Hybrid Generation Systems and Fuel Cell: Introduction and Intelligent Control of Fuel Cell Power Plants

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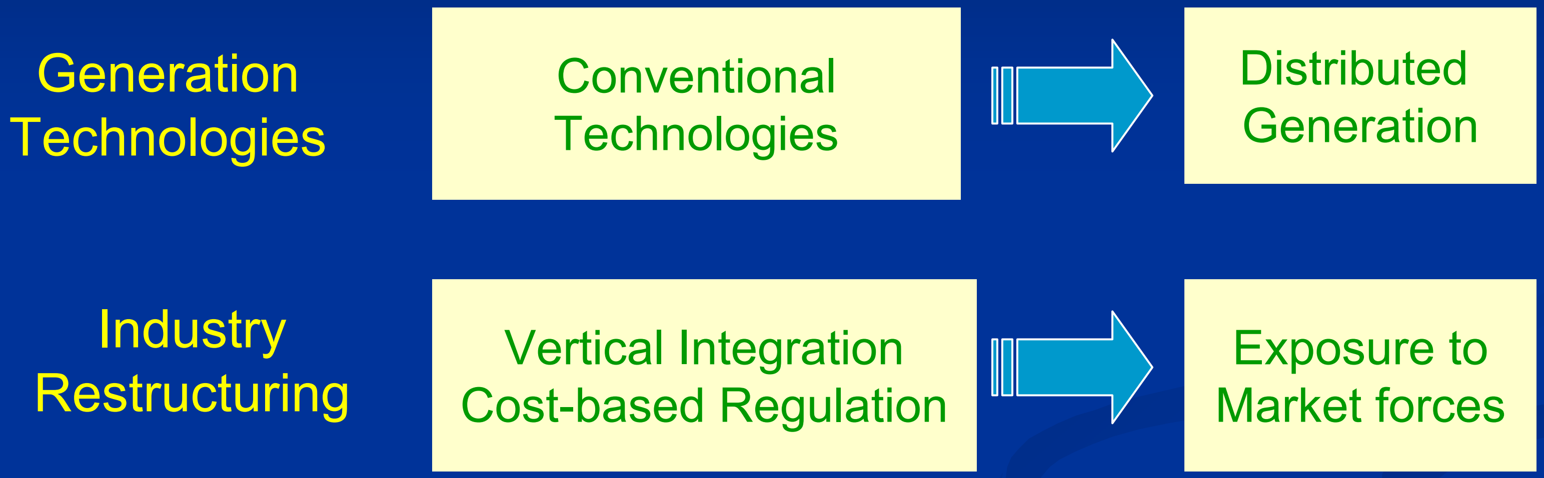
I. Introduction

☐ DG in competitive electric market



Generation Technologies

Conventional Technologies

Distributed Generation

Industry Restructuring

Vertical Integration Cost-based Regulation

Exposure to Market forces

☐ Benefits of DG

- high fuel efficiency
- short construction time
- modular installation
- low capital expense

1. Deregulation in Electricity Energy Markets

1. Electricity Restructuring

- ☐ Transition: regulation ⇨ competition

  - to provide ample electricity at reasonable prices, states open retail markets to competition

- ☐ Wholesale level (1996)

  - FERC (Federal Energy Regulatory Commission) provided open access to transmission systems

- ☐ Retail level

  - some states required utilities to divest generation assets as part of restructuring

2. Changes in Wholesale Electricity Market

- ☐ Enactment of Public Utility Regulatory Policies Act (1978)

  - promote independent electricity generation

- ☐ FERC adopted open-access transmission policies (1980)

  - promote competition in wholesale power markets

- ☐ Enactment of Energy Policy Act (1992)

  - promote non-utility generation

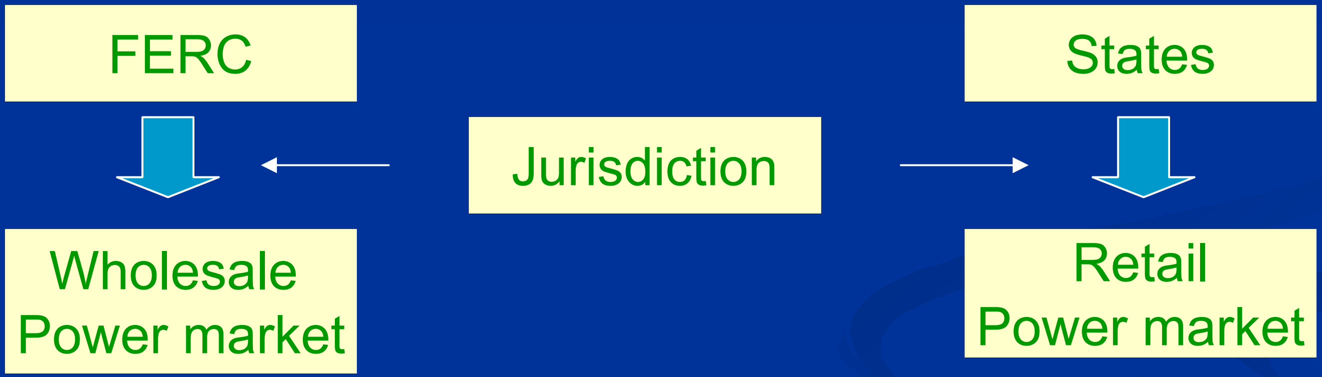
- ☐ FERC took large step with open-access Rule (1996)

  - provide greater access to the transmission grid

3. Changes in Retail Electricity Market

- Increased competition in wholesale markets

  ⇨ encourage to open retail electricity markets



FERC

States

Jurisdiction

Wholesale Power market

Retail Power market

- Most new electricity generation is built by independent power producers

  ⇨ success rides on ability to generate electricity at a low cost

2. Future Energy Sources

1. Hydrogen

- The most common element in the universe
  - FC converts hydrogen into energy w/o detrimental environmental effects, producing water as a by-product
  - energy for extracting hydrogen: fuel, renewable sources, nuclear, fossil
    - extremely clean and efficient w/o combustion
- Conversion into Electricity: Fuel Cell
  - NASA developed to generate electricity, heat, water in space vehicles
  - 1st generation (1995): commercial market for stationary power applications
  - 2nd generation : hybrid fuel cell/turbine
- Primary challenge
  - cost reduction for producing, storing, transporting
  - size and weights reduction

2. Strategy of DOE

❑ DOE's Fossil Energy Program

- developing natural gas-powered fuel cells for future DG applications
  - extract hydrogen from natural gas, biomass, coal
- H_2 will reduce oil consumption and emissions of greenhouse gases.

