Power Electronics for Renewable Energy Integration into Hybrid AC/DC Microgrids

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Outlines

Introduction

Series-distributed Renewable Generation System Integrated to AC Bus

Differential Power Processing Renewable Generation System Integrated to DC Bus

Control of AC/DC Interfacing Converters

Summary & Perspective

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- Introduction
- Series-distributed Renewable Generation System Integrated to AC Bus
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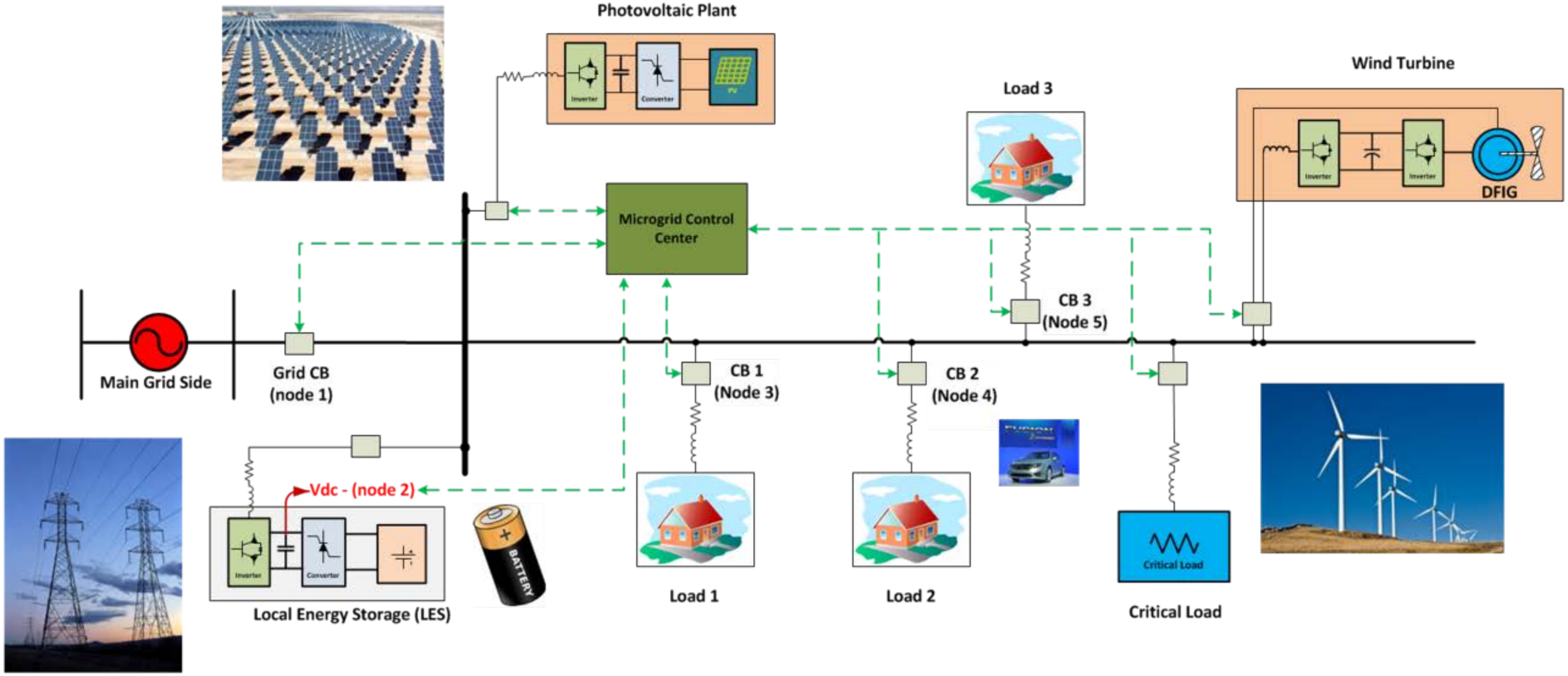
- Summary & Perspective

Introduction

- **Microgrid is the main solution to integrate renewable energy into power system**



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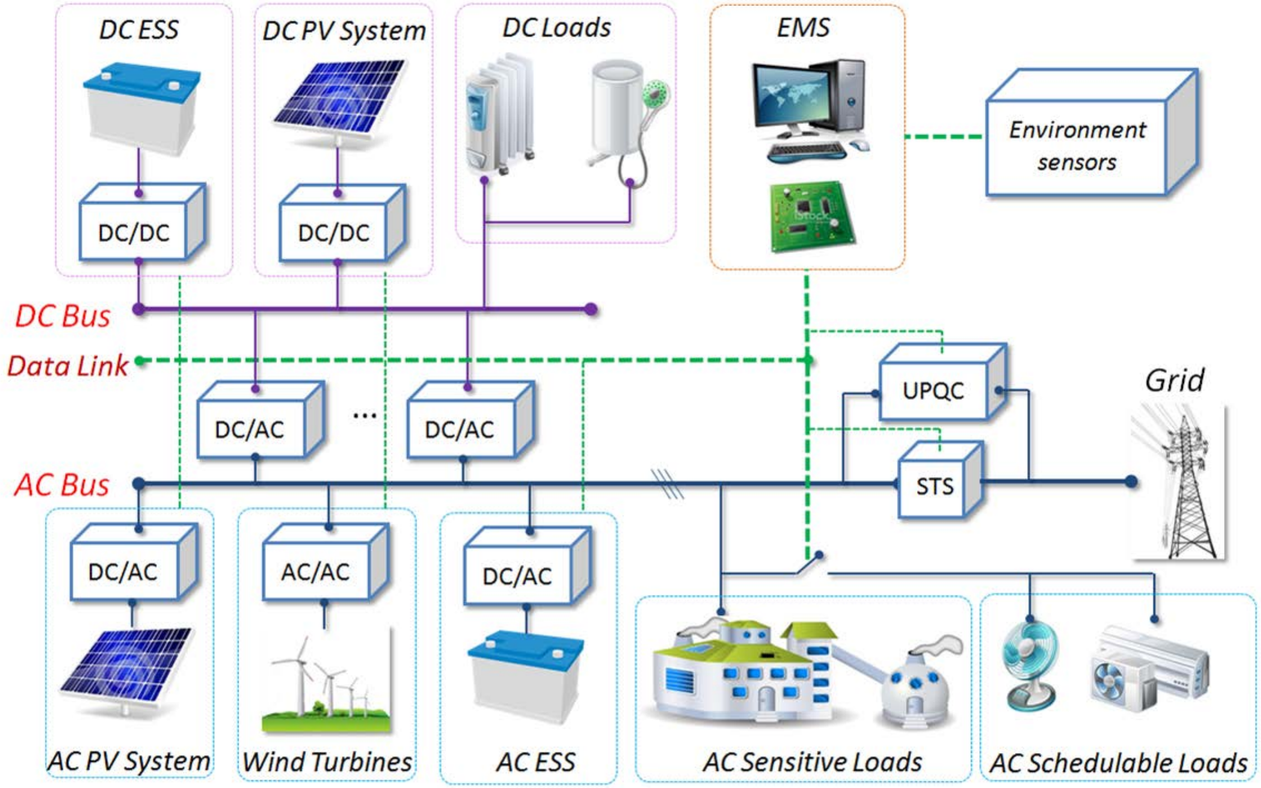
Department of Electrical Engineering

Introduction

- **Hybrid AC/DC microgrid will play a very important role in the future, which features both advantages of AC microgrid and DC microgrid.**



Introduction

- **Power electronics converters are key elements to connect renewable energy sources to microgrids.**
- **AC bus integration technique——**

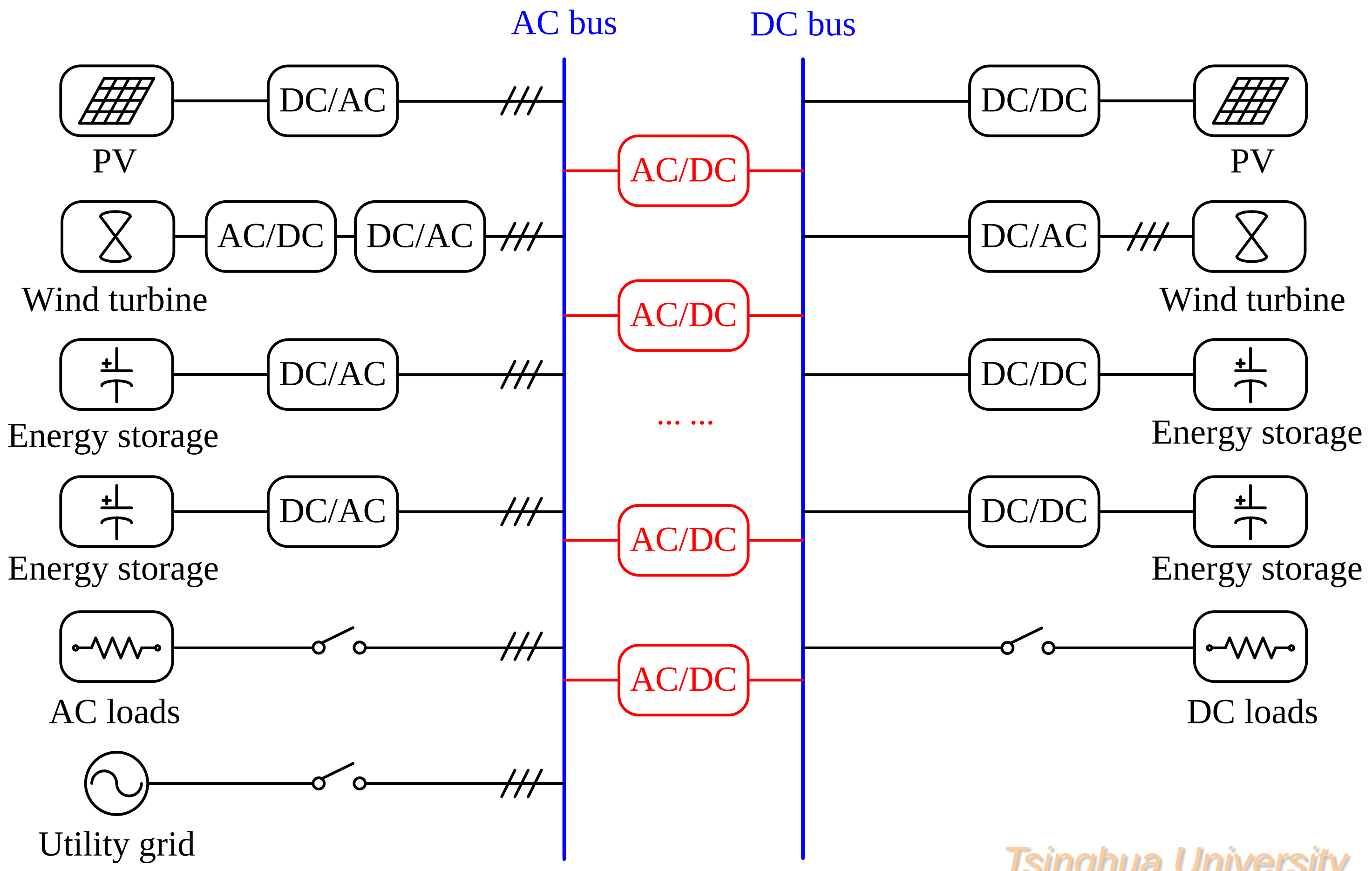
  Series-connected distributed renewable generation system
- **DC bus integration technique——**

  Differential power processing (DPP) based renewable generation system
- **Connection technique of AC and DC buses—**

  Hierarchical control of AC/DC interfacing converters with power quality improvements

Research Background

- **Hybrid AC/DC microgrid will play a very important role in future energy networks**



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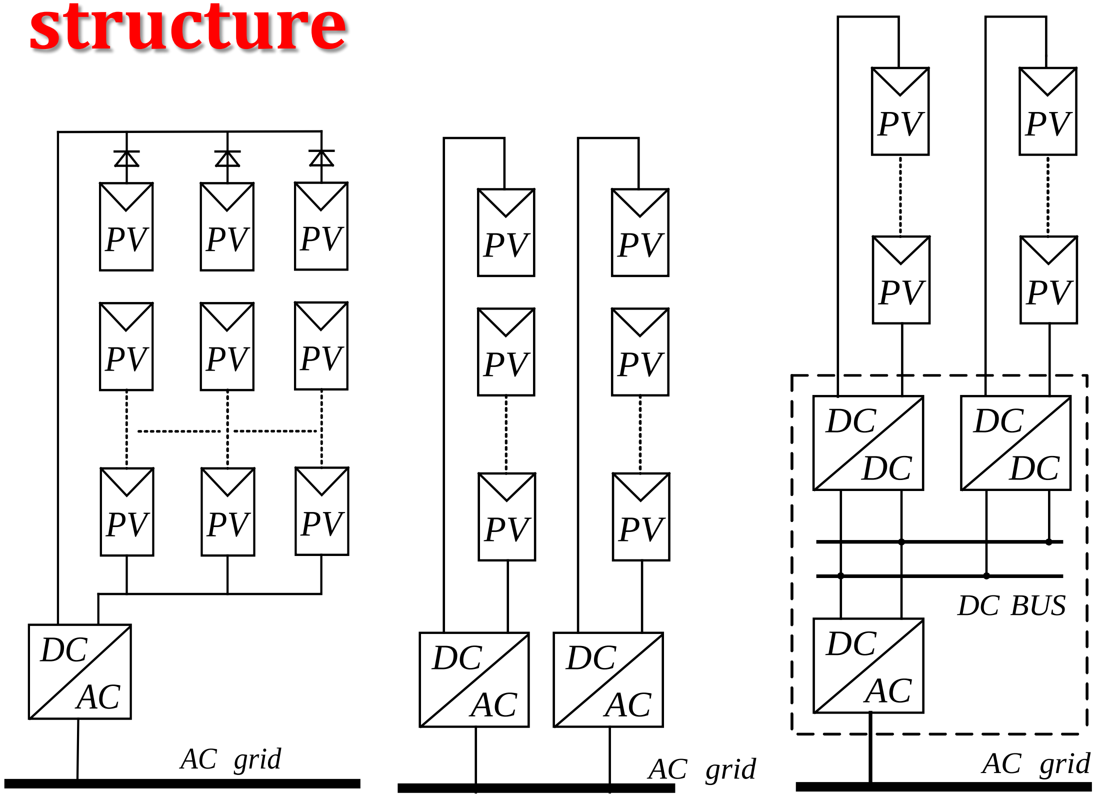
Series-distributed Renewable Generation System Integrated to AC Bus

Conventional distributed PV generation system structure



Centralized String Multi-string

Drawbacks

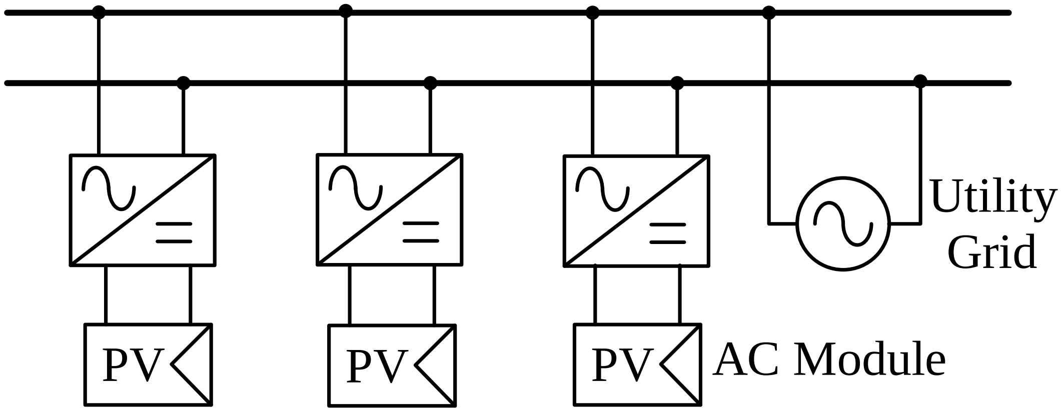
- Series-connected PV panels generate DC high-voltage
- Power mismatch
- Without PV monitor
- Non-redundant Inverter

Panel-level MPPT

Series-distributed Renewable Generation System Integrated to AC Bus

AC module structure Micro-inverter

Install at resident building and commercial building with the requirement for high reliability



