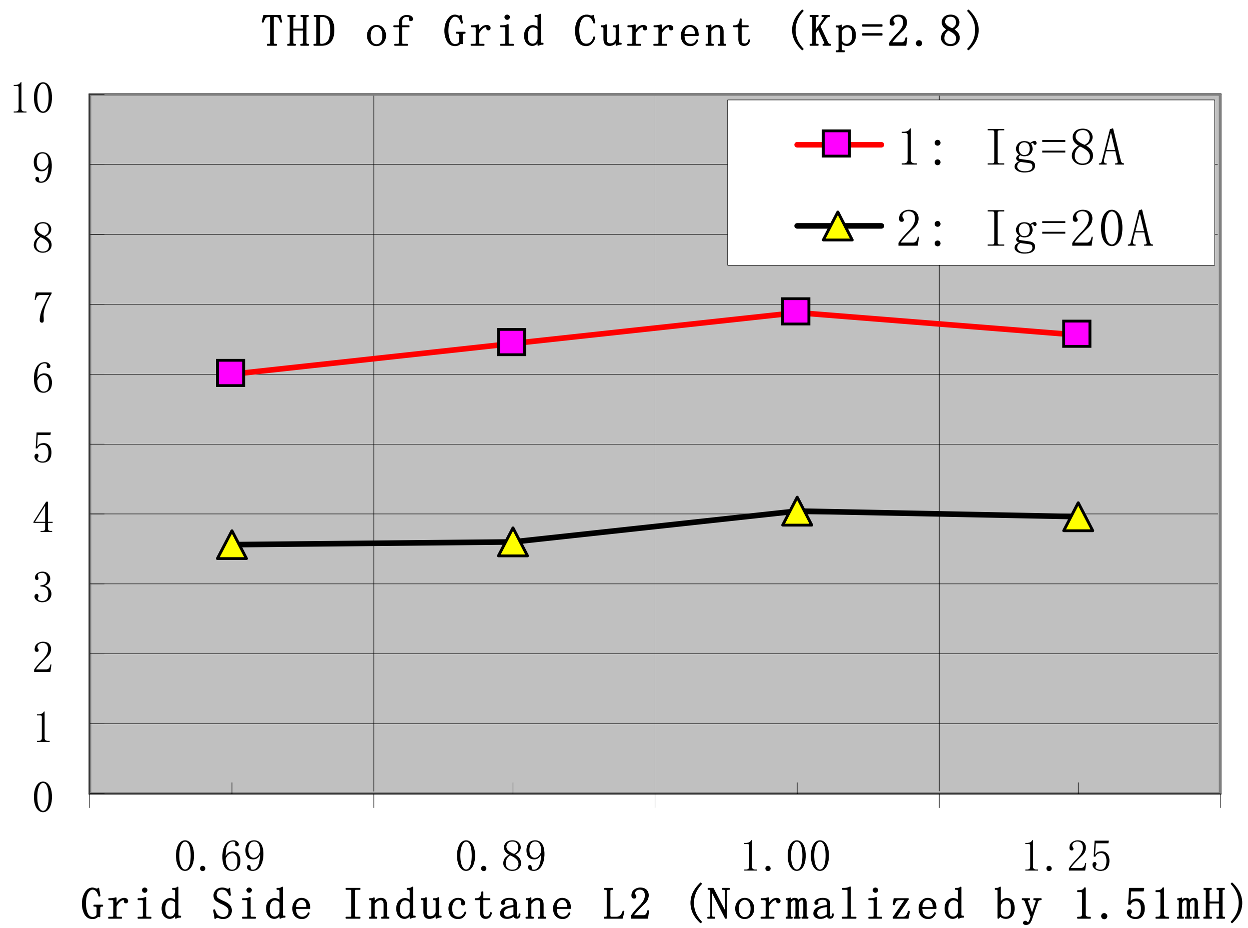
$I_{12}$ WCFC (blue doted line)

- Bandwidth 10 times higher and better dynamics
- Higher Gain in lower freq. band
- Improved Current tracking ability and higher gird current quality