❑ Goal of DOE Hydrogen Program

- developing hydrogen technology for transportation sector
- commercialization on hydrogen-powered fuel cell vehicle in 2015
- beginning of mass market penetration in 2020

- ❑ Renewable Energy Technologies
  - water, wind, solar, geological, biomass ⇨ electricity, fuel, heat
  - Non-hydro power renewable energy: wind, solar, geological, biomass
    - continuously renewable, clean
    - generate income for farmers and landowners
  - not experienced price volatility of other energy resources
- ❑ Long-term challenge of Renewable Energy: economy
  - Greater costs than other energy source

    ⇨ declined sharply in recent years due to improved technology
  - percentage expectation of non-hydropower renewable energy in total electricity generation: 2 % ⇨ 2.8 % by 2020

II. Distributed Generation

- Definition
  - any modular generation located at or near the load center
  - photovoltaic, mini-hydro, wind, fuel cells/microturbines
- Current Trend

Power market liberalization → Renewed interest for DG → Increase of smaller power producer

∗ EPRI Research: 25% of new generation will be DG by 2010

Positive Impacts	Operating Conflicts
▪ voltage support and improved power quality ▪ diversification of power sources ▪ reduction in transmission and distribution losses ▪ improved reliability	▪ over-current protection, ▪ voltage regulation ▪ power quality problems ▪ Ferroresonance

- 5 major contributions to the renewed interest in DG

  (International Energy Agency)

  - Electricity market liberalization
  - Developments in DG technology
  - Constraints on the construction of new transmission lines
  - Increased customer demand for highly reliable electricity
  - Environmental concerns

1. DG Technologies

- Combined Heat and Power
  - overall energy efficiency increase: electricity + heat
  - reciprocating engines, microturbines and fuel cells
- Renewable Energy Generation
  - wind turbines, small and micro hydro power, photovoltaic arrays, solar thermal power, geothermal power
- Effect of dispersed small-scale generators
  - avoid costly investment in large, often polluting central plants
  - deploy generating assets more flexibly
  - reduce T & D losses

2. Types of Distributed Resources

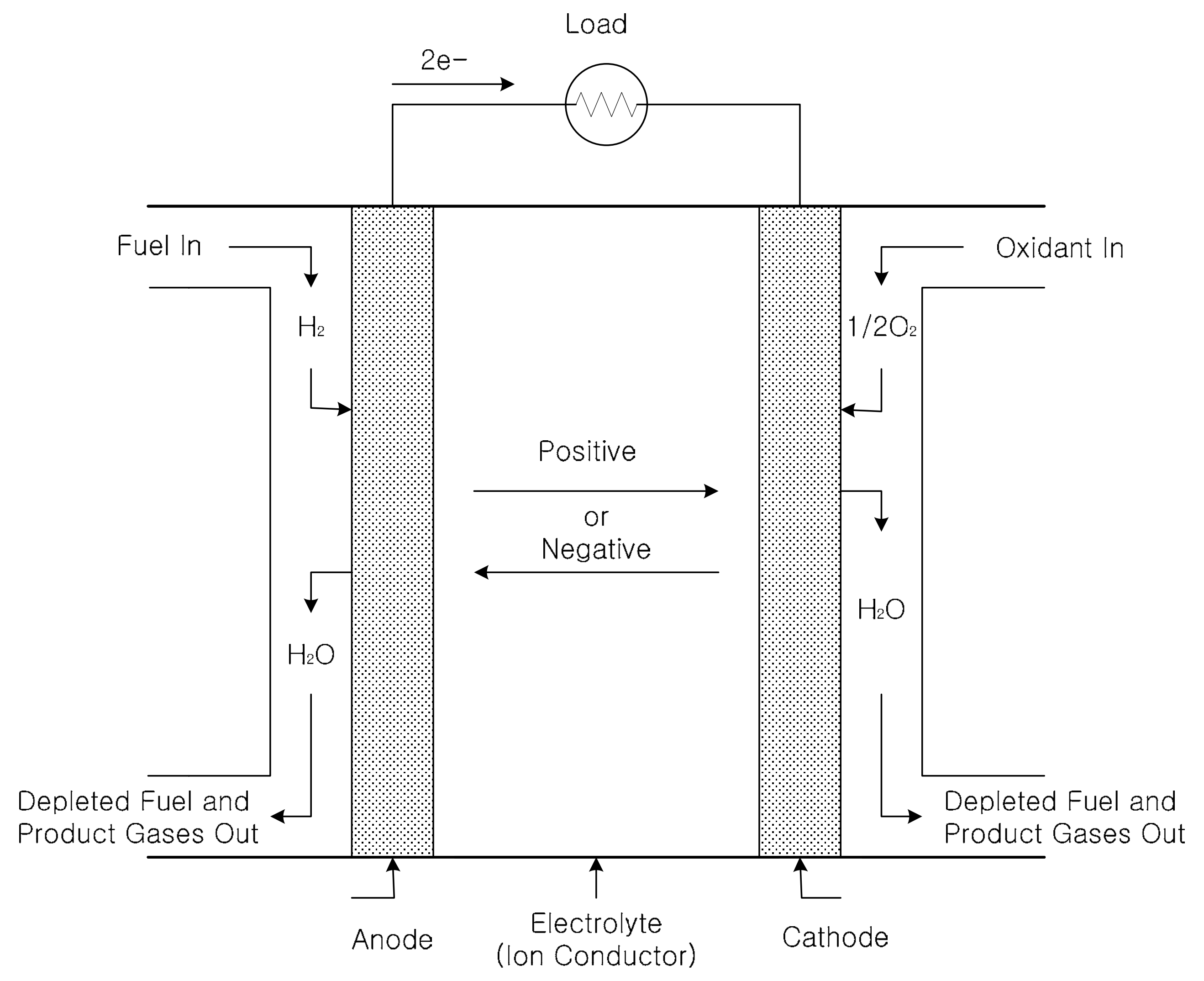
- ☐ wind, biomass
  - constrained by availability of wind and land
- ☐ photovoltaics
  - less cost-competitive compared with natural gas
- ☐ fuel cells and microturbines
  - overall system efficiency improvement
    - generate electricity more cheaply and efficiently than gas-fired plant
  - recovery of pollutants including greenhouse gases
    - emits no carbon
  - photovoltaic-wind-FC configuration
    - increase of environmental sustainability
    - decrease of external costs in electric power generation