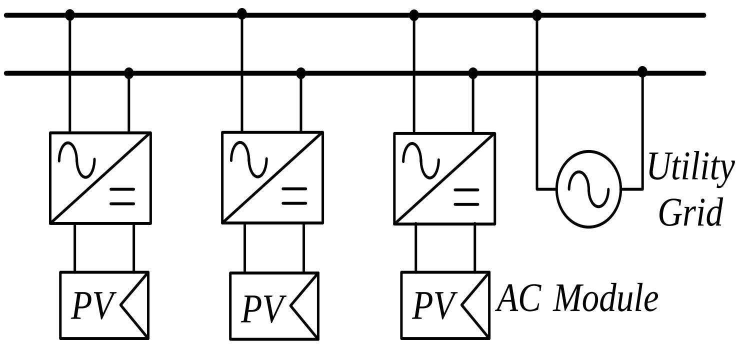
Merits:

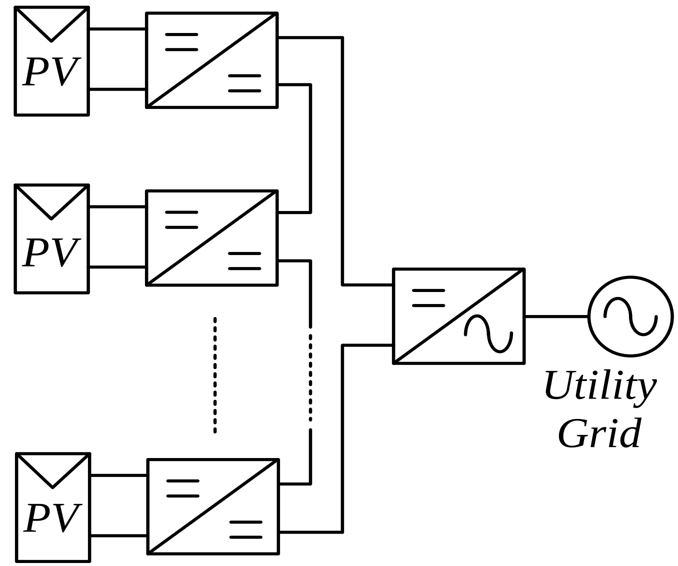
- ✓ Panel-level MPPT
- ✓ High reliability
- ✓ non-existed DC high-voltage
- ✓ PV panel monitor

Drawbacks:

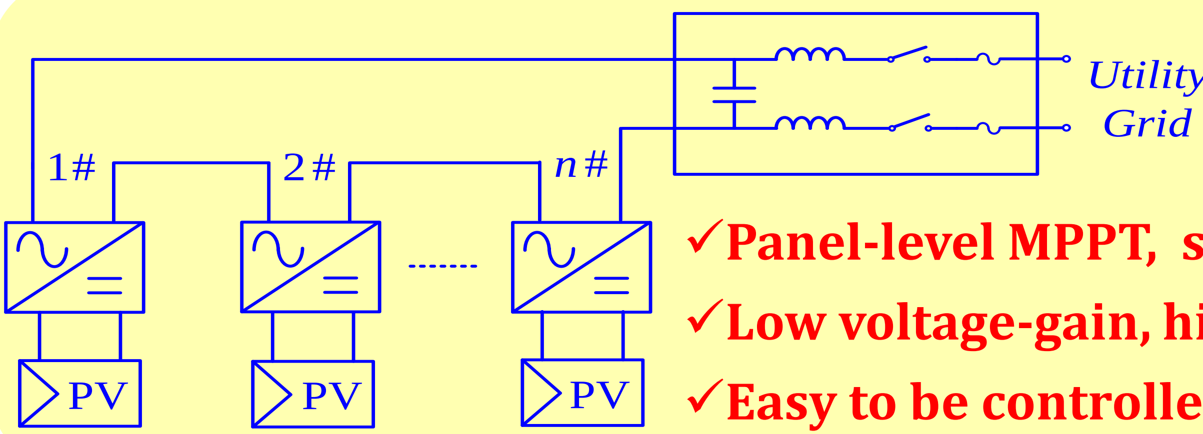
- ➢ high voltage-gain
- ➢ Efficiency improvement hardly
- ➢ high cost per watt
- ➢ complex system control

Series-distributed Renewable Generation System Integrated to AC Bus





Distributed series-connected PV generation system



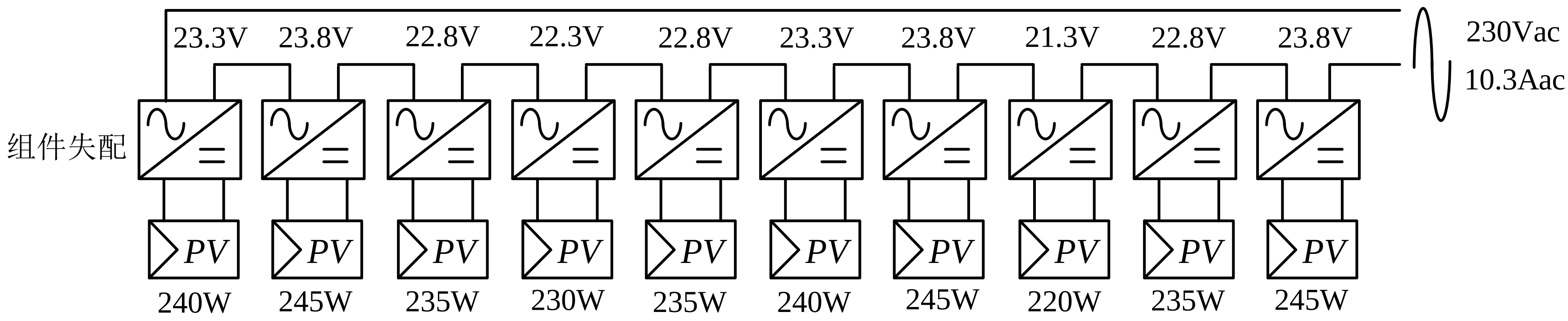
- ✓ **Panel-level MPPT, statement monitor**
- ✓ **Low voltage-gain, higher efficiency**
- ✓ **Easy to be controlled by state grid order**

Series-distributed Renewable Generation System Integrated to AC Bus

The idea of research and develop distributed PV grid-tied generation system with high efficiency, high reliability and low cost

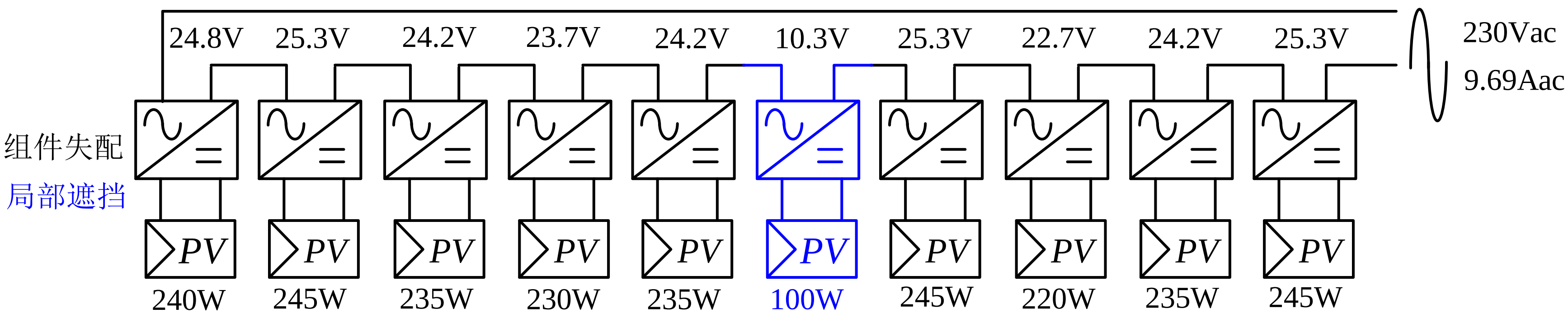
- **Each PV panel interfaced with a power electronics converter to realize panel-level MPPT .**
- **Each PV panel are series-connected by using converters, and DC high-voltage is non-existed.**
- **Distributed dc-ac conversion with low voltage-gain. The efficiency can be improved, and the hardware cost can be reduced.**

Series-distributed Renewable Generation System Integrated to AC Bus



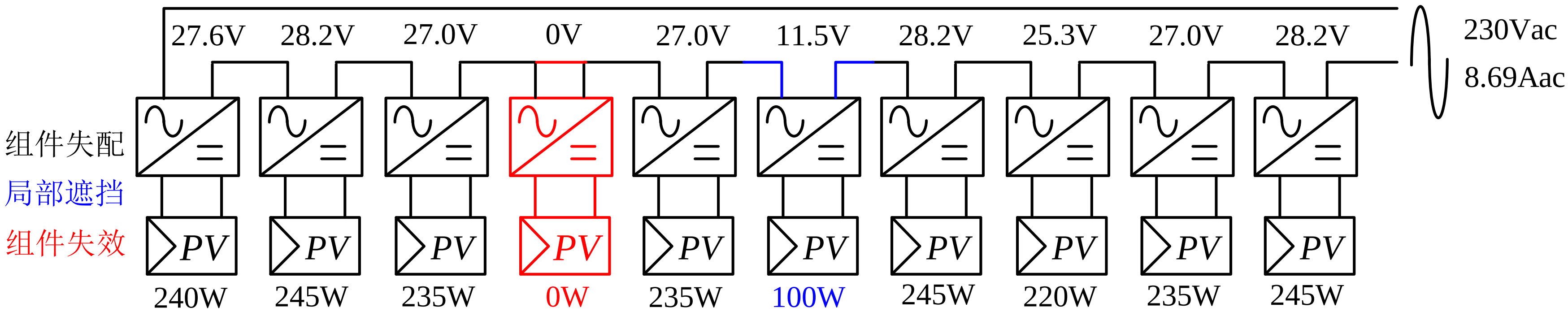
- **The output current of each micro-inverter is the same. The sum of each micro-inverter output voltage is equal to the utility grid voltage.**
- **When the output power of each PV panel is mismatch, each micro-inverter regulates its output voltage according to the output power of interfaced PV panels.**

Series-distributed Renewable Generation System Integrated to AC Bus



- When one of PV panels is in shadow, the total output power is reduced. Since the sum of each micro-inverter output voltage is clamped by the utility grid voltage, the output current of the PV system is reduced.
- The output voltage of the micro-inverter interfaced with shadowed PV panel is reduced. The output voltages of the other micro-inverters are increased.

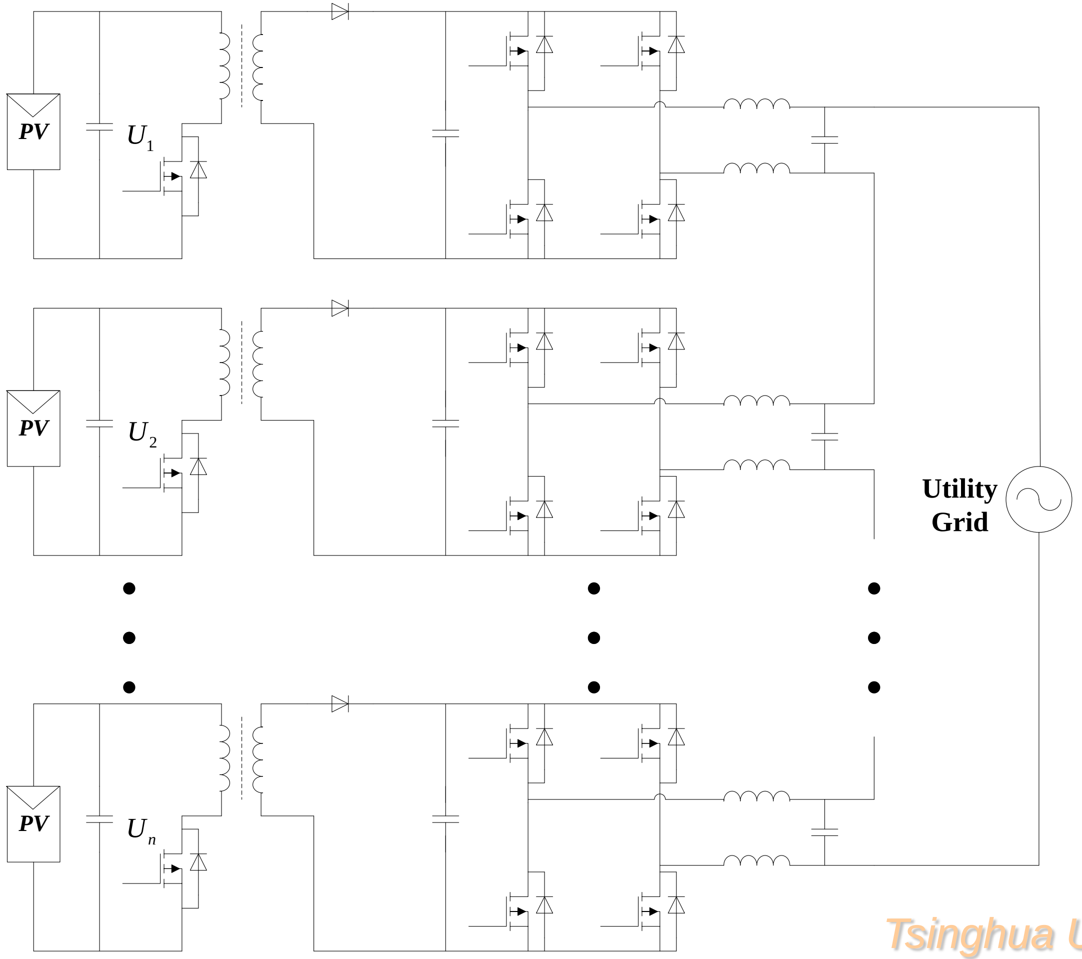
Series-distributed Renewable Generation System Integrated to AC Bus



- **When one of PV panels is failure, the total output power is reduced. Since the sum of each micro-inverter output voltage is clamped by the utility grid voltage, the output current of the PV system is reduced.**
- **The output voltage of micro-inverter interfaced with the failure PV panel is zero. The output voltages of the other micro-inverters are increased.**

Series-distributed Renewable Generation System Integrated to AC Bus

The typical structure of the distributed series-connected PV grid-tied generation system



Series-distributed Renewable Generation System Integrated to AC Bus

Control Strategy— hybrid control of current source and voltage source

One of micro-inverters, which control the grid-tied current of the PV system, is enabled as the current-source controlled inverter.

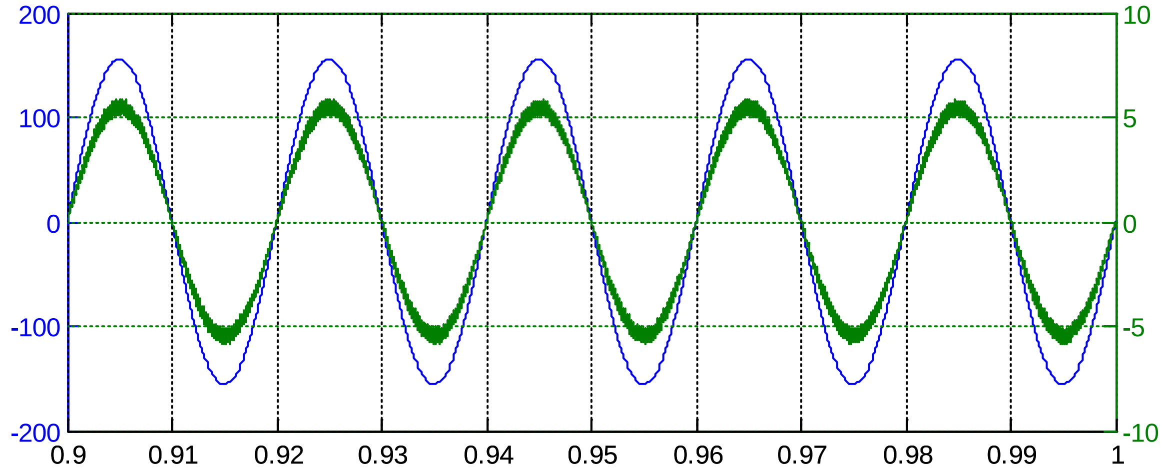
The other micro-grid inverters, which control output voltages according to their interfaced PV panels, are operated as voltage-source controlled inverters.