# Gird current THD

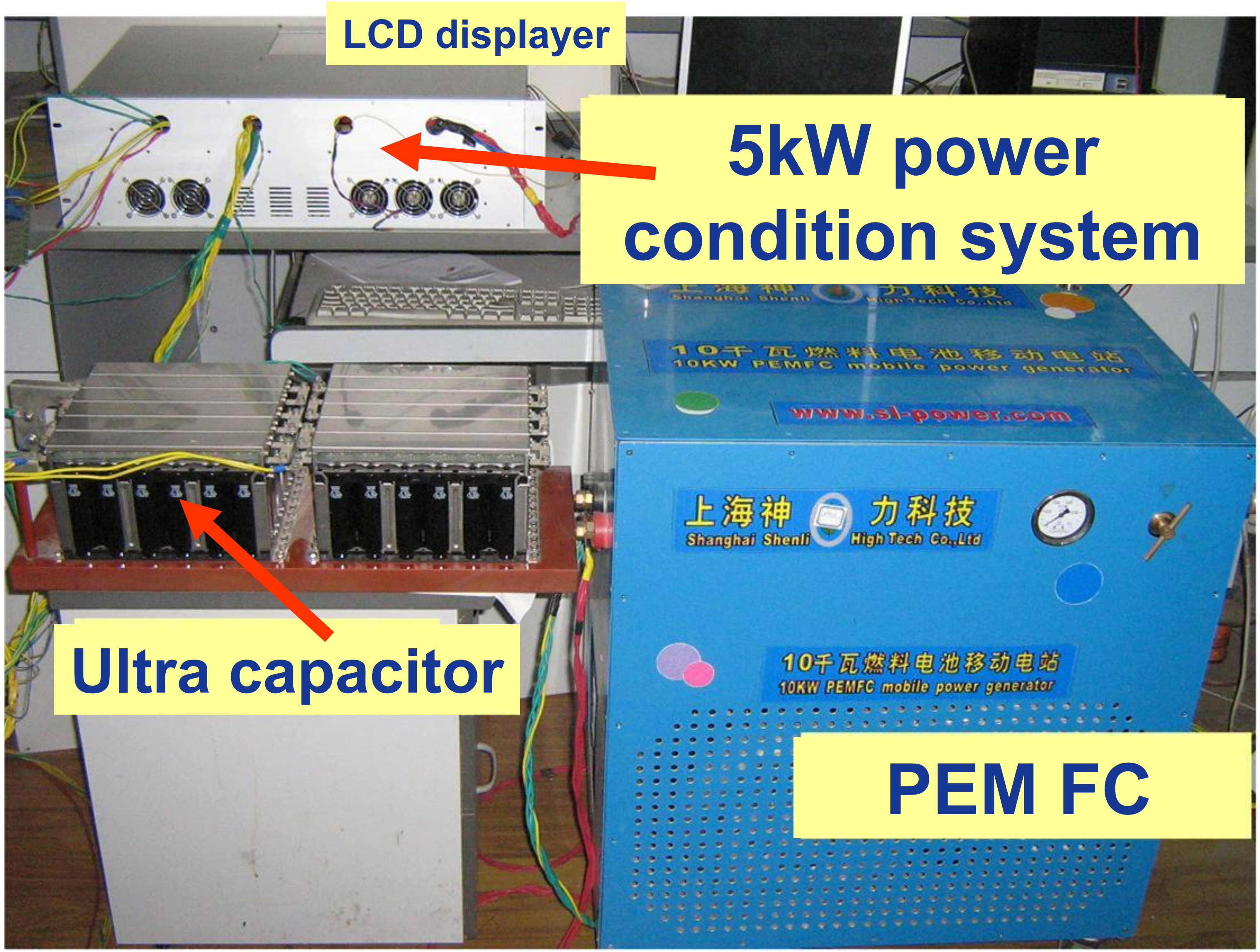


# Current THD vs. inductor *$L_2$* variation

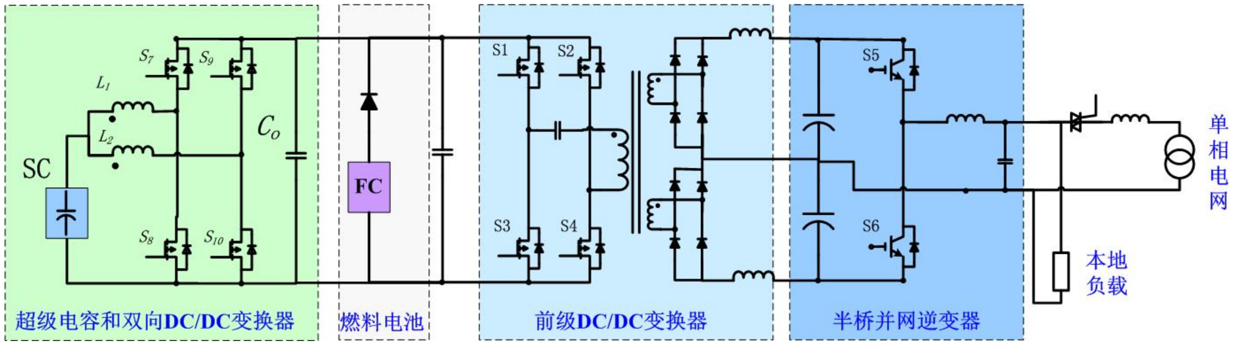


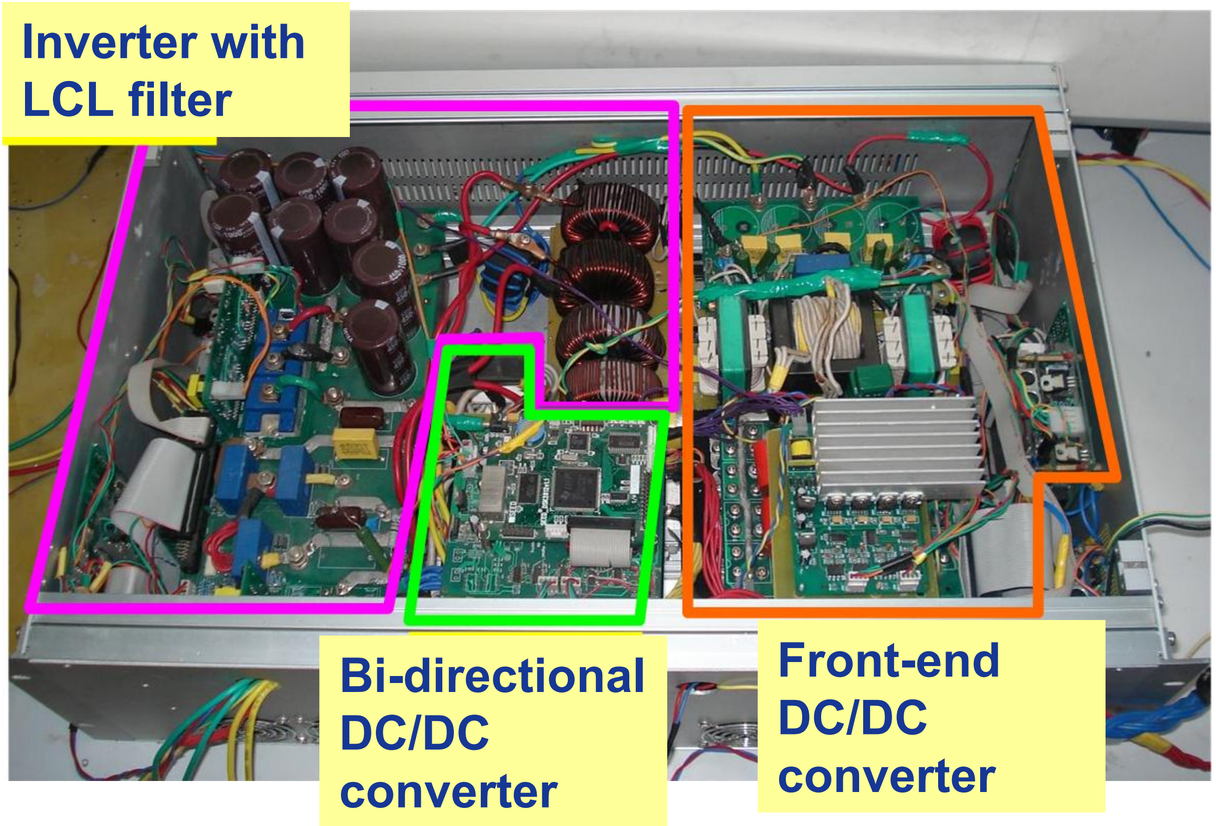