III. Fuel Cells

- ☐ electrochemical devices
  - chemical energy (fuel) ⇨ electrical energy (DC)

- ☐ Advantages
  - High energy conversion efficiency
  - Modular design
  - Very low emissions
  - Low noise
  - Fuel flexibility
  - Cogeneration capability
  - Rapid load response, relative to prime mover generation

Basics of Fuel Cell



1. Types of Fuel cells

	PAFC	**MCFC**	**SOFC**	**PEMFC**
Electrolyte	Phosphoric Acid	Molten Carbonate Salt	Ceramic	Polymer
Operating Temperature	375°F (190°C)	1200° F (650°C)	1830°F (1000°C)	175°F (80°C)
Fuels	Hydrogen (H_2) Reformate	H_2/CO/ Reformate	H_2/CO_2 /CH_4 Reformate	H_2 Reformate
Reforming	External	External Internal	External Internal	External
Oxidant	O_2/Air	CO_2/O_2/Air	O_2/Air	O_2/Air
Efficiency	40-50%	50-60%	40-80%	40-50%

1. Phosphoric Acid Fuel Cells (PAFC)

- The most commercially developed type
  - hospitals, nursing homes, hotels, office buildings, schools, utility power plants, and airport terminals
  - 40% efficiency, 85% if co-generated heat
  - stationary and vehicle applications are possible
  - size: 50 kW to 500 kW

- favorable characteristics
  - Packaged systems are available with extremely high reliability
  - Very low noise and vibration
  - Negligible emissions

2. Molten Carbonate Fuel Cells (MCFC)

- ❑ The most attractive for base-loaded power generation
  - high fuel-to-electricity efficiencies
  - operate 1200 °F
  - internally reform
  - size: 250 kW to 5 MW
  - mainly stationary devices
- ❑ Potential applications
  - Industrial
  - Government facilities
  - Universities
  - Hospitals

3. Solid Oxide Fuel Cells (SOFC)

- ❑ Wide variety of applications
  - size: kW ~ MW for large high-power application

    - base-loaded utility applications
  - industrial generating station, vehicles
  - efficiency: 60%, 80% in co-generation
  - size: 5 ~ 250 kW
  - mainly stationary devices
- ❑ Potential applications
  - Residential cogeneration
  - Small commercial buildings
  - Industrial facilities

4. Proton Exchange Membrane Fuel Cells (PEMFC)

- Compelling advantage in size
  - operate at low temperature: 200 degrees Fahrenheit
  - high power density, vary output quickly
  - size: sub kW ~ 500 kW
  - stationary and vehicle
- Potential applications
  - Automotive
  - Residential (<10 kW), both with and without cogeneration
  - Commercial (10 - 250 kW), both with and without cogeneration
  - Light industrial (<250 kW), both with and without cogeneration
  - Portable power (several kW and smaller)