Merits： Control strategy is easy to implement

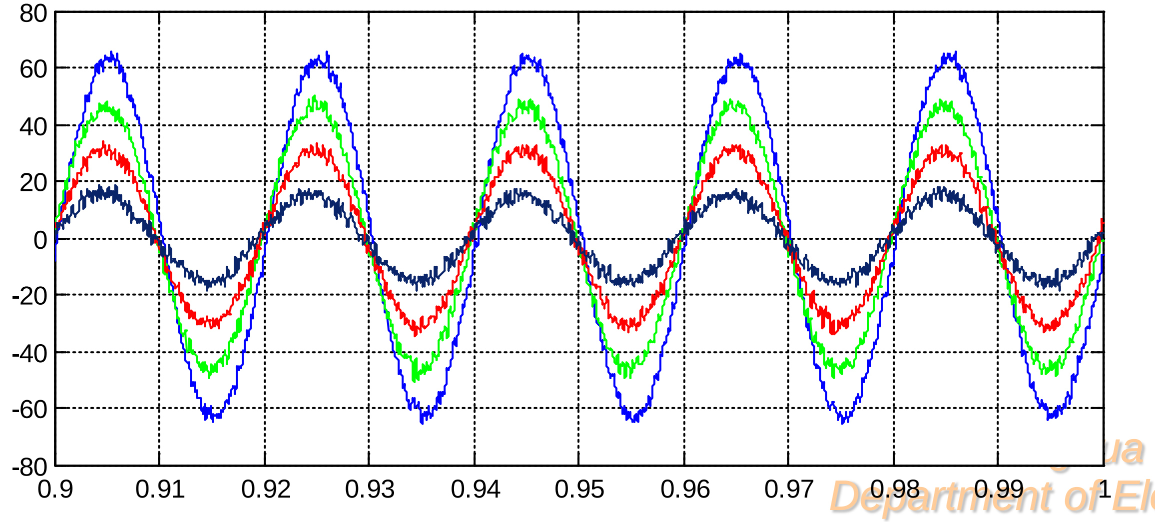
Drawbacks： The current-source controlled inverter is the key inverter of the PV system. If the current-source controlled inverter is damaged, the system can not be continue operation. Therefore, the redundancy of the system is weak.

Series-distributed Renewable Generation System Integrated to AC Bus

The waveforms of grid-tied current and utility grid voltage



The waveforms of each micro-inverter output voltage



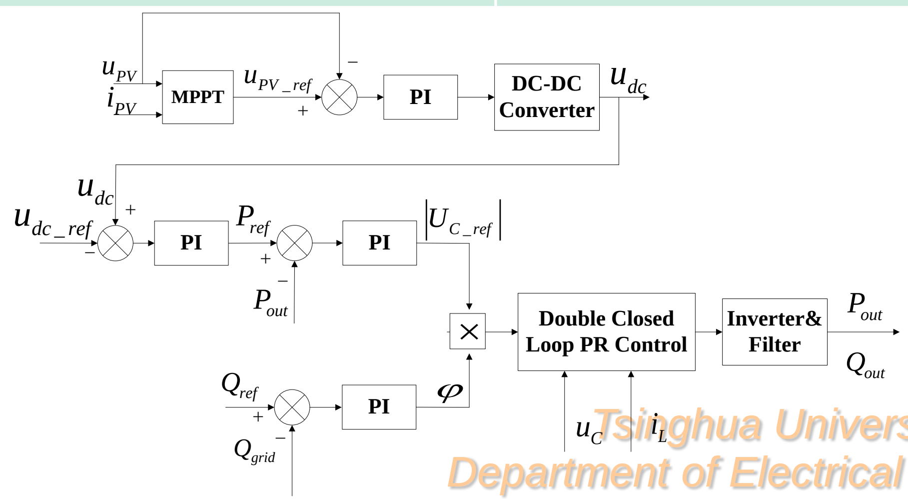
Series-distributed Renewable Generation System Integrated to AC Bus

Control Strategy— Distributed control

Idea: All of the micro-inverters are voltage-source controlled. The output voltage of each inverter is regulated according to the active power. The output phase of each inverter is regulated according to the reactive power.

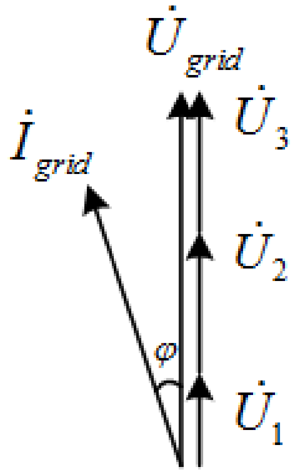
	Parallel System	Series System
Power Distribution	Output Current	Output Voltage
Active Power	Voltage Phase	Voltage Amplitude
Reactive Power	Voltage Amplitude	Voltage Phase

PQ control for Series-connected PV Systems



Series-distributed Renewable Generation System Integrated to AC Bus

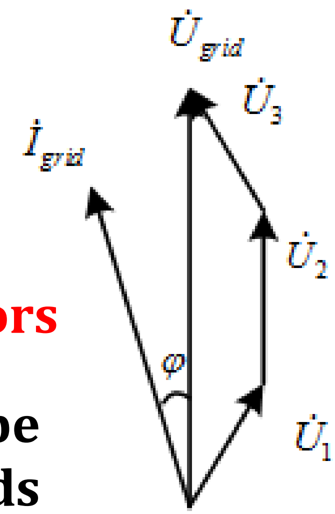
Discussion of the active and reactive powe control for each micro-inverters



Current strategy: **The output voltage of each micro-inverter is almost in phase with the utility grid. The ratio of reactive power and active power of each inverter is the same.**

Improvement Target: **The ratio of reactive power and active power of each inverter is different.**

$$\sqrt{P_i^2 + Q_i^2} = U_i I_{grid} = \text{Const}$$

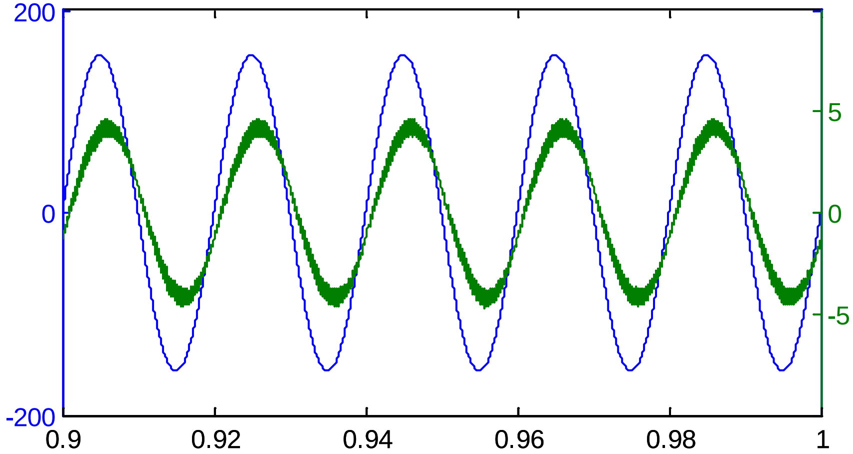


The polygon rule is used to synthesis voltage vectors

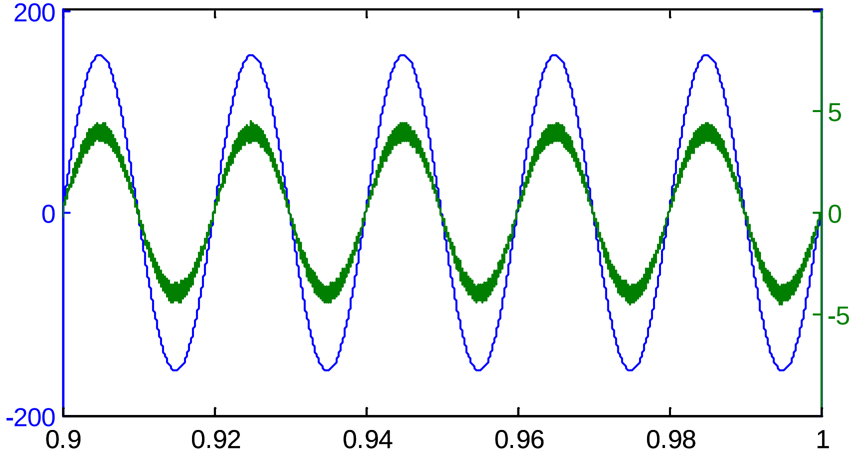
Drawbacks: **The circulating reactive power may be exist. The control of each micro-inverter depends on the communication.**

Series-distributed Renewable Generation System Integrated to AC Bus

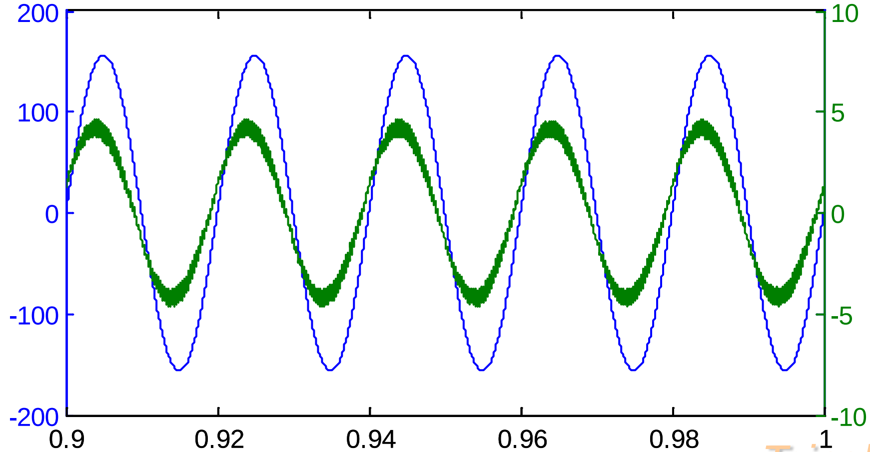
utility grid voltage(blue), grid-tied current(green）



P=300W Q=-100Var



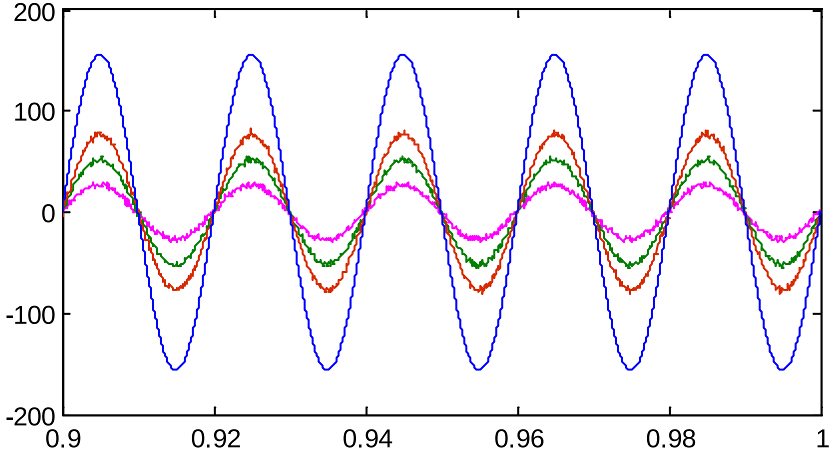
P=300W Q=0Var



P=300W Q=100Var

Series-distributed Renewable Generation System Integrated to AC Bus

utility grid voltage(blue)
output voltages of each micro-inverter (red， green, pinch)



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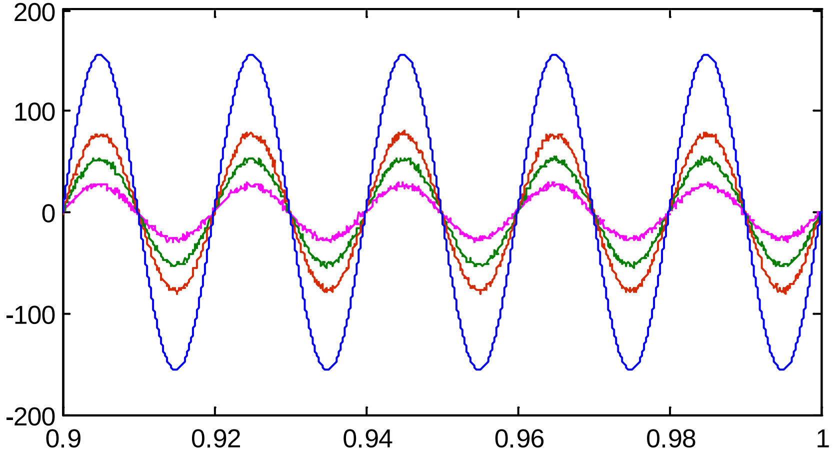

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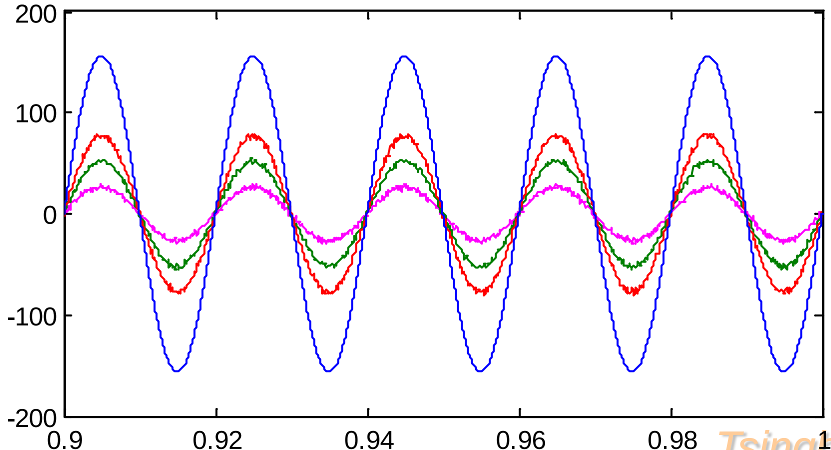

P=300W Q=100Var

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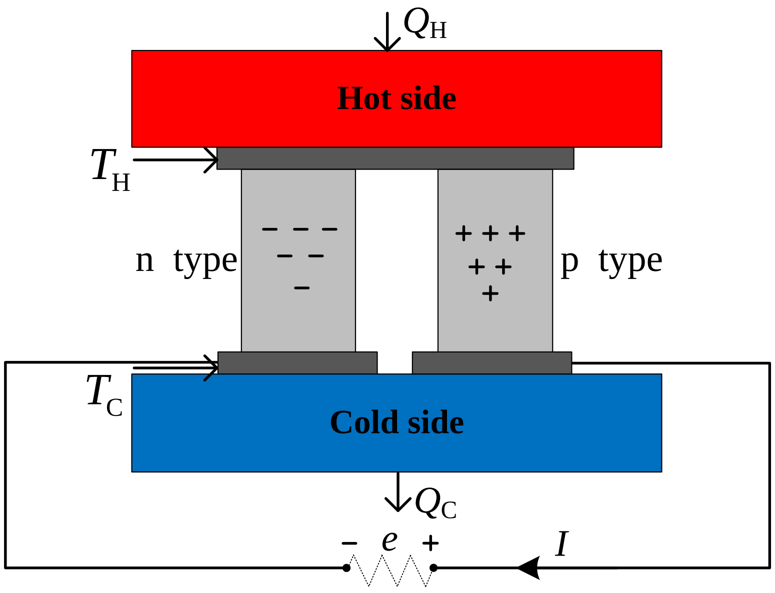
Differential Power Processing Renewable Generation System Integrated to DC Bus

Generation systems connected to DC bus are studied, to take TEG(thermoelectric generation) as an example :



Schematic diagram of TEG

Advantages of TEG:

- Environmentally friendly for waste heat generation
- A wide range of heat source
- High reliability and long lifetime

Problems :

- Power mismatch due to differences of the modules characteristics and temperature

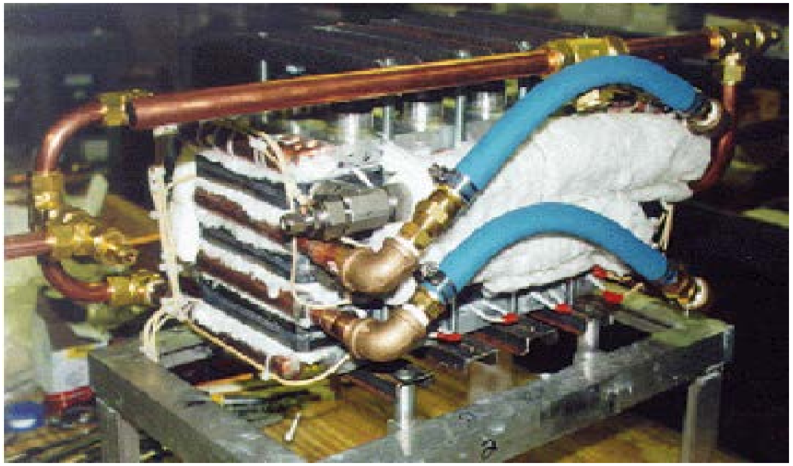
Differential Power Processing Renewable Generation System Integrated to DC Bus

Main applications of TEG system according to different heat sources：

Waste heat recovery TEG: to take car exhaust and industrial waste heat as heat sources, is used for improving the utilization rate of power