**WCFC is robust to variation of inductor L2 of LCL filter**

# 6. Prototype and experiment

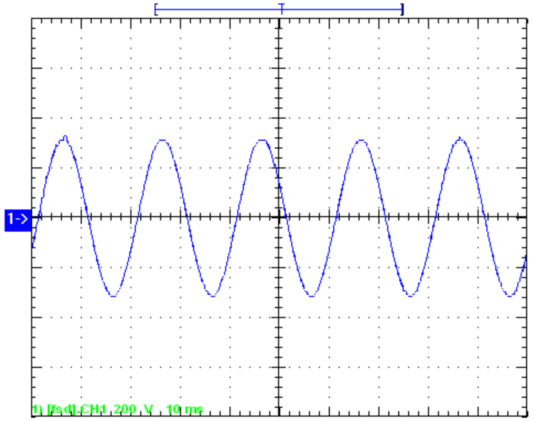


# 5kW power condition system

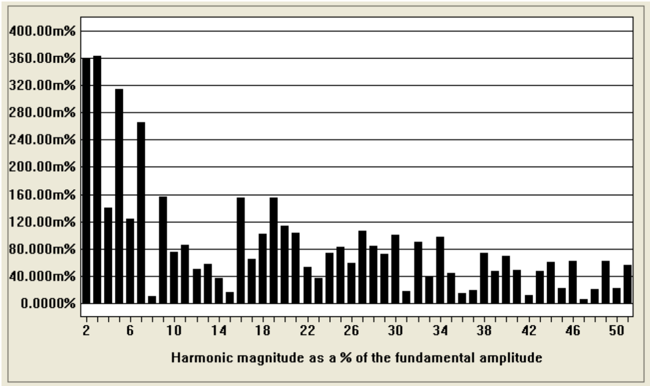