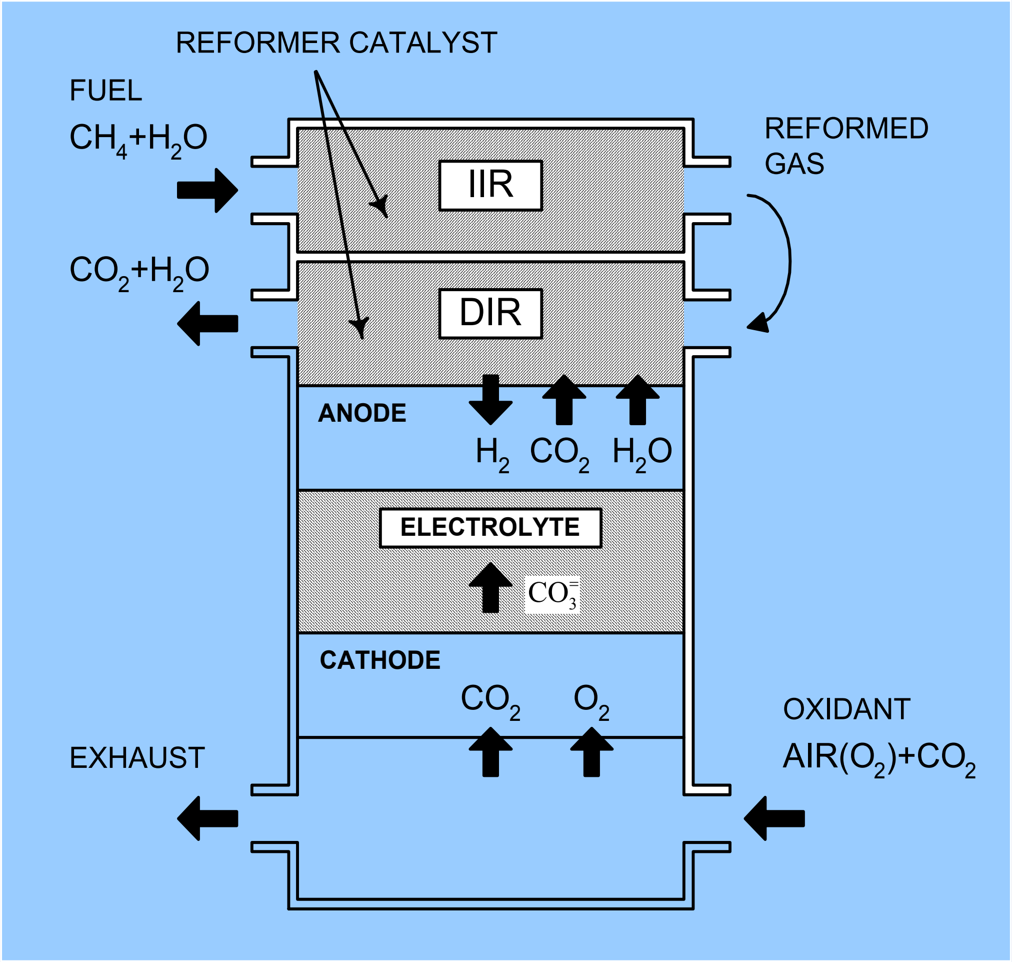
2. Specific Applications

- ☐ Stationary Power Sources
  - connected to the utility grid
  - premium power quality
    - cleaner, less polluting, more secure, more reliable
    - hospital, plastic extruder, data center, telecommunication switching center, cell phone towers
  - emergency backup electricity
    - residential homes, small commercial business, larger commercial or industrial companies
  - baseload/lifeline electricity, energy self-sufficiency, remote off-grid locations
  - such DG is modular, provides ease of siting, ensures lower capital cost

- Portable Power Sources
  - emergency equipment
  - hand-held power tools
  - road signs
- Micro Power Sources
  - hand-held computers: 3 Wh
  - notebook computers: 40 Wh
  - cellular phones: 3 Wh
- Vehicles
  - because of high efficiency ⇨ FC reduce dependency on imported oil
  - reduce vehicle emissions

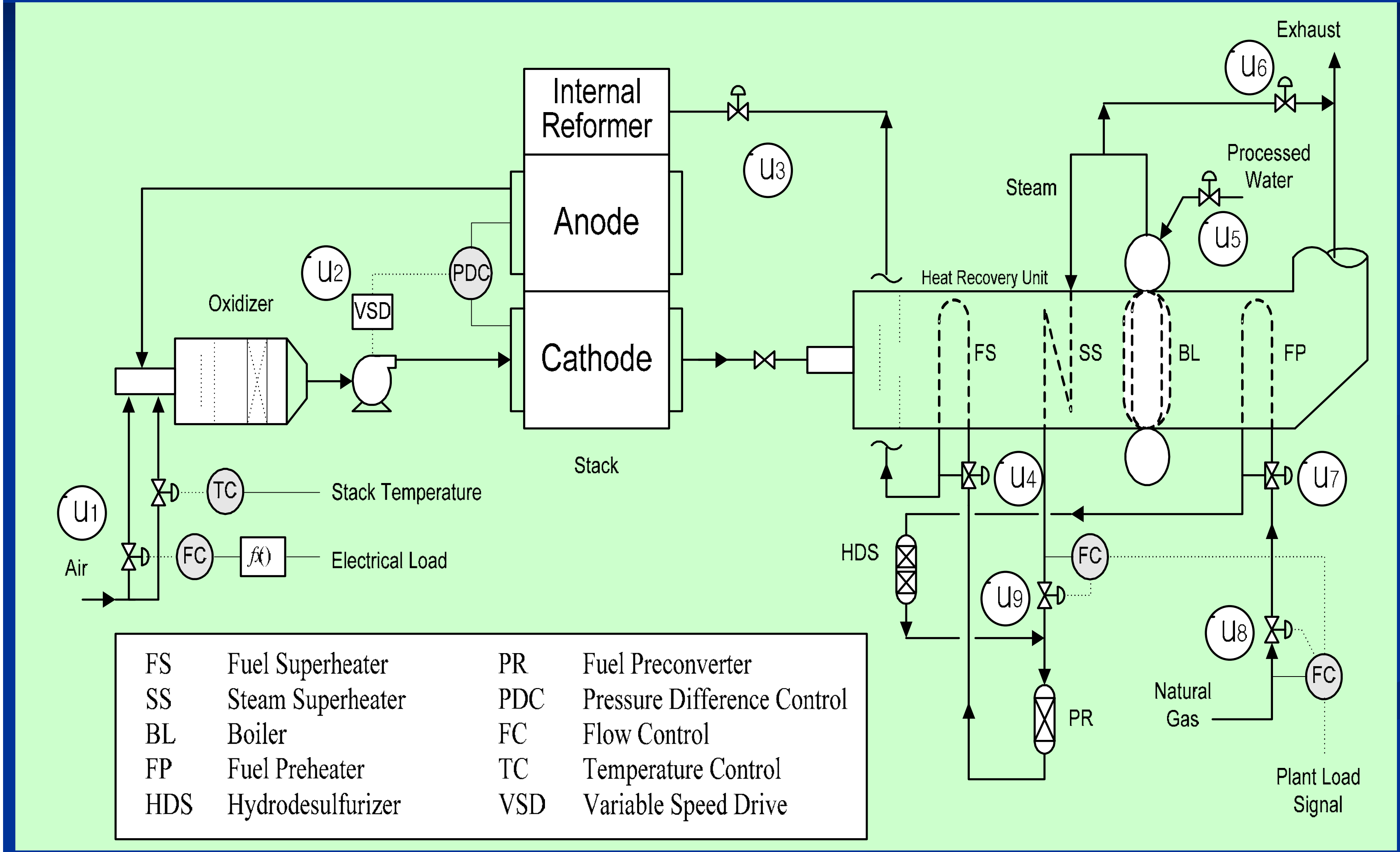
IV. FC Plant as a DG Source

1. Molten Carbonate Fuel Cell (MCFC)



- Santa Clara Demonstration Project (SCDP)
  - 125 kW × 16 stacks = 2 MW
  - RU: convert hydrocarbon into gas mixture of hydrogen and carbon compounds called “reformate”
    - indirect internal reforming + direct internal reforming
- Assumptions
  - a single stack temperature
  - representation of mass inventory
  - water-gas shift reaction at equilibrium
  - inclusion of appropriate kinetics for reforming reaction

Process Flow Diagram of SCDP



FS	Fuel Superheater	PR	Fuel Preconverter
SS	Steam Superheater	PDC	Pressure Difference Control
BL	Boiler	FC	Flow Control
FP	Fuel Preheater	TC	Temperature Control
HDS	Hydrodesulfurizer	VSD	Variable Speed Drive