Fuel TEG: to take fuel gas or hydroxyl fuel as heat sources, is used for some special applications such as field survival and pipe protection

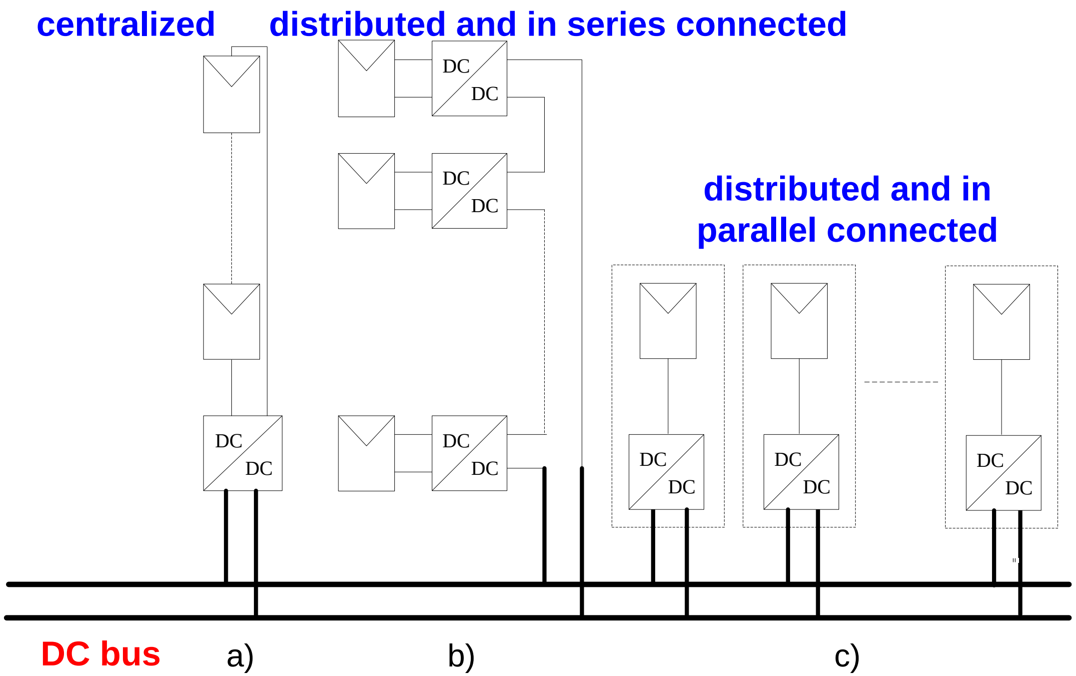
330W waste heat generator of engine gas



500W waste heat generator of refuse burning

Differential Power Processing Renewable Generation System Integrated to DC Bus

Referring to the structure of photovoltaic generation systems connected to DC bus, there are centralized and distributed topologies in TEG systems

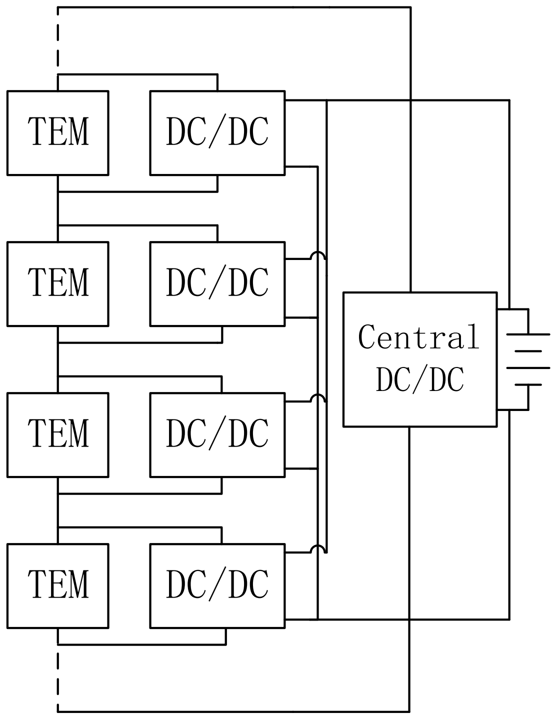


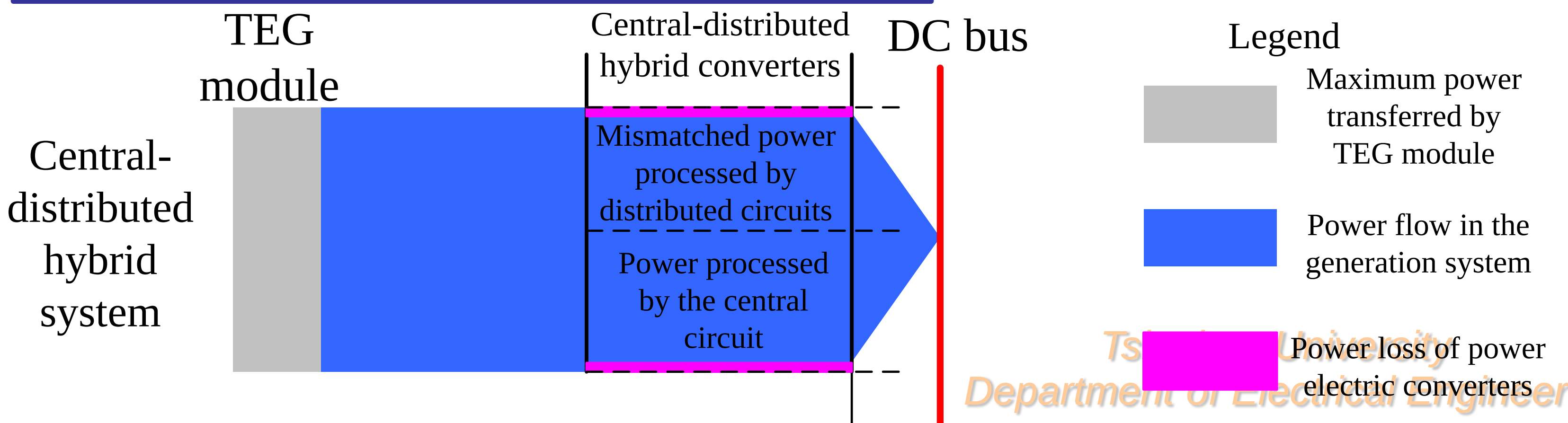
Central system has higher conversion efficiency but lower MPPT efficiency;
Distributed system has high MPPT efficiency but lower conversion efficiency;
To achieve the highest power transform efficiency, the central-distributed hybrid scheme based on power balancing mechanism is adopted.

Differential Power Processing Renewable Generation System Integrated to DC Bus

Improved parallel power balancing system

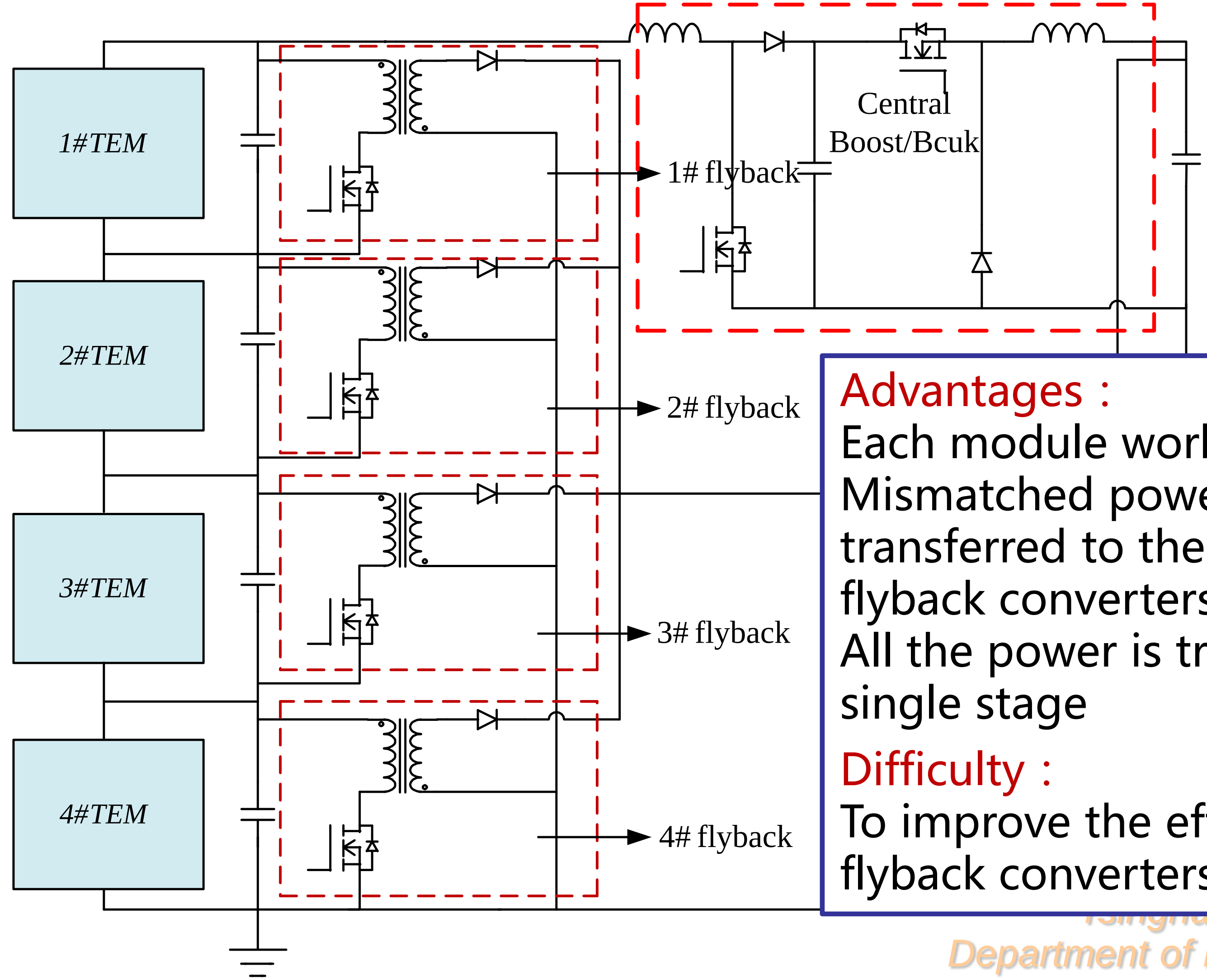
- When power matches, only central circuit works.
- Only mismatched power is processed by distributed circuits
- All the power is transformed by single stage
- Isolated circuits are adopted in distributed converters





Differential Power Processing Renewable Generation System Integrated to DC Bus

Improved parallel power balancing system

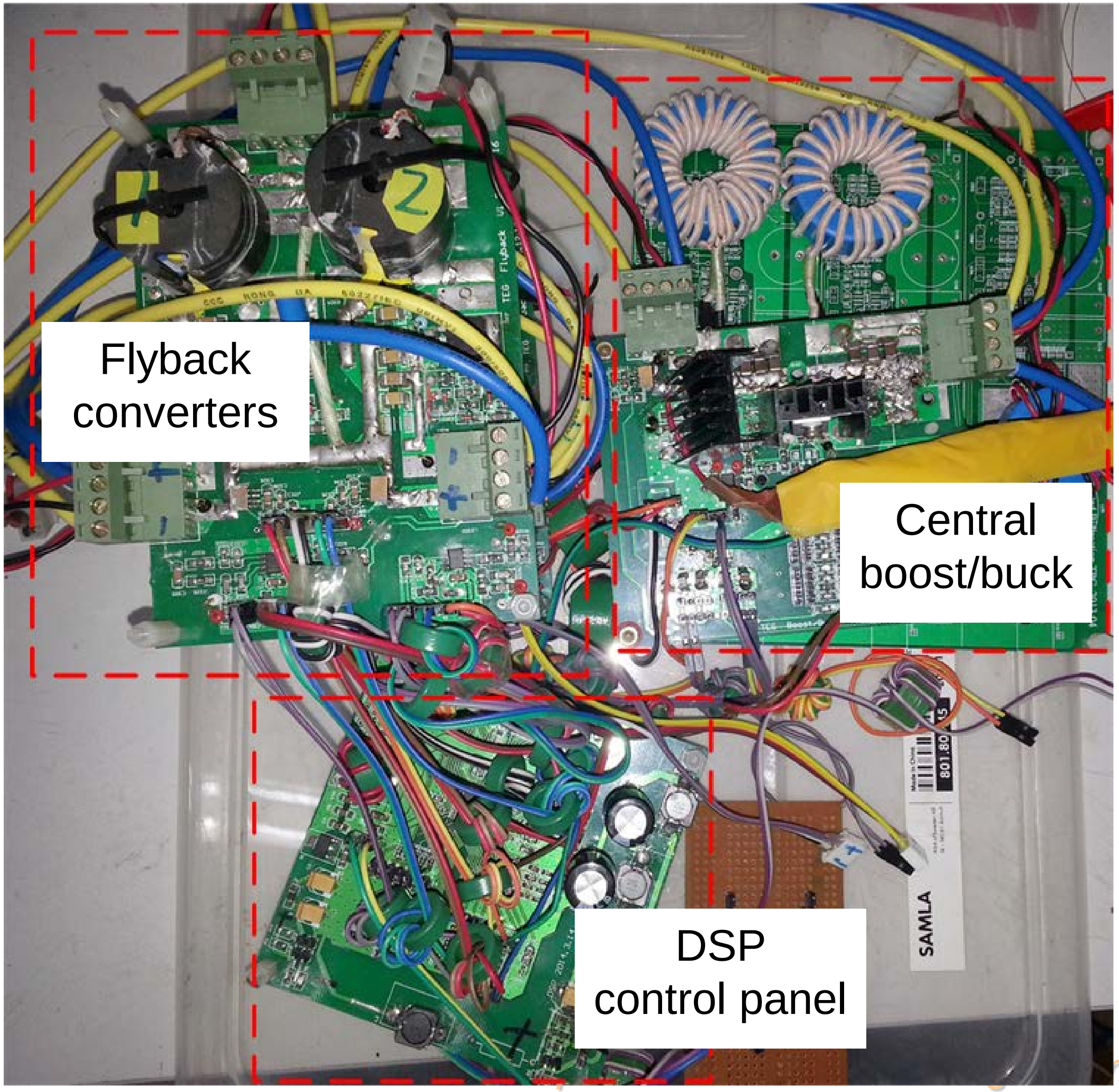


Advantages：
Each module works at its MPP;
Mismatched power is directly transferred to the output by flyback converters;
All the power is transformed by single stage