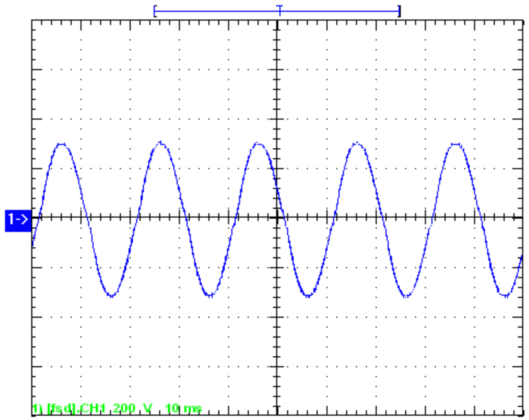
# Stand-alone operation(1)



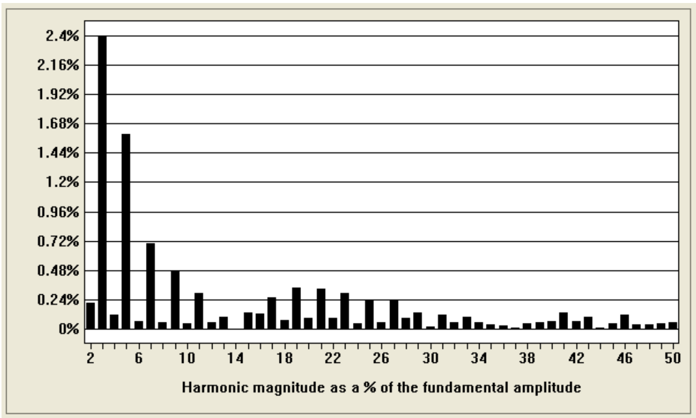
Inverter output voltage at no load
Voltage：200V/div
time：10ms/div