Principle of MCFC

- cathode electrochemical reaction

$$\frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{=}$$

- anode electrochemical reaction

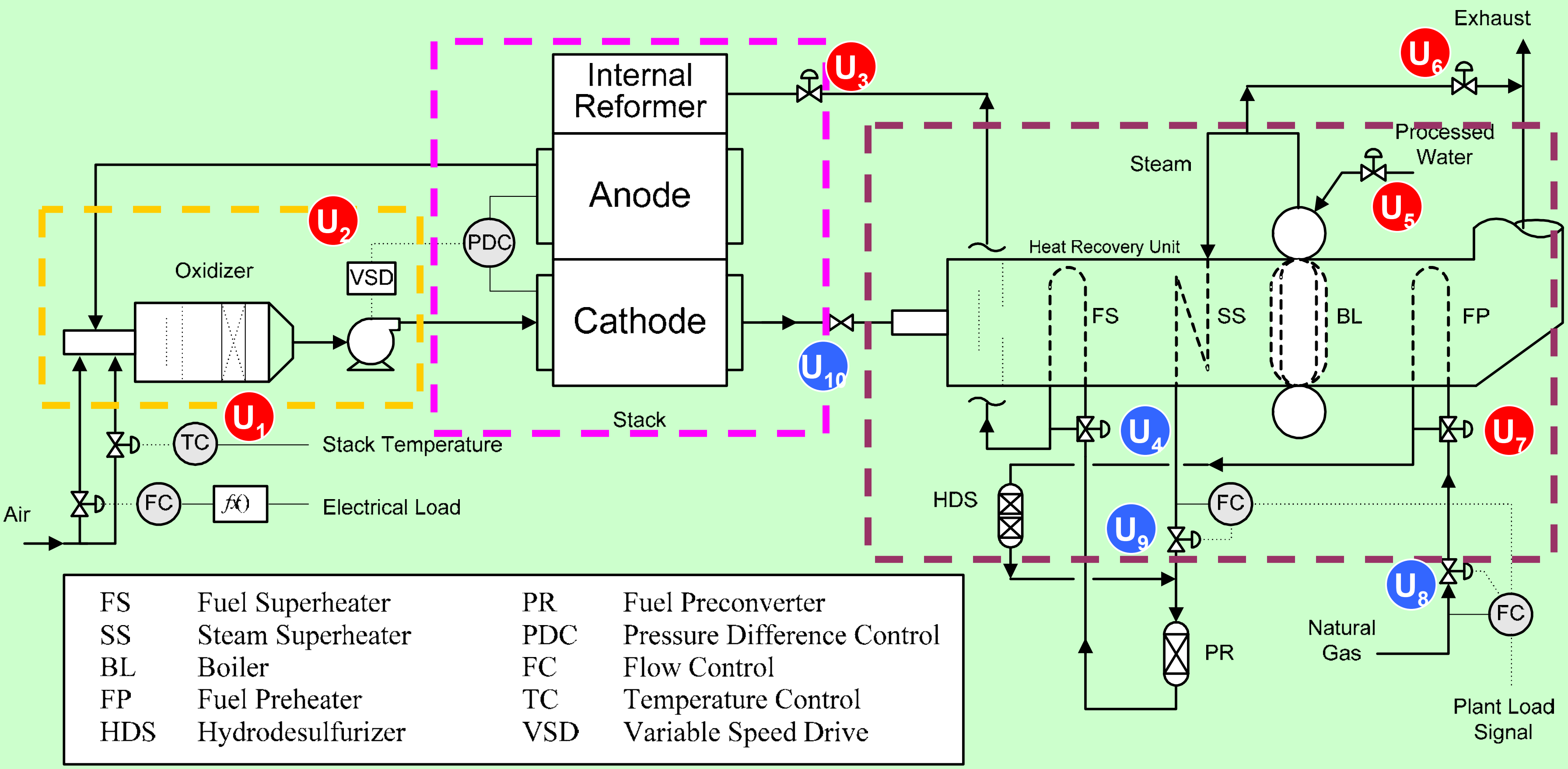
$$H_2 + CO_3^{=} \rightarrow H_2O + CO_2 + 2e^-$$

- reforming and water-gas shift (WGS) reactions

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad \text{Reforming}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad \text{Water-Gas Shift}$$

2. Operation and control of the SCDP



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SS	Steam Superheater	PDC	Pressure Difference Control
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- Fixed Setpoint

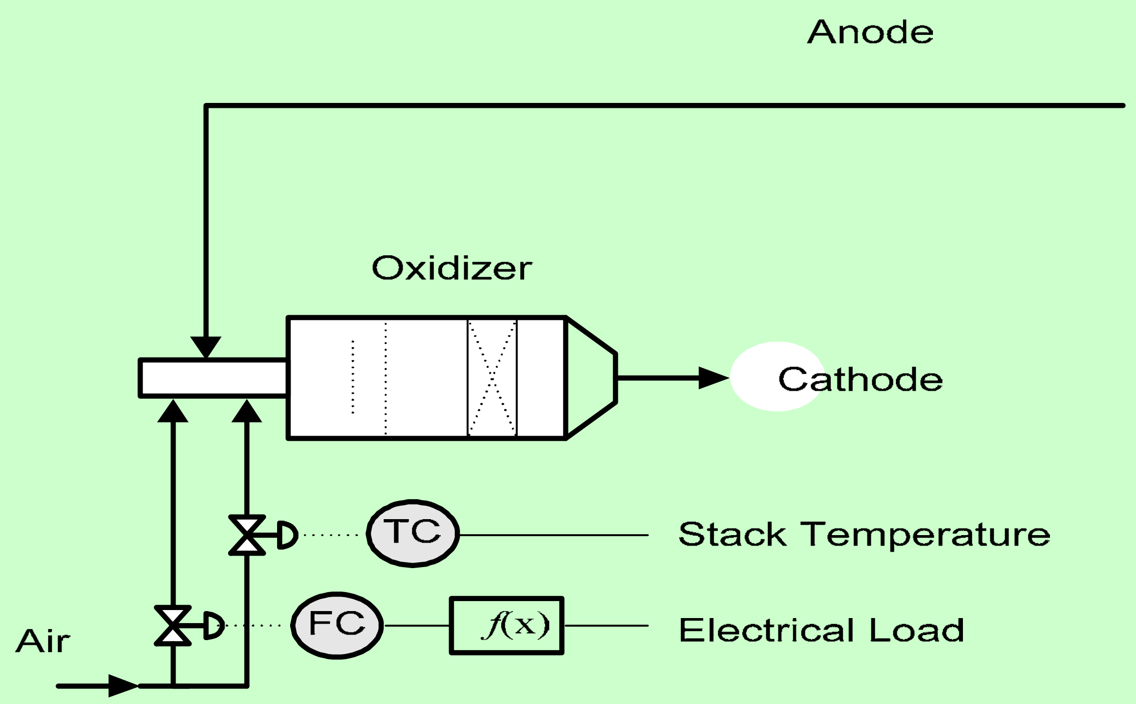
  stack temperature (u1), stack differential pressure (u2), stack RU back pressure (u3), steam drum level (u5), steam drum pressure (u6), natural gas temperature (u7)
- Load Dependent