Difficulty：
To improve the efficiency of flyback converters。

Differential Power Processing Renewable Generation System Integrated to DC Bus

Experimental prototype of improved parallel power balancing system

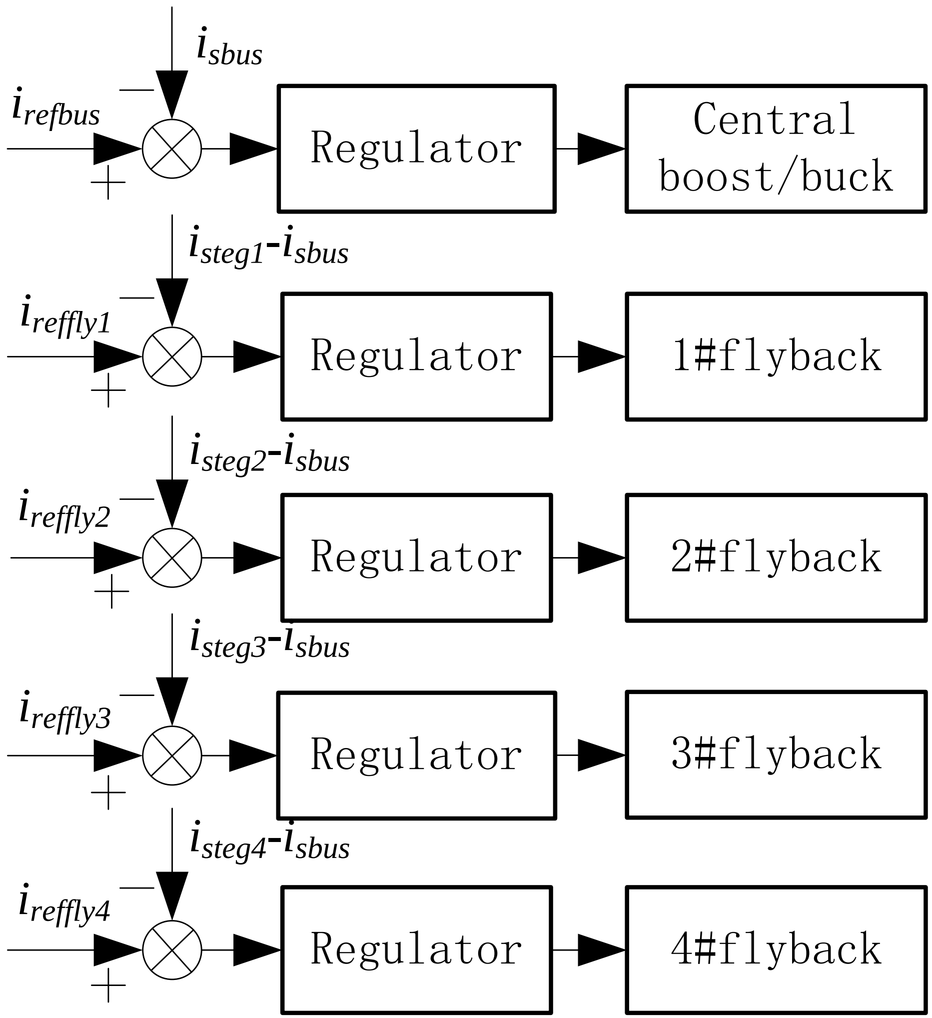


Differential Power Processing Renewable Generation System Integrated to DC Bus

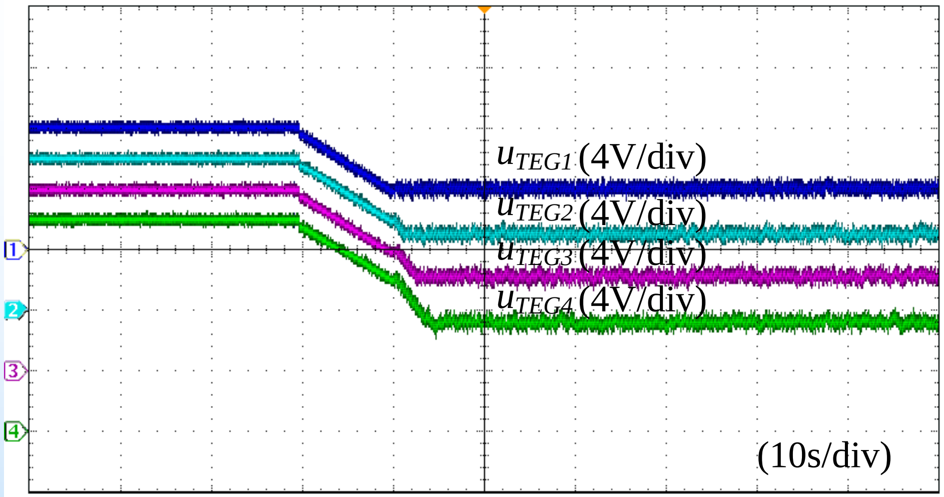
Control principle of the improved parallel power balancing system

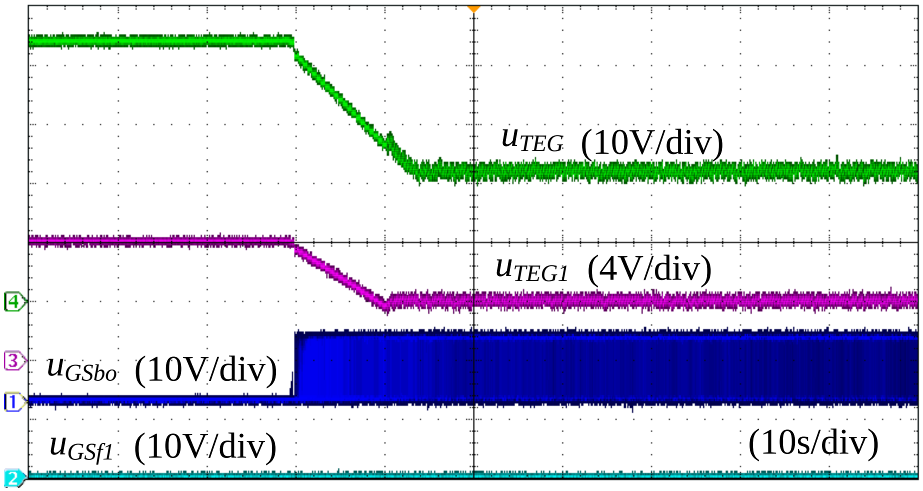
- The bus current is controlled by the central circuit and regulated to the MPP current

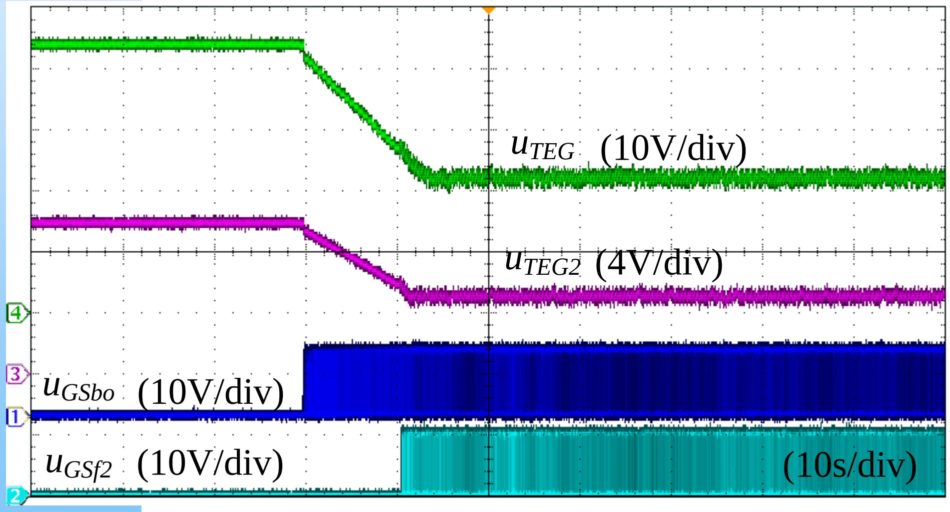
- Differential currents are controlled by distributed circuits, and makes each TEG module reach its MPP



Differential Power Processing Renewable Generation System Integrated to DC Bus







Internal resistance of each module is 2Ω;

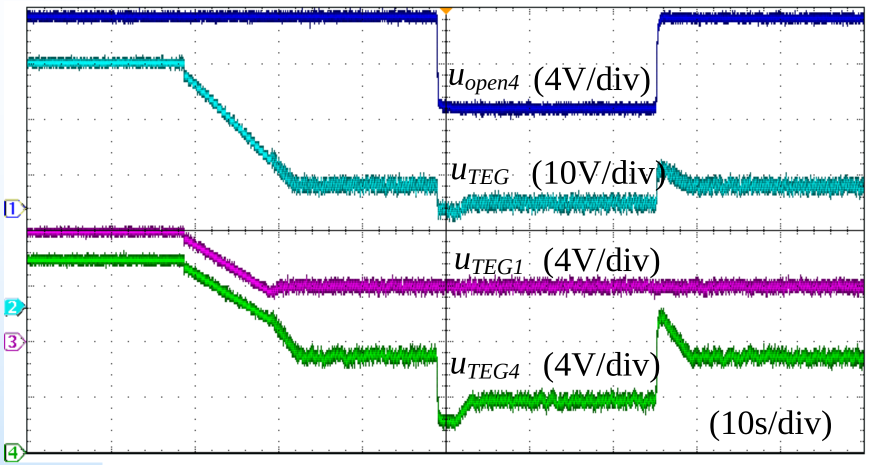
Open circuit voltages of 4 TEG modules are 8V, 10V, 12V and 14V, respectively. 1#flyback is turned off for 1#TEG has the smallest MPP current.

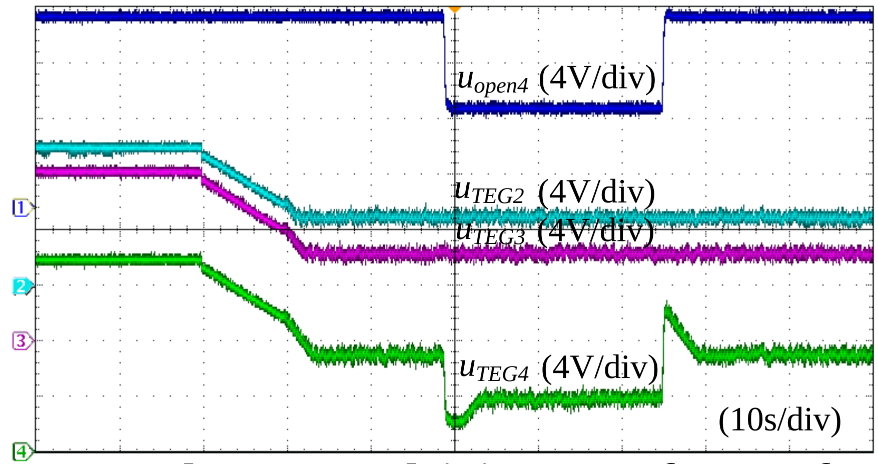
u_{TEG1}, u_{TEG2} , u_{TEG3} , u_{TEG4} and u_{TEG} are output voltages of 4 TEG modules and the bus voltage.

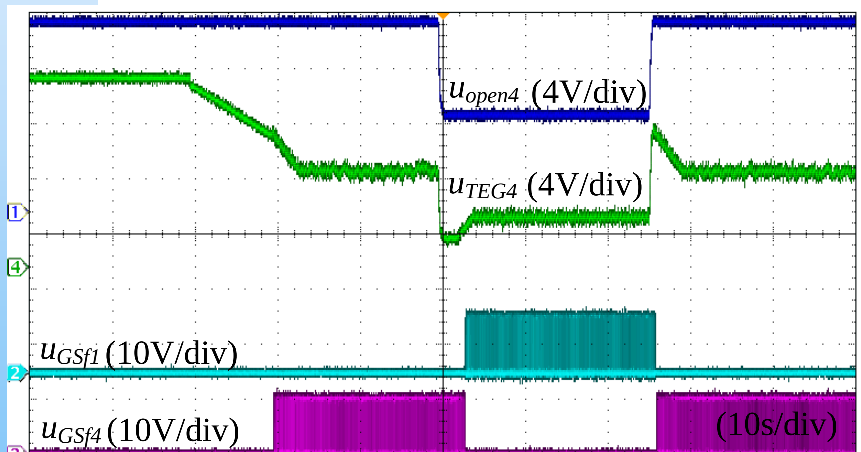
u_{GSbo} is the driving waveform of switch in the boost converter. u_{GSf1} and u_{GSf2} are driving waveforms of switches in 1# and 2# flyback.

Results of steady experiment: each TEG module works at its MPP

Differential Power Processing Renewable Generation System Integrated to DC Bus







Results of dynamic experiment:

temperature variation leads to voltage jump

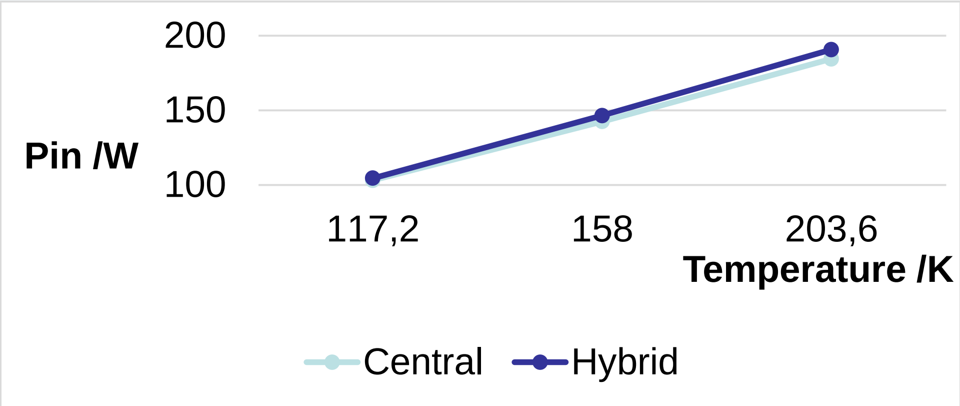
u_{GSf1} and u_{GSf4} are driving waveforms of switches in 1# and 4# flyback.

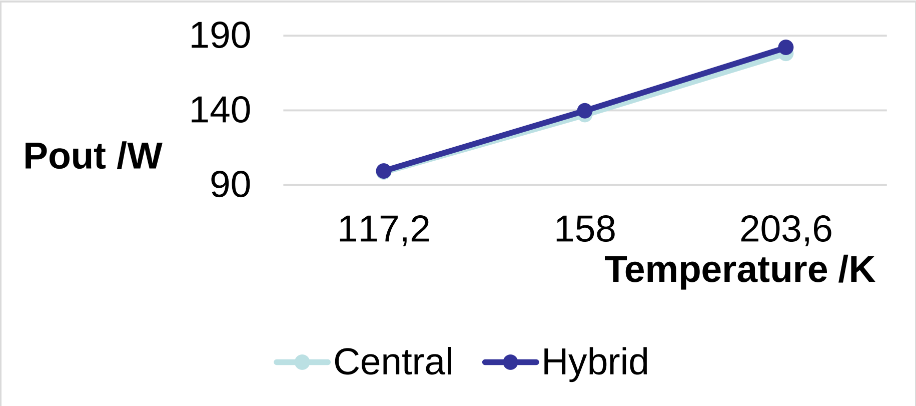
The open circuit voltage of 4#TEG, u_{open4} changes from 14V to 7V and then jumps to 14V.

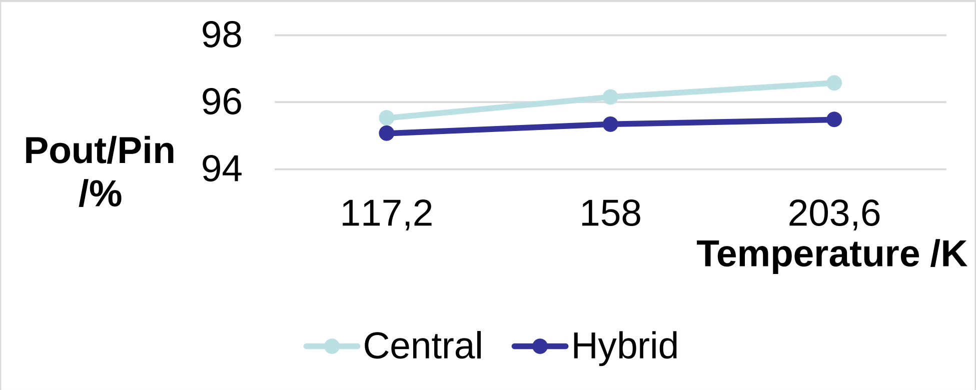
When u_{open4} is 7V 4#TEG has the smallest MPP current and therefore 1#flyback is turned on and 4#flyback is turned off.

When u_{open4} returns to 14V 4#TEG has the largest MPP current so 1#flyback is turned off and 4#flyback is turned on.

Differential Power Processing Renewable Generation System Integrated to DC Bus







Results of efficiency comparison——

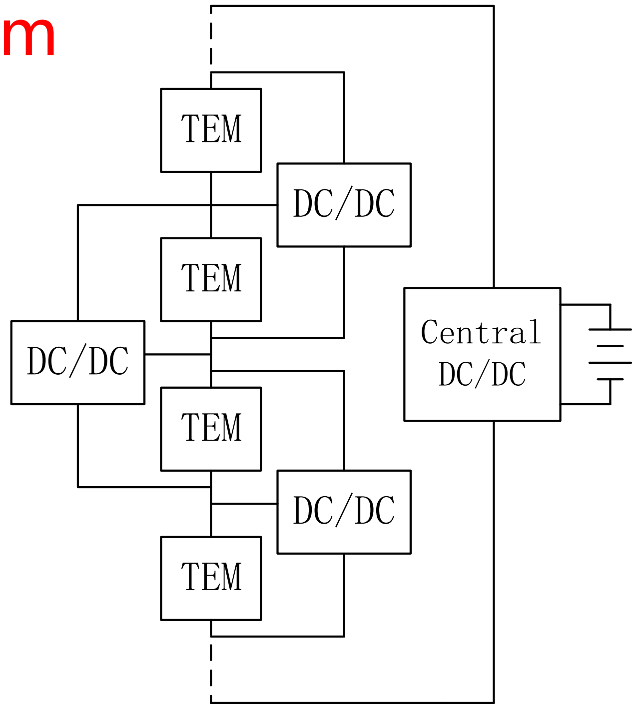
The system contains 4 TEG modules and the temperature differences are distributed linearly.