Inverter output voltage harmonics

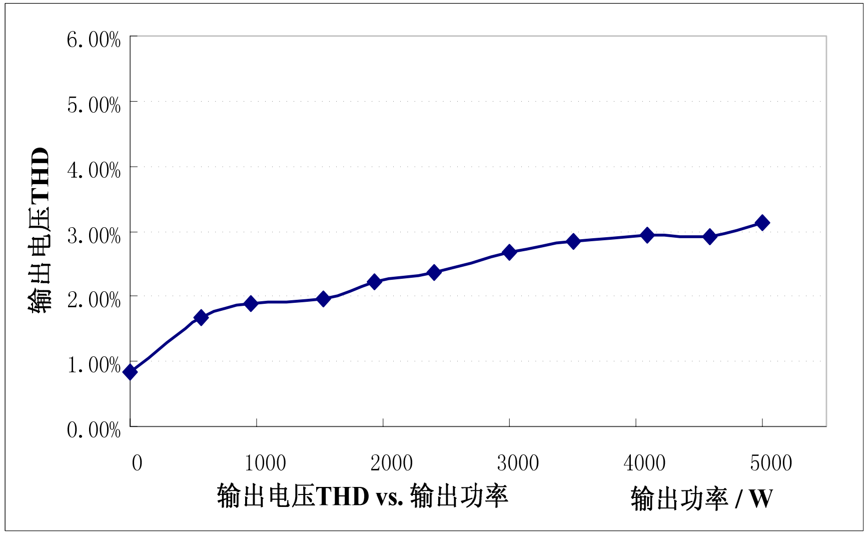


Inverter output voltage at rated load
Voltage：200V/div
time：10ms/div

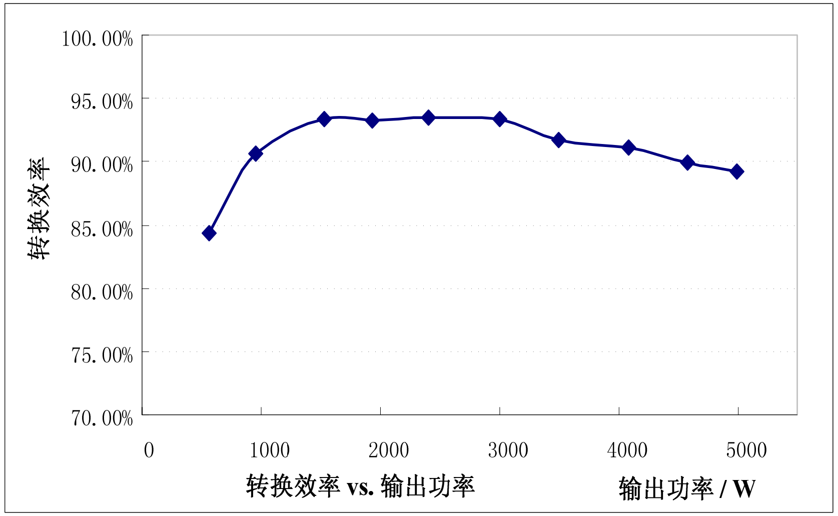



Inverter output voltage harmonics

# Stand-alone operation（2）

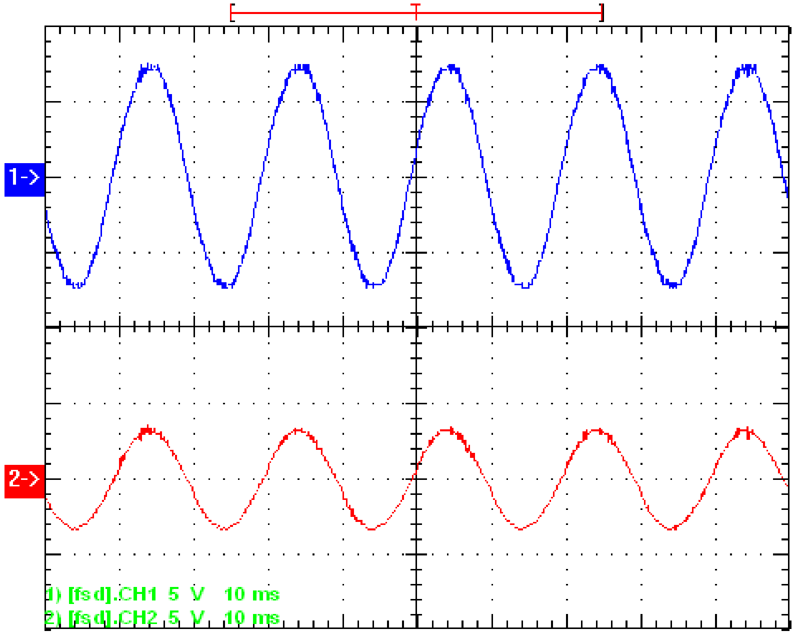


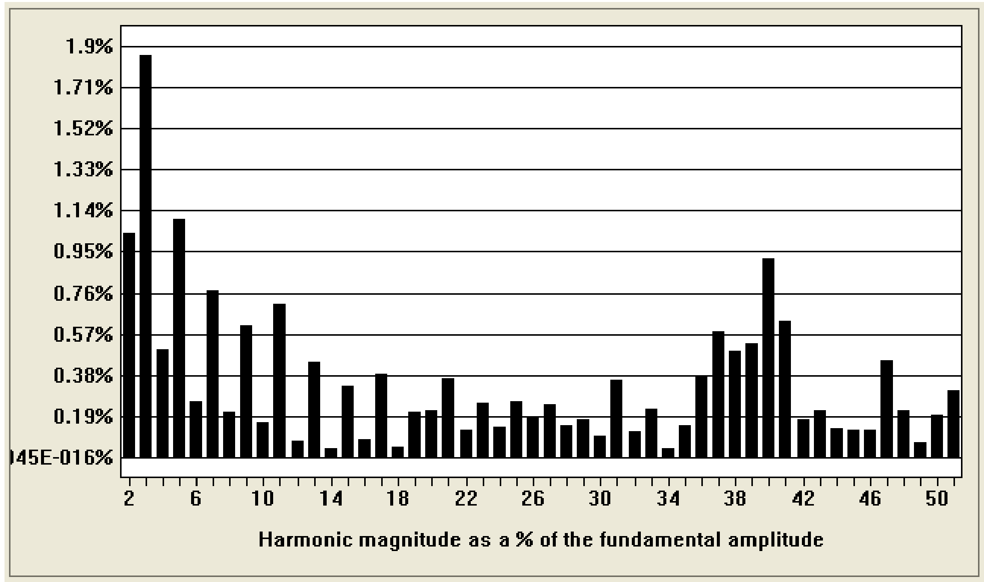

Output THD vs load




Power conversion efficiency vs. load

# On-Gird operation(1)




Gird voltage (upper) Gird current (lower)