  RU inlet temperature (u4), natural gas flow (u8), steam flow (u9), net AC power (u10)

Control Loops in the SCDP

Control Loop	Regulated Quantity	Setpoint	Actuation
1	Stack Temperature	1250 °F	Air Flow Valve
2	Stack Differential Pressure	0.012 psia	Booster Blower Speed
3	Stack RU Back Pressure	20.1 psia	Regular Valve
4	RU Inlet Temperature	Load Dependent	Fuel Superheater Bypass (Splitter Valve)
5	Steam Drum Level (Volume)	10.9 ft^3	Feedwater Flow Valve
6	Steam Drum Pressure	50 psia	Pressure Relief Valve
7	Natural Gas Temperature	700°F	Fuel Preheater Bypass (Splitter Valve)
8	Natural Gas Flow	Load Dependent (75% Fuel Utilization)	Flow Valve
9	Steam Flow	Load Dependent (2/1 Steam-Carbon Ratio)	Flow Valve
10	Net AC Power	Load Demand	Inverter Current

1. Oxidizer Subsystem



- input: Air (O_2), anode off-gas (H_2O,CO_2)
- output: cathode input-gas (O_2, CO_2)
- control variable: stack temperature

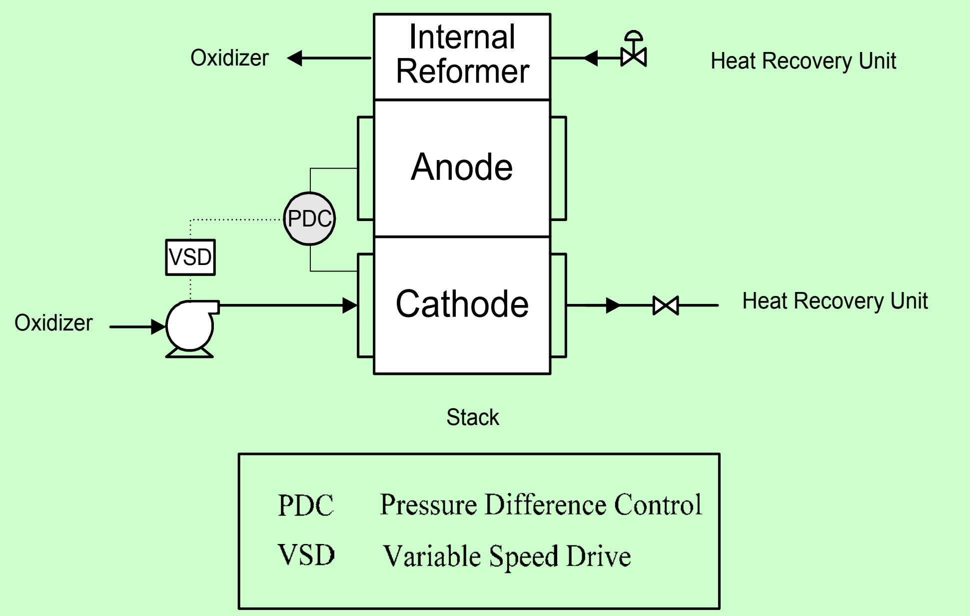
$$(\bar{h}_{ox}, X_{ox}, T_{ox}) = f(\bar{h}_{air}, \bar{h}^{gas}_{ox}, x_{air}, x^{gas}_{ox})$$

$\bar{h}_{ox}, \bar{h}_{air}, \bar{h}^{gas}_{ox}$: vectors of molar entalpy at oxidizer, air, off-gas temp.

$X_{ox}, X_{air}, X^{gas}_{ox}$: composition of oxidizer, air, anode-off gas

T_{ox} : temperature of oxidizer, x_{air}, x^{gas}_{ox} : mole fractions of air, oxidizer gas

2. Fuel Cell Stack Subsystem



- input: input : fuel (H_2), steam(H_2O), oxidizer output(O_2, CO_2)
- output: anode exhaust (H_2O, CO_2), cathode exhaust (heat, power)
- control variable: RU backpressure, stack differential pressure