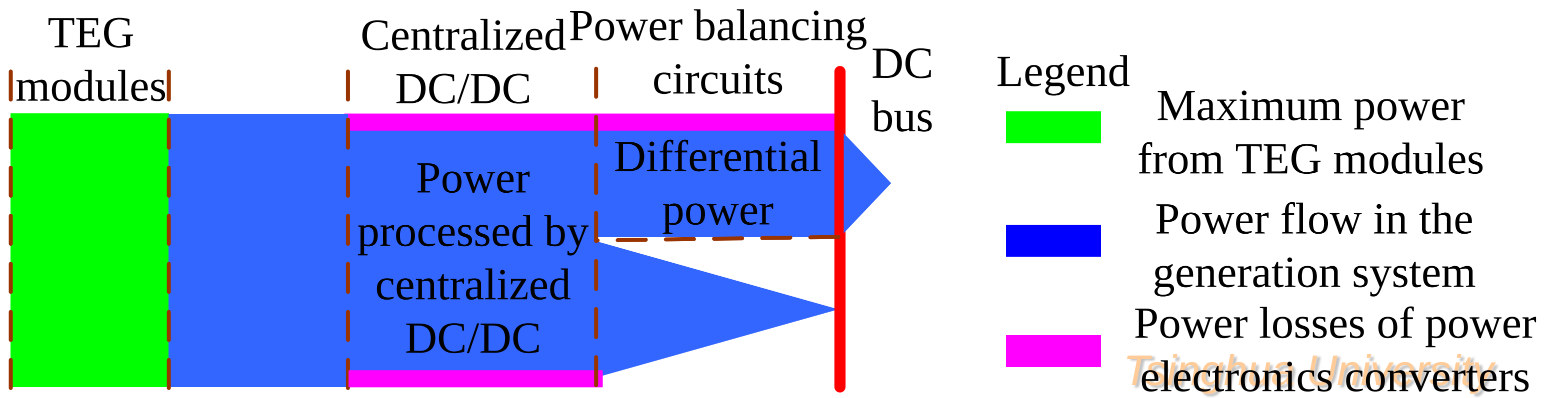
The improved parallel power balancing system based on central-distributed hybrid scheme has lower efficiency compared with the central system. However, with higher MPPT efficiency, the whole system has higher energy conversion efficiency.

Differential Power Processing Renewable Generation System Integrated to DC Bus

Cascaded power balancing system

- When power matches, only central circuit works.
- Only mismatched power is processed by power balancing circuits
- None isolated topology can be adopted in power balancing circuits
- Part of the mismatched power is transformed by multiple stages





Differential Power Processing Renewable Generation System Integrated to DC Bus

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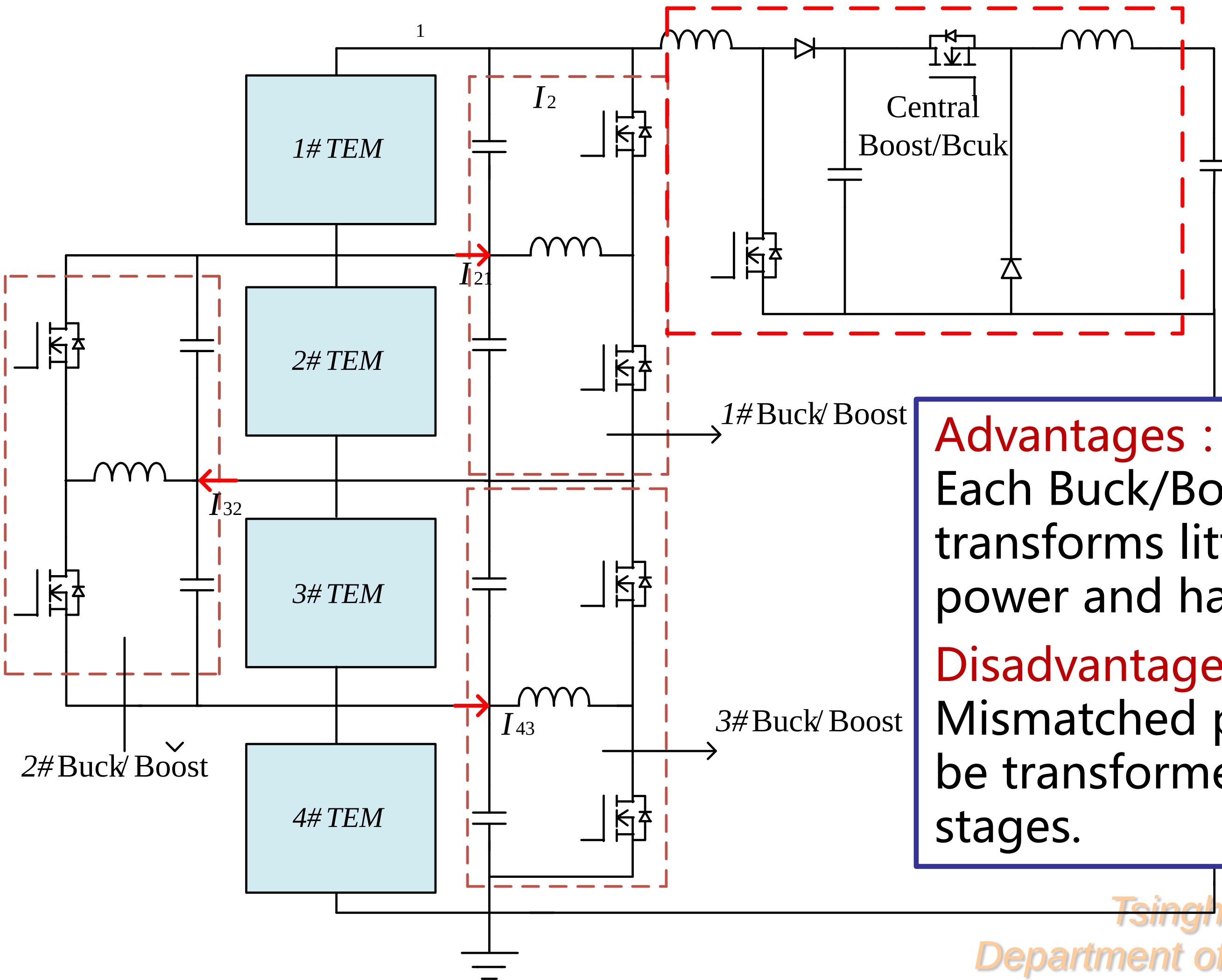
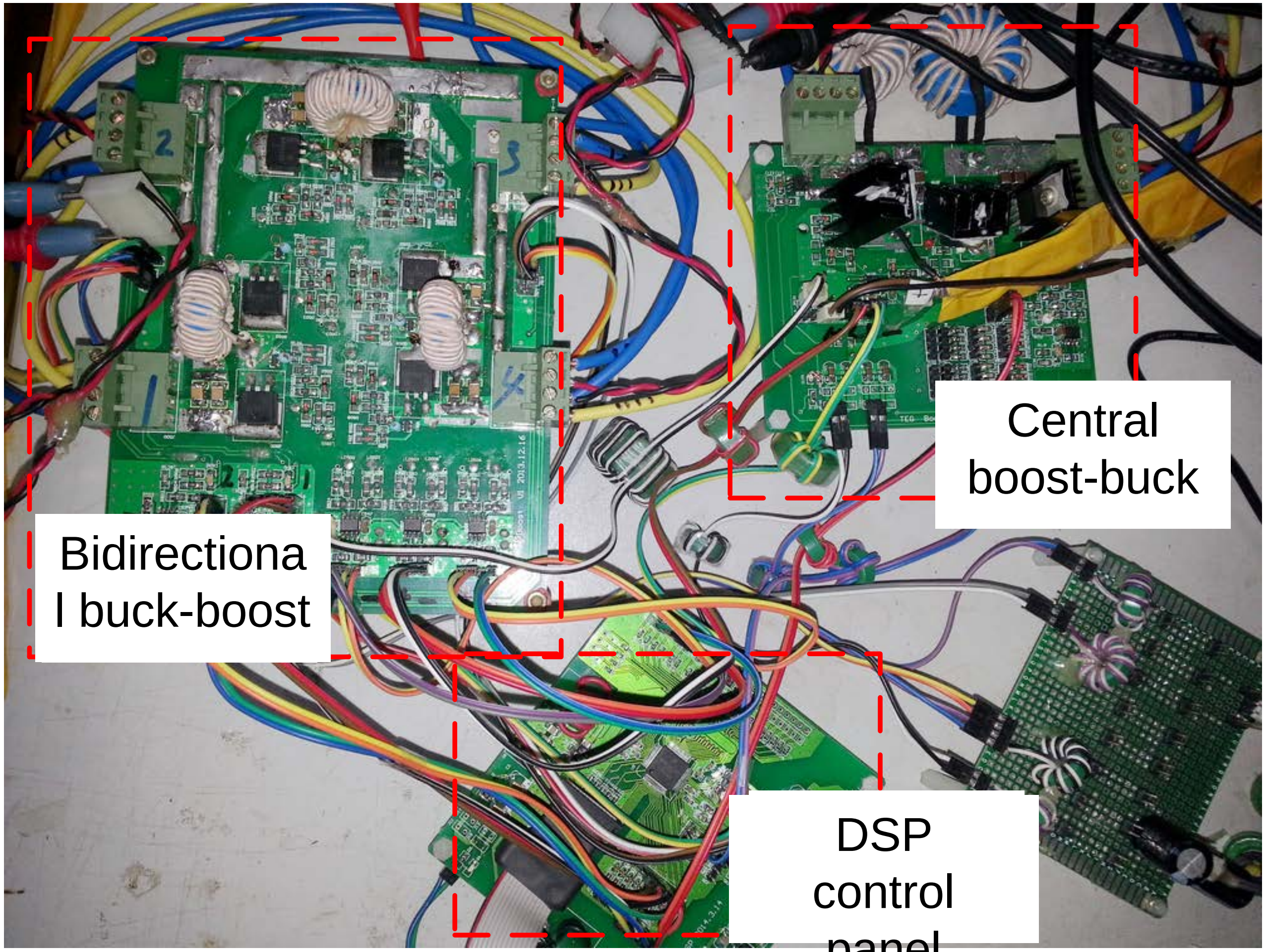


Advantages：
Each Buck/Boost converter transforms little mismatched power and has high efficiency.

Disadvantages：
Mismatched power needs to be transformed by multiple stages.

Differential Power Processing Renewable Generation System Integrated to DC Bus

Experimental prototype of cascaded power balancing system



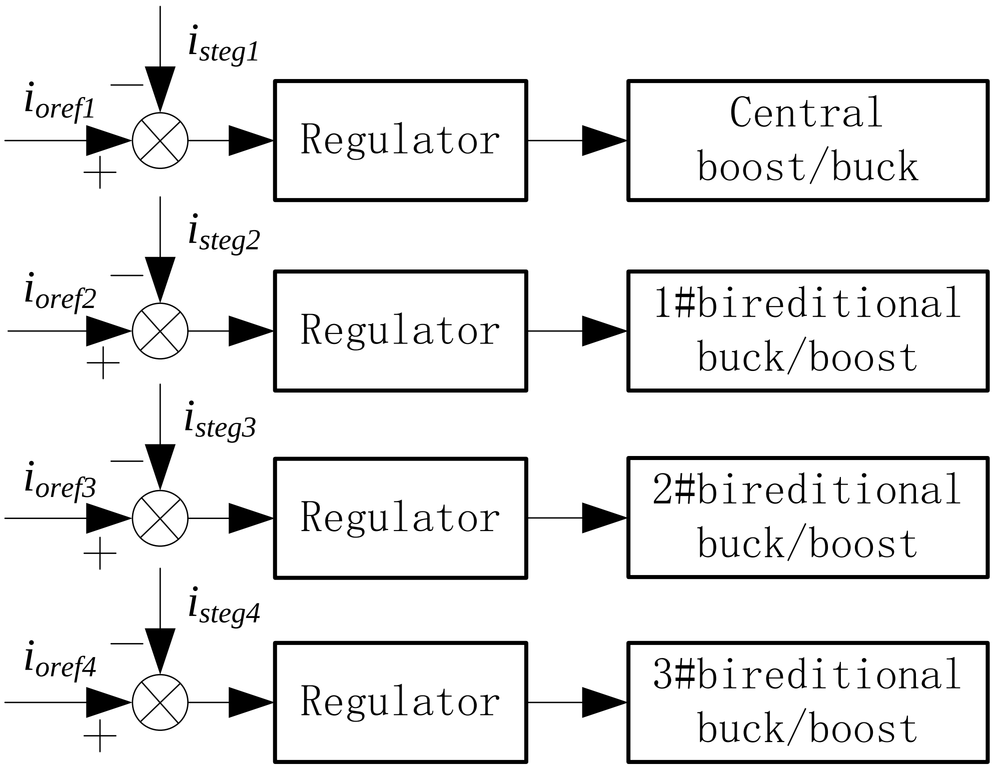
Differential Power Processing Renewable Generation System Integrated to DC Bus

Control principles of cascaded power balancing system

- N TEG modules, one central circuit and N-1 power balancing circuits must work together

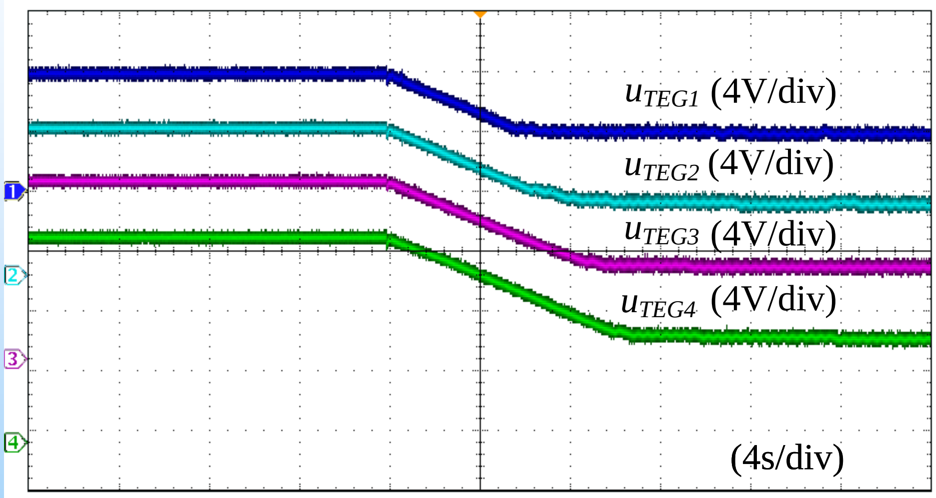
- The bus current is controlled by the central circuit and regulated to the MPP current

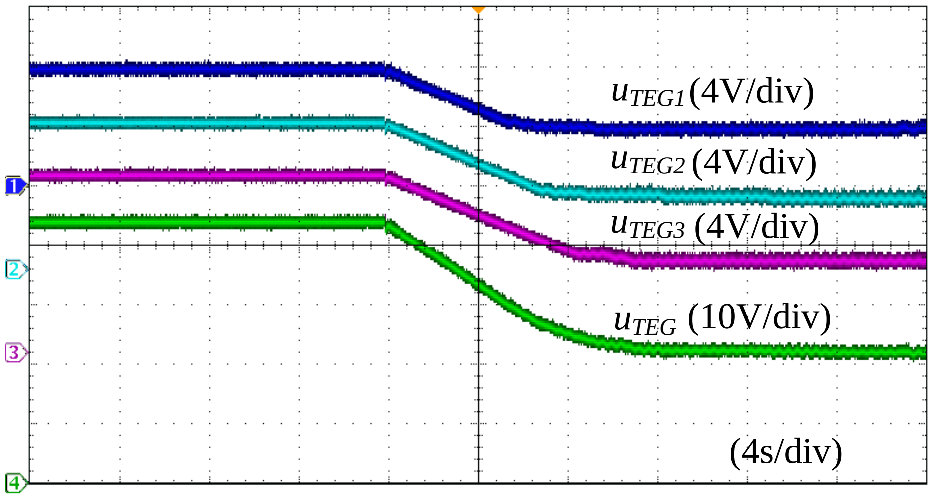
- Differential currents are controlled by power balancing circuits to make each TEG module reach its MPP



Differential Power Processing Renewable Generation System Integrated to DC Bus

Results of steady experiment——
Each module works at its MPP





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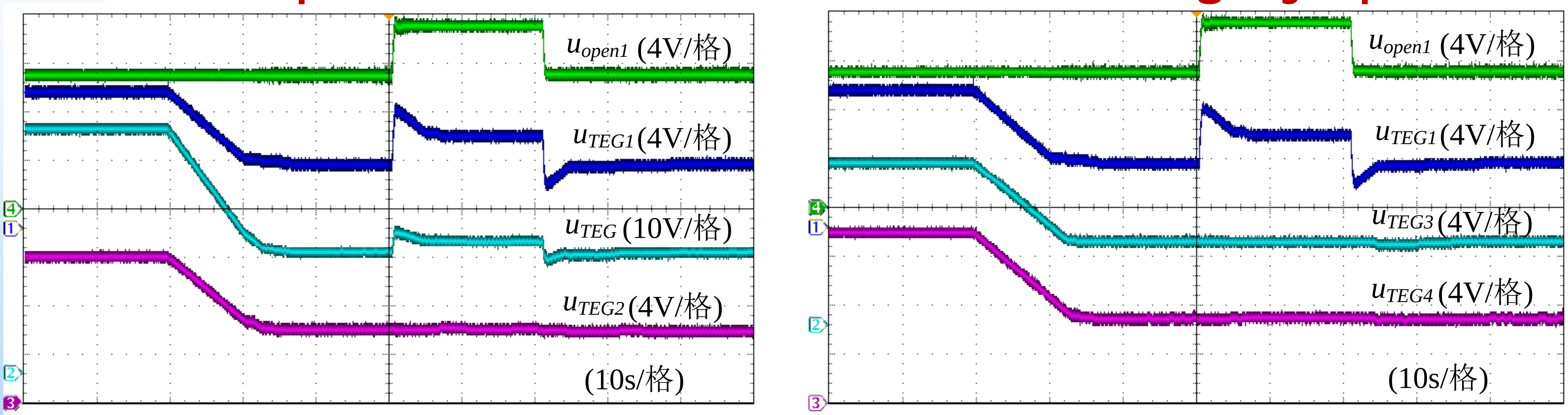
Differential Power Processing Renewable Generation System Integrated to DC Bus

Results of dynamic experiment——Temperature variation leads to voltage jump



Internal resistance of each module is 2Ω;

Open circuit voltages of 4 TEG modules are 8V, 10V, 12V and 14V, respectively.

u_{TEG1}, u_{TEG2} , u_{TEG3} , u_{TEG4} and u_{TEG} are output voltages of 4 TEG modules and the bus voltage.