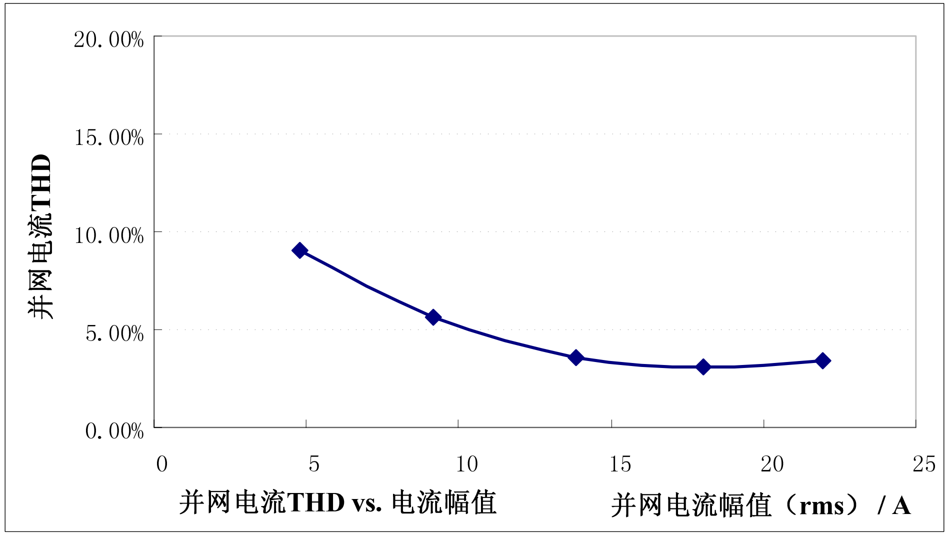
Gird voltage：200V/div，

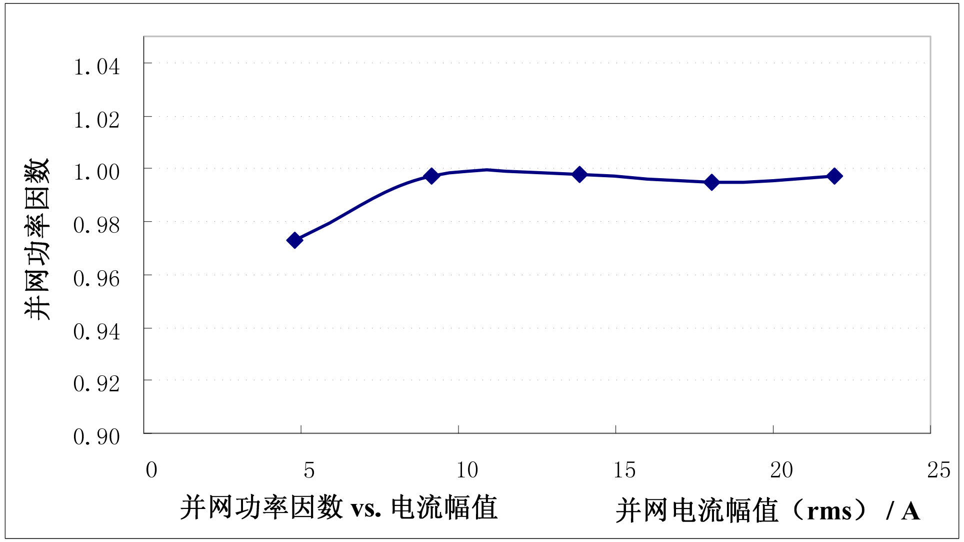
Gird current：45A/div

Time：10ms/div

Gird current harmonics spectrum

# On-Gird operation(2)

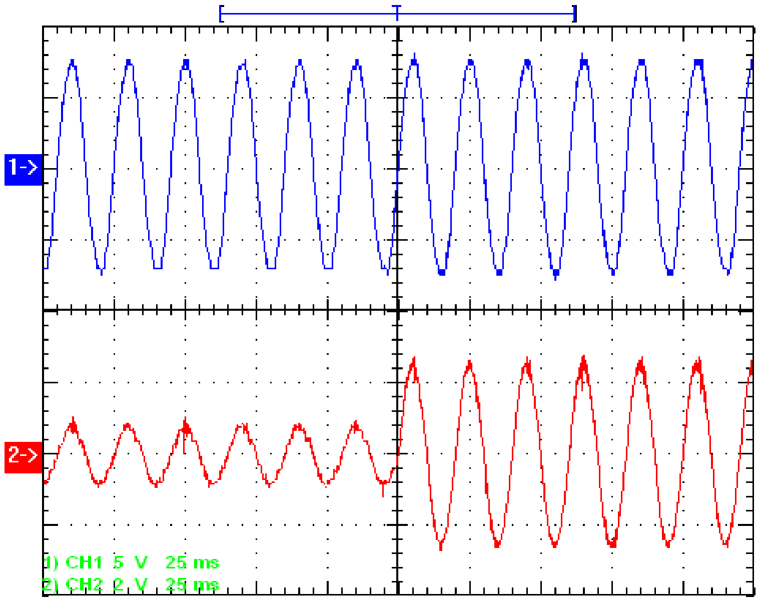


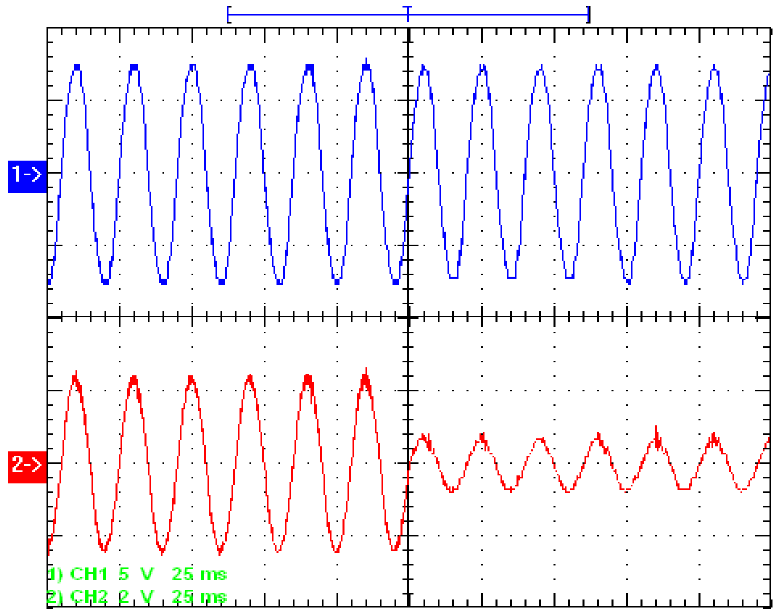

Gird current THD vs Gird current

Power factor vs Gird current

# On-Gird operation dynamics



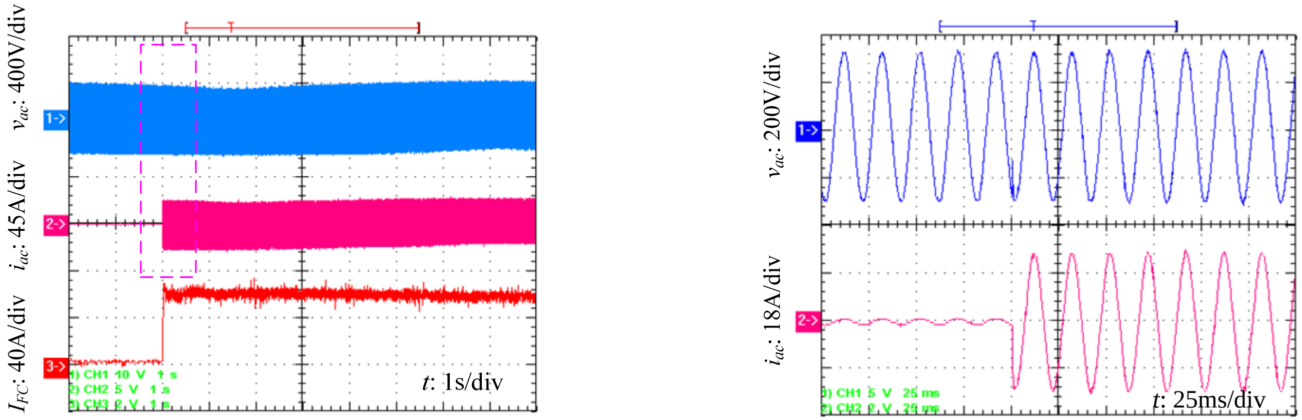

Current step up 6A→18A rms



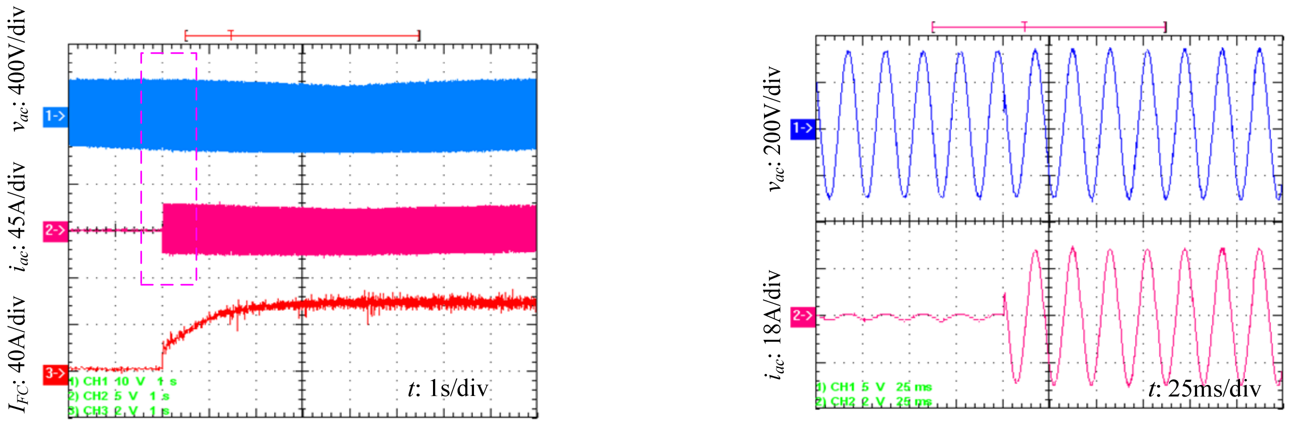

current step down： 18A→6A rms ）

voltage： 200V/div