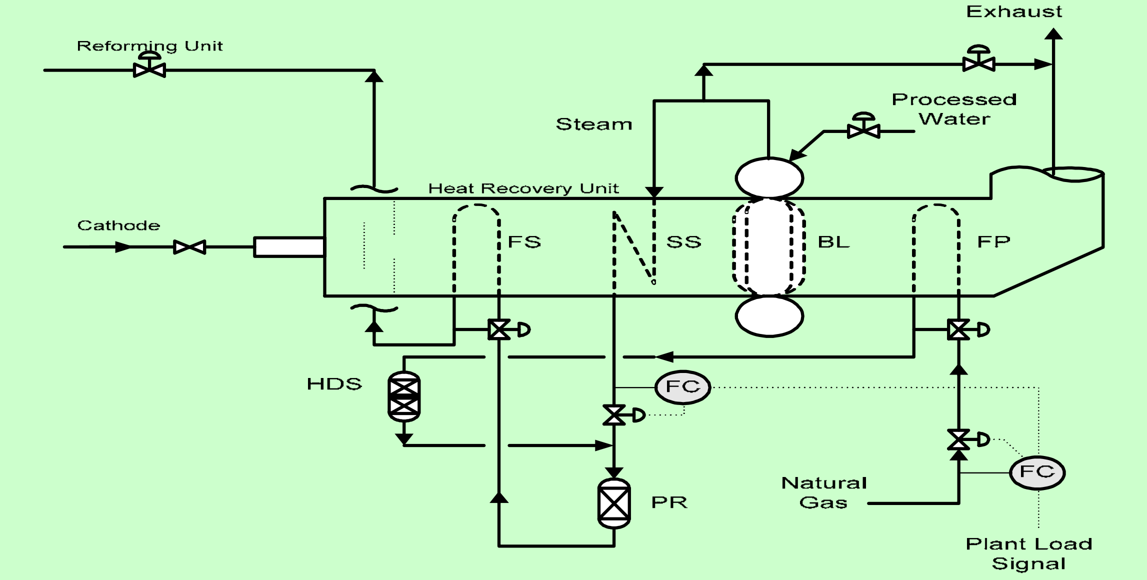
$$(x_{H_2O,a}, x_{CO_2,a}, \overline{h}_s, P_{dc}) = f(x_{H_2,ru}, x_{H_2O,ru}, x_{O_2,c}, x_{CO_2,c}, T_s, P_a, P_c)$$

$x_{H_2O,a}, x_{CO_2,a}, x_{H_2,ru}, x_{H_2O,ru}, x_{O_2,c}, x_{CO_2,c}$: mole fractions of anode exhaust (H_2O, CO_2), fuel (H_2) and steam (H_2O), cathode inlet (O_2, CO_2)

$\overline{h}_s$: molar enthalpies at stack temperature, P_{dc} : stack dc power

T_s : stack solid average temperature, P_a, P_c : anode (cathode) outlet pressure

3. Heat Recovery Unit Subsystem



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SS	Steam Superheater	FC	Flow Control
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FP	Fuel Preheater	VSD	Variable Speed Drive
HDS	Hydrodesulfurizer		

- input : water (H_2O), natural gas (CH_4), heat from stack
- output : fuel (CH_4), steam (H_2O), steam exhaust
- control variable : natural gas flow and temperature, Drum level and pressure, RU inlet temperature, steam flow, exhaust temperature

$$(x_{H_2}, x_{H_2O}, \mathrm{H_t}) = f(\mathrm{V_d}, \mathrm{P_d}, w_{ng}, w_{steam}, \mathrm{H_t^{in}}, \mathrm{T_{gas}^{in}}, \mathrm{T_{ru}^{in}}, \mathrm{T_t})$$

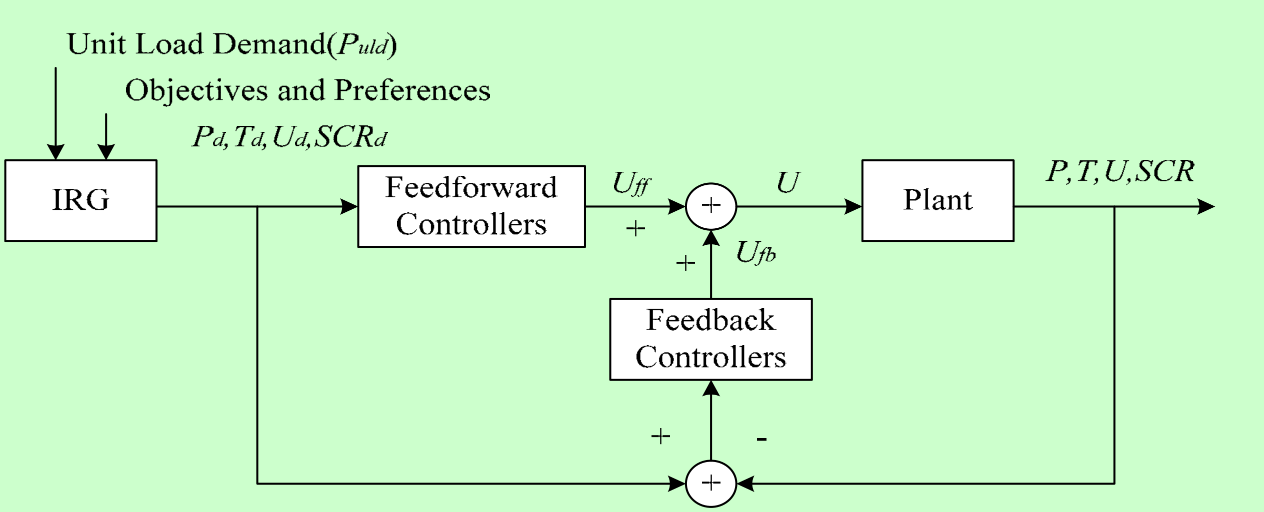
x_{H_2}, x_{H_2O}: mole fractions of fuel (H_2) and steam (H_2O), $\mathrm{H_t}$, $\mathrm{H_t^{in}}$: specific enthalpy of tube-side and inlet [Btu/lbm]

$\mathrm{V_d}, \mathrm{P_d}$: steam drum volume and pressure, w_{ng}, w_{steam} : natural gas and steam flow

$\mathrm{T_{gas}^{in}}, \mathrm{T_{ru}^{in}}, \mathrm{T_t}$: temperature of input natural gas, RU inlet, and superheater exhaust