The open voltage of 1#TEG, u_{open1} changes from 11V to 15V and then returns to 11V。

Outlines

Introduction

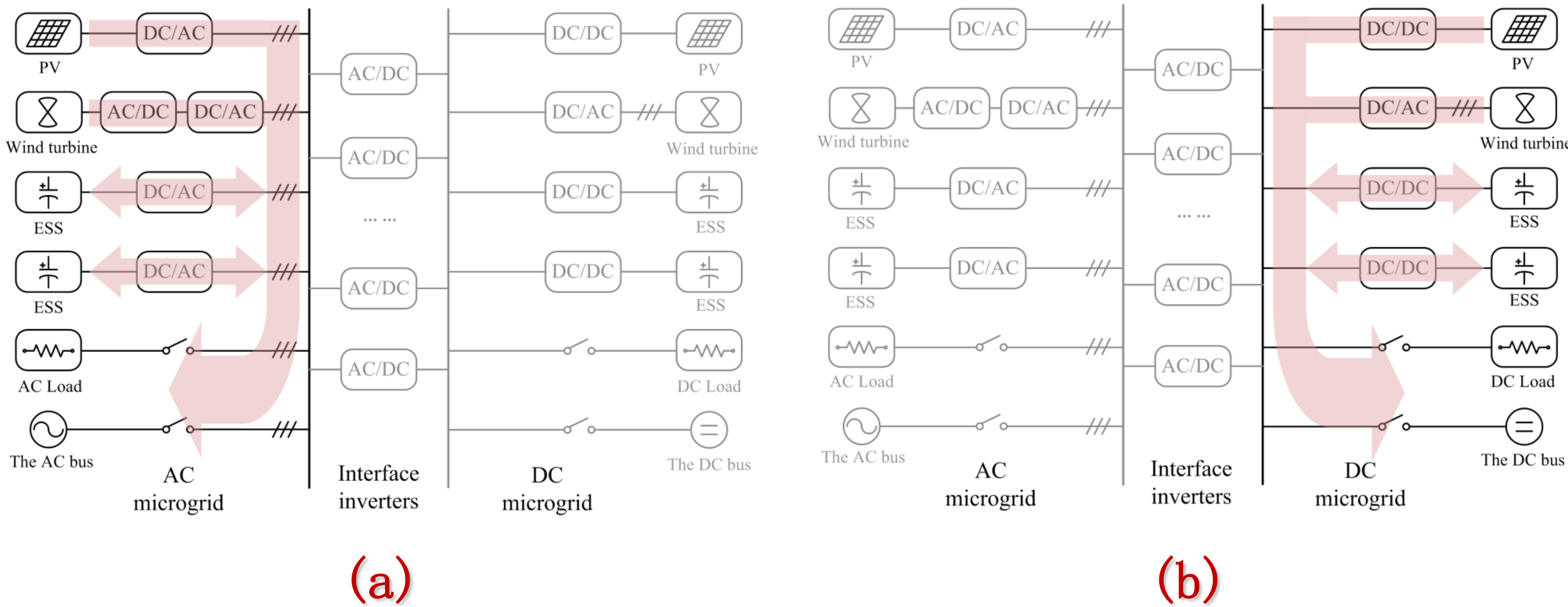
Series-distributed Renewable Generation System Integrated to AC Bus

Differential Power Processing Renewable Generation System Integrated to DC Bus

Control of AC/DC Interfacing Converters

Summary & Perspective

Control of AC/DC Interfacing Converters



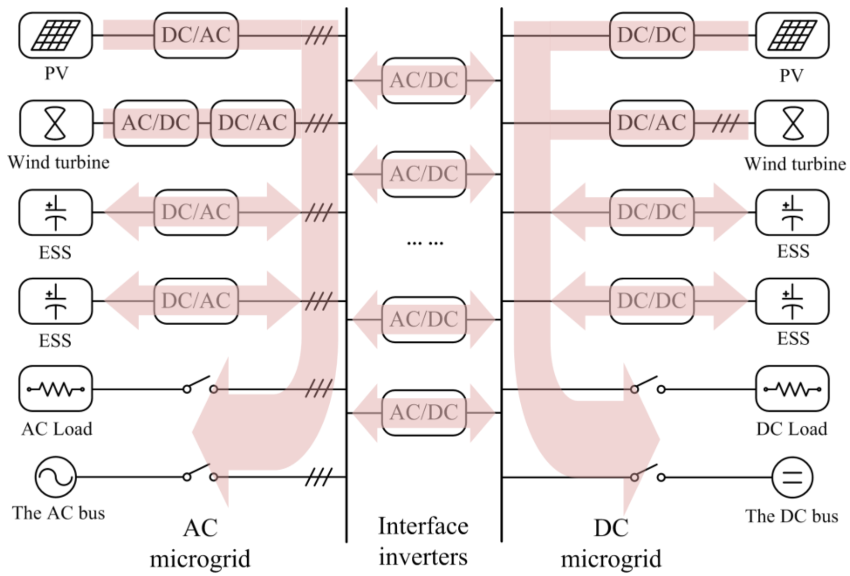
Different operation modes in an ac-dc hybrid microgrid

(a) AC microgrid operation (b) DC microgrid operation

(c) AC and DC microgrid in hybrid operation

(d) DC to AC power flow (e) Ac to DC power flow

Control of AC/DC Interfacing Converters



(c)

Different operation modes in an ac-dc hybrid microgrid

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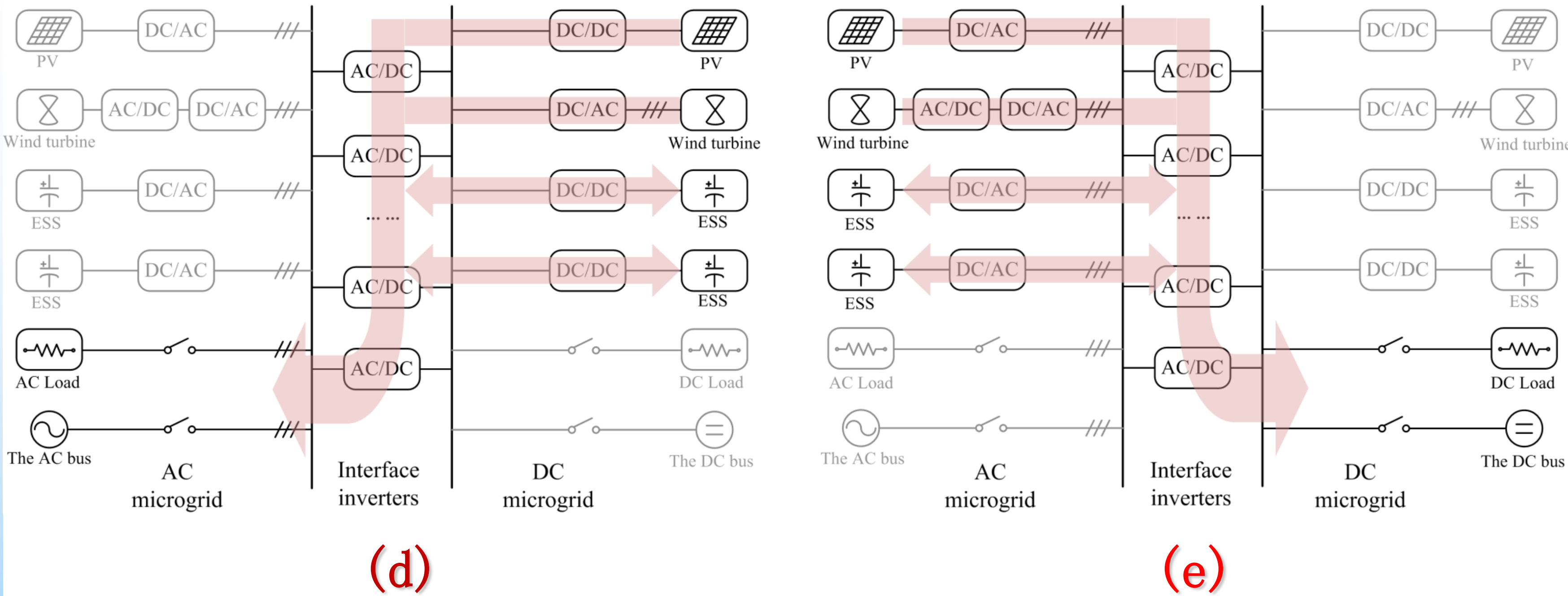
Control of AC/DC Interfacing Converters



Different operation modes in an ac-dc hybrid microgrid

(a) AC microgrid operation (b) DC microgrid operation

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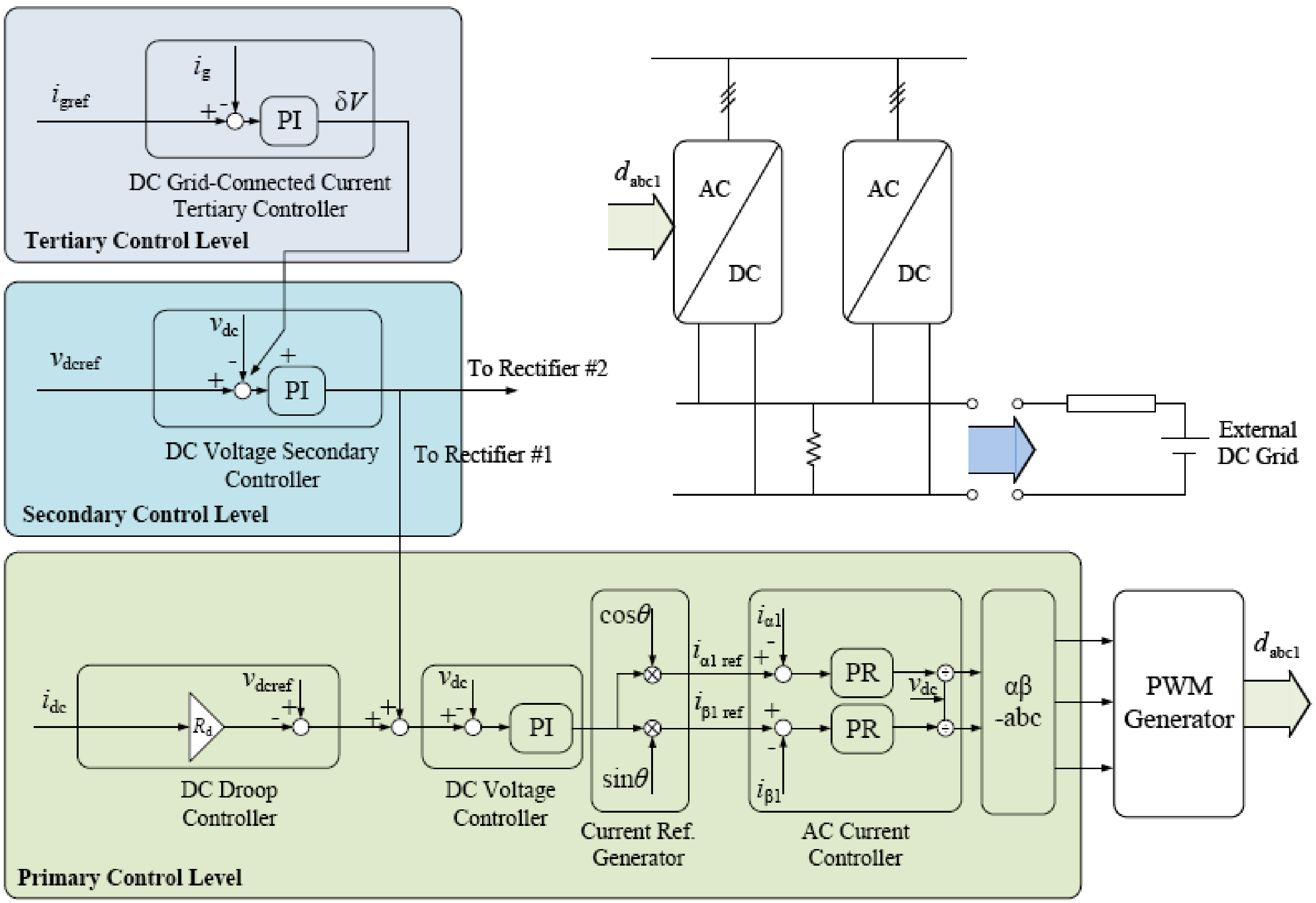
Control of AC/DC Interfacing Converters

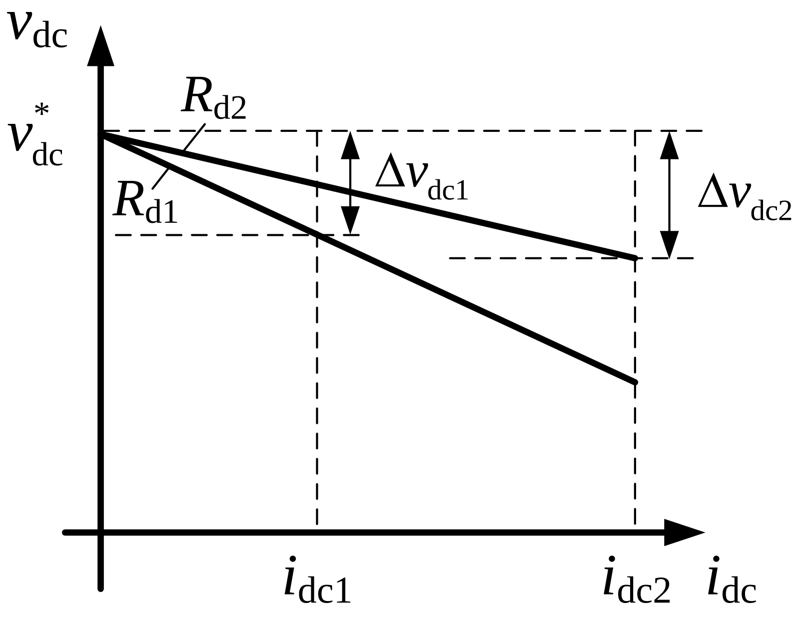
DC hierarchical control System for the interfacing converters between AC and DC buses (mode (e))