current： 18A/div
time： 10ms/div

# Testing of energy management (load stepping up)



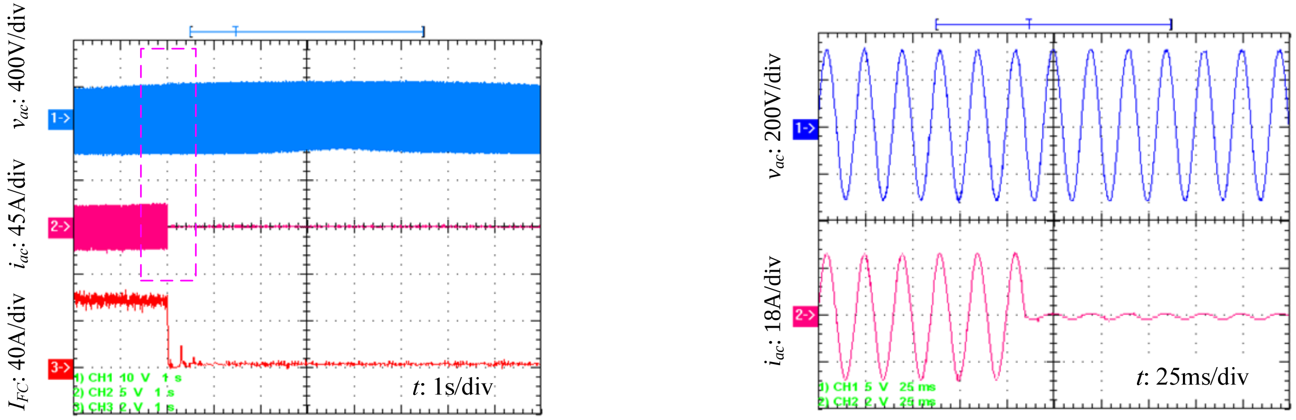

**(a) Without energy management**



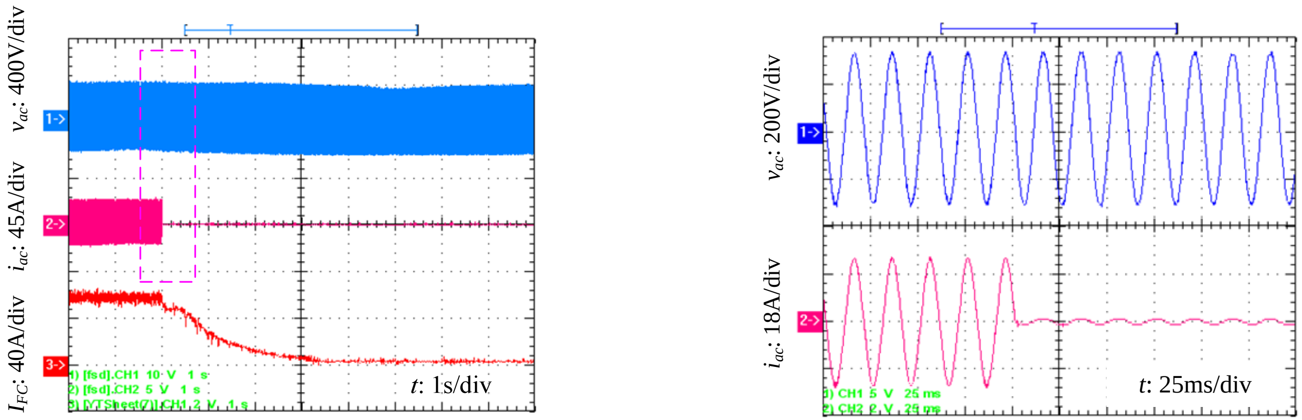

**(b) With energy management**

With energy management, FC output changes slowly when load steps up

# Testing of energy management (load stepping down)




**(a) Without energy management**




**(b) With energy management**

With energy management, FC output changes slowly when load steps down

# 7. Summary

- ✓ PEMFC output characteristics is investigated by the experiment, which is base for power conversion design
- ✓ Two stage power conversion structure is studied for PEMFC power system and efficiency improvement is studied
- ✓ Energy management design is investigated with respect to the control loop design and bi-directional DC/DC converter
- ✓ The weighted current feedback control (WCFC) is presented to the inverter with LCL filter. Gird control dynamics is improved and Gird interface current quality is improved.
- ✓ Experiment results with 5 kW PEMFC power system is presented.

Thanks