3. Intelligent Control for a Fuel Cell Power Plant

1. Development of Intelligent Reference Governor

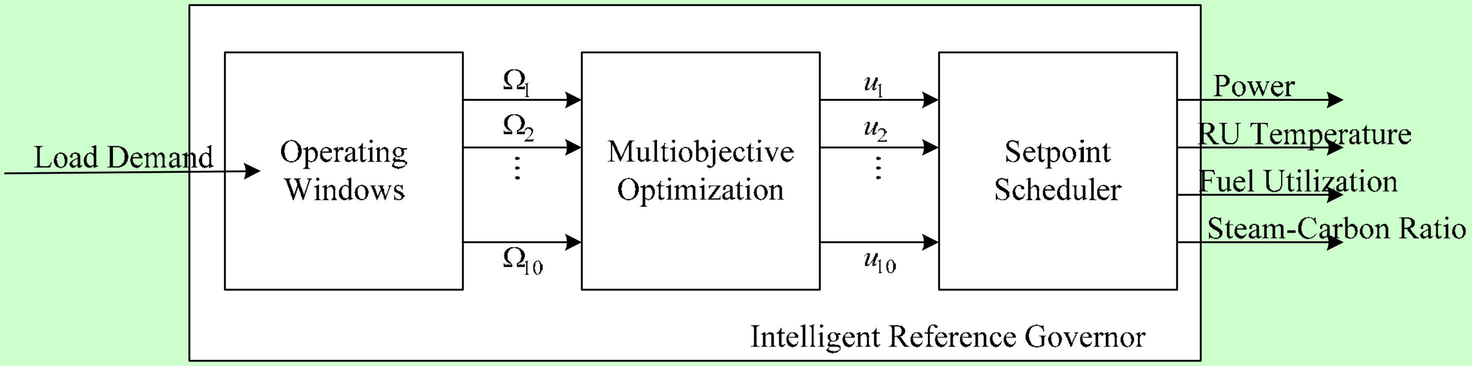


Present System
Nonlinear mapping function

Intelligent System
Optimization techniques: PSO, DE

- ❑ conflicting operational requirements
  - minimization of fuel consumption and heat loss rate, maximization of duty life, minimization of pollutant emission, minimization of load tracking error

Configuration of IRG



- optimal mappings from unit load demand P_{uld} to setpoint P_d, T_d, U_d, SCR_d

$$SP_P : (P_{uld}, t) \to (P_d, t) \qquad SP_T : (P_{uld}, t) \to (T_d, t)$$
$$SP_U : (P_{uld}, t) \to (U_d, t) \qquad SP_{SCR} : (P_{uld}, t) \to (SCR_d, t)$$

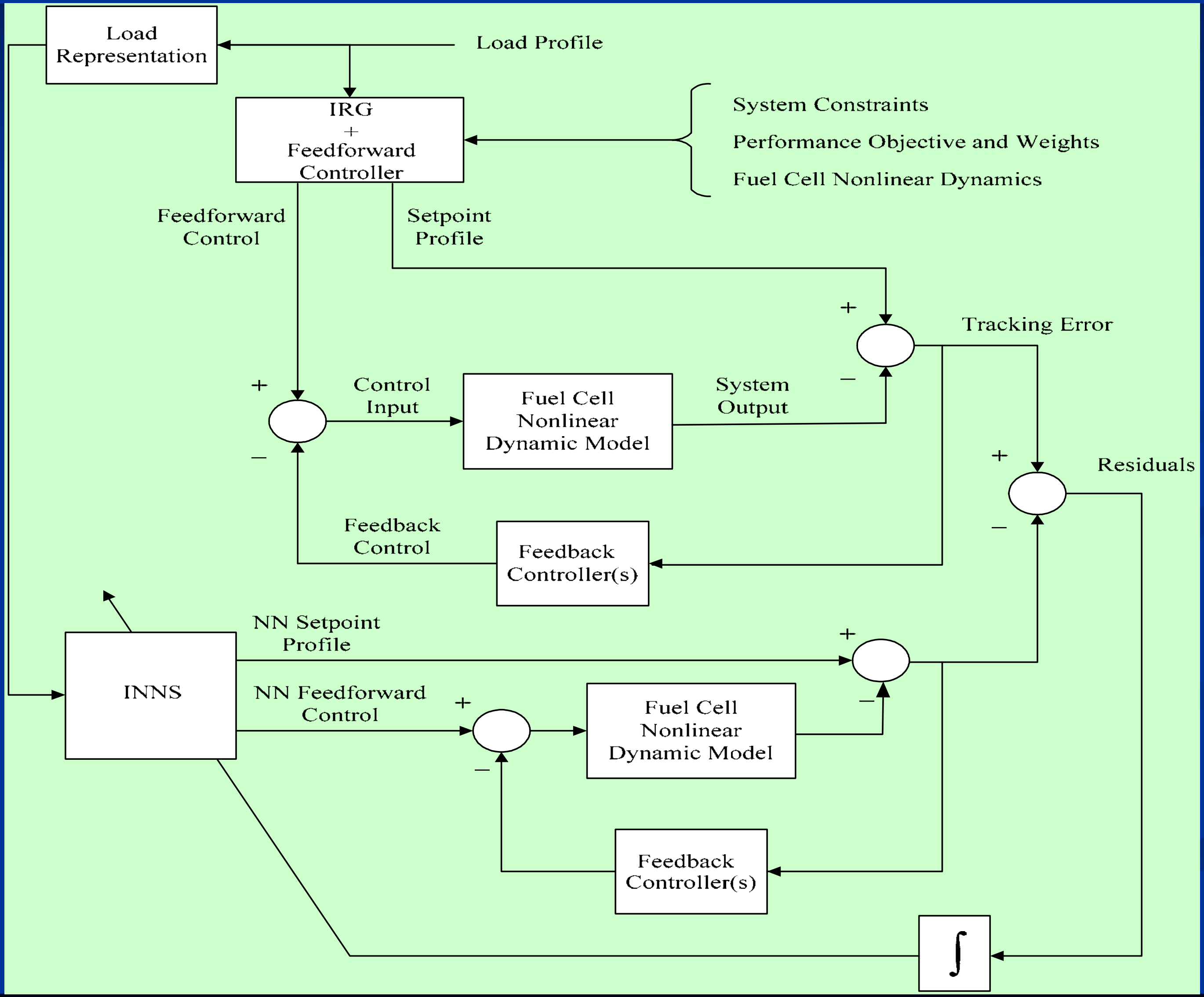
- Design process in three steps

- Determination of feasibility regions $(\Omega_1, \Omega_2, \ldots, \Omega_{10})$ for decision variables $(u_1, u_2, \ldots, u_{10})$
- Solution of multiobjective optimization problem to find optimal steady-state Control signals $(u_1^*, u_2^*, \ldots, u_{10}^*)$
- Calculation of setpoints (P_d, T_d, U_d, SCR_d) through evaluation of steady-state model

2. Development of Intelligent NN Supervisor