Control of AC/DC Interfacing Converters

The problem of droop control

- Bus voltage drop
- Inaccurate load sharing



The principle of droop control

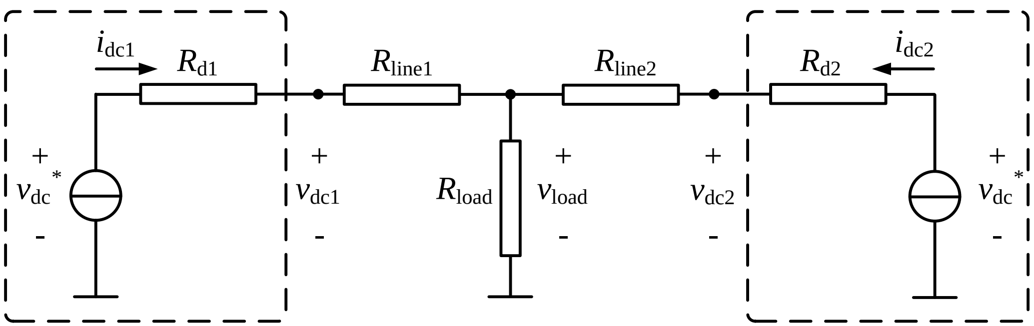
Control of AC/DC Interfacing Converters

The problem of droop control

- Bus voltage drop
- Inaccurate load sharing

$$v_{\mathrm{dc}} = v_{\mathrm{dc}}^{*} - i_{\mathrm{dc1}} \cdot R_{\mathrm{d1}}$$

$$v_{\mathrm{dc}} = v_{\mathrm{dc}}^{*} - i_{\mathrm{dc2}} \cdot R_{\mathrm{d2}}$$



The equivalent circuit for DC side of microgrid

$$v_{\mathrm{load}} = v_{\mathrm{dc}}^{*} - i_{\mathrm{dc1}} \cdot R_{\mathrm{d1}} - i_{\mathrm{dc1}} \cdot R_{\mathrm{line1}}$$

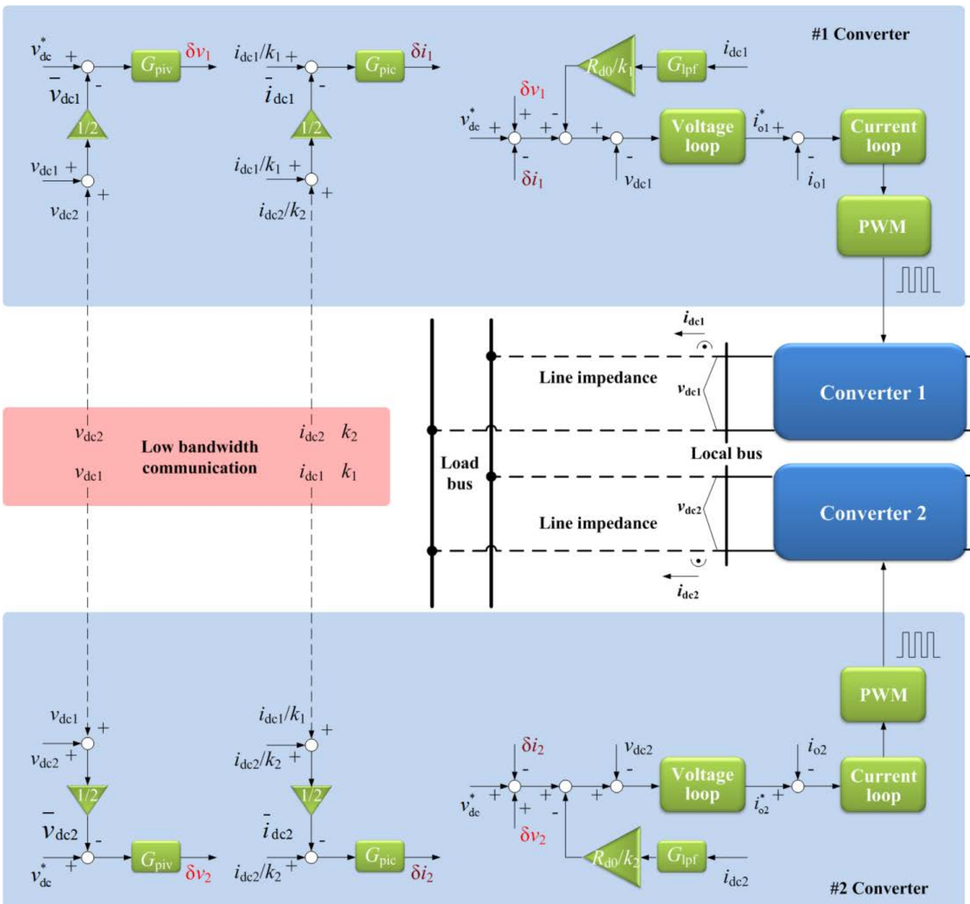
$$v_{\mathrm{load}} = v_{\mathrm{dc}}^{*} - i_{\mathrm{dc2}} \cdot R_{\mathrm{d2}} - i_{\mathrm{dc2}} \cdot R_{\mathrm{line2}}$$

$$\frac{i_{\mathrm{dc1}}}{i_{\mathrm{dc2}}} = \frac{R_{\mathrm{d2}}}{R_{\mathrm{d1}}} + \frac{R_{\mathrm{line2}} - R_{\mathrm{d2}} / R_{\mathrm{d1}} \cdot R_{\mathrm{line1}}}{R_{\mathrm{d1}} + R_{\mathrm{line1}}}$$

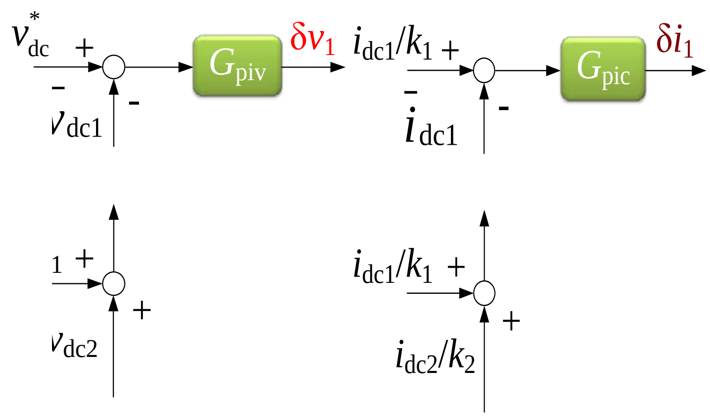
$$\frac{R_{\mathrm{line1}}}{R_{\mathrm{line2}}} = \frac{R_{\mathrm{d1}}}{R_{\mathrm{d2}}}$$

Control of AC/DC Interfacing Converters

The improved droop control:



The load sharing of improved droop



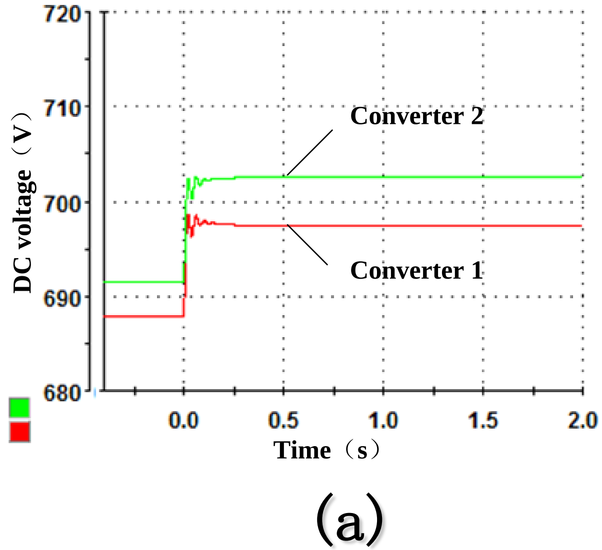
The mean value of voltage and current controller

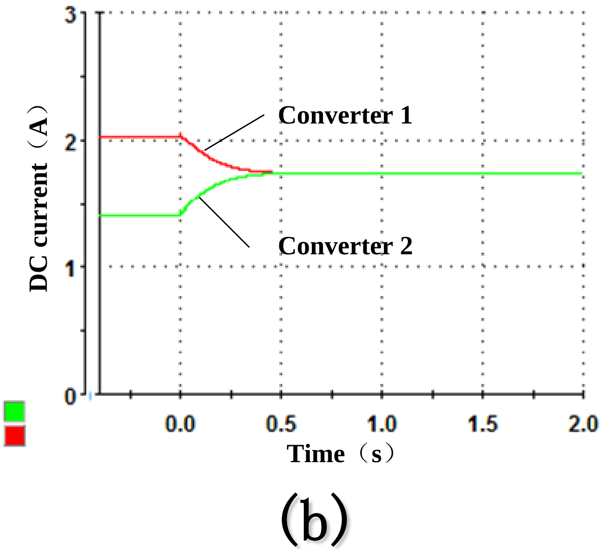
The DC output voltage and current are transferred between converters by a low-bandwidth communication networks, the problems are solved simultaneously based on the proposed controller.

Control of AC/DC Interfacing Converters

The experiment for improved droop control

- The influence of communication delay



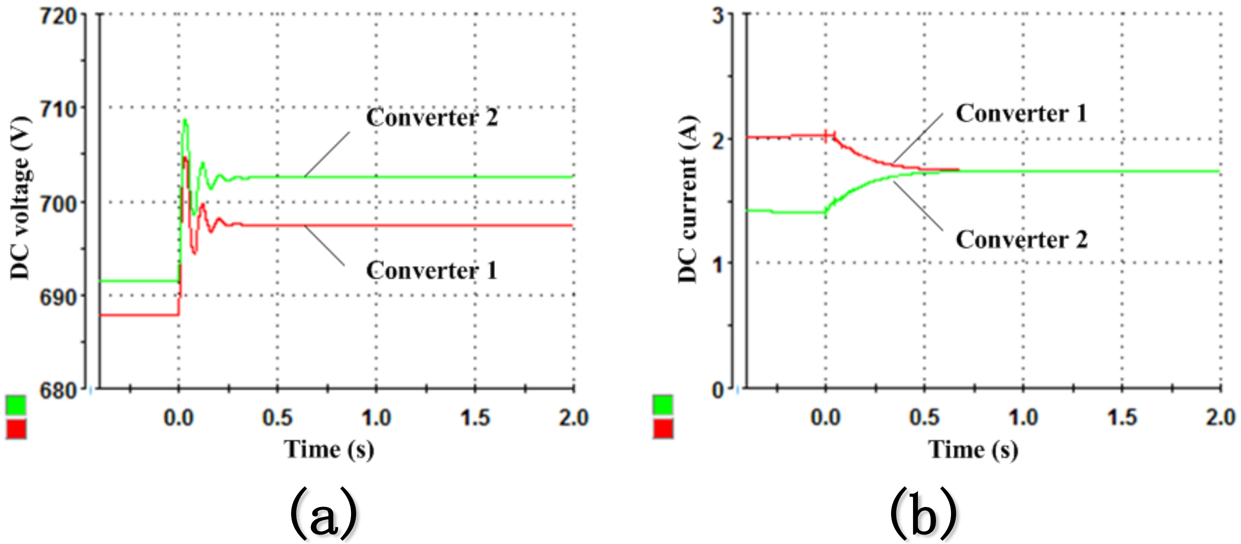


The results of original and improved control
（Communication delay：1μs）
(a) The DC voltage (b) The DC current

Control of AC/DC Interfacing Converters

The experiment for improved droop control

- The influence of communication delay



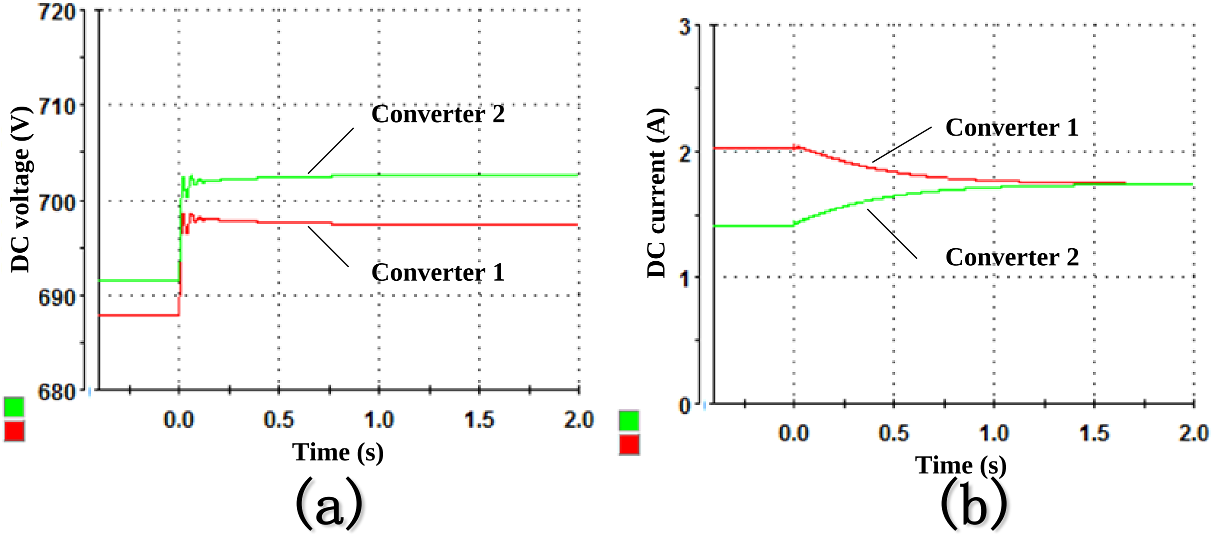
The results of original and improved control
（Communication delay：20ms）
(a) The DC voltage (b) The DC current

•The system stability can be guaranteed with large communication delay

Control of AC/DC Interfacing Converters

The experiment for improved droop control

- The influence of line impedance



The results of original and improved control

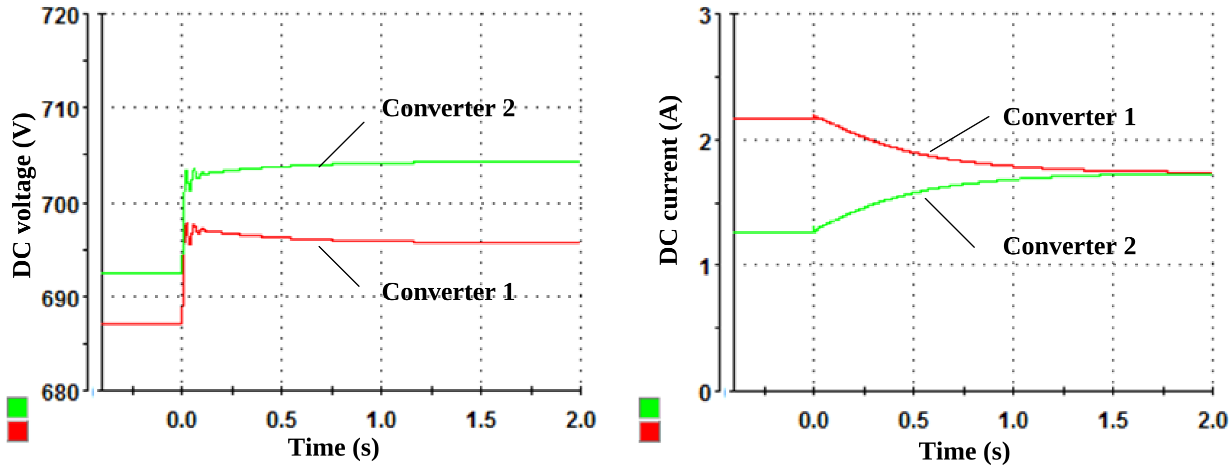
（ $R_{line1}/R_{line2}=1/4$ ）

(a) The DC voltage (b) The DC current

Control of AC/DC Interfacing Converters

The experiment for improved droop control

- The influence of line impedance



(a) (b)

The results of original and improved control

（ $R_{line1}/R_{line2}=1/8$ ）

(a) The DC voltage (b) The DC current

•The system stability can be guaranteed with different line impedance

Outlines

Introduction

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Summary & Perspective

Summary

- For AC bus access: A series renewable energy distributed power generation systems and corresponding distributed control strategy is proposed. The MPPT of single disturbed power generator is ensured, and the system is implemented based on low-gain converter, the system efficiency is improved, and the system is suitable for grid scheduling.
- For the DC bus access: Two novel energy power balanced generation systems are propose. The MPPT of disturbed power generator is guaranteed and the maximum energy conversion efficiency of whole system is achieved through the optimization of power flow.
- For interfacing converter: A improved load sharing strategy based on droop control is proposed. The mean value of DC voltage and current is controlled based on a low-bandwidth communications network. The bus voltage is restored and the load sharing accuracy is improved.

Perspective

- Research on the control of renewable energy generator involving in the maintenance of the grid voltage, frequency, and on optimization control when the power quality improvement is required.
- Research on the control strategy when the DC bus voltage fluctuations resulting from AC bus malfunction.
- Research on the novel interface switch based on a solid state power electronics transformer (SST) in AC/DC hybrid microgrid.

End

Thank you for your attention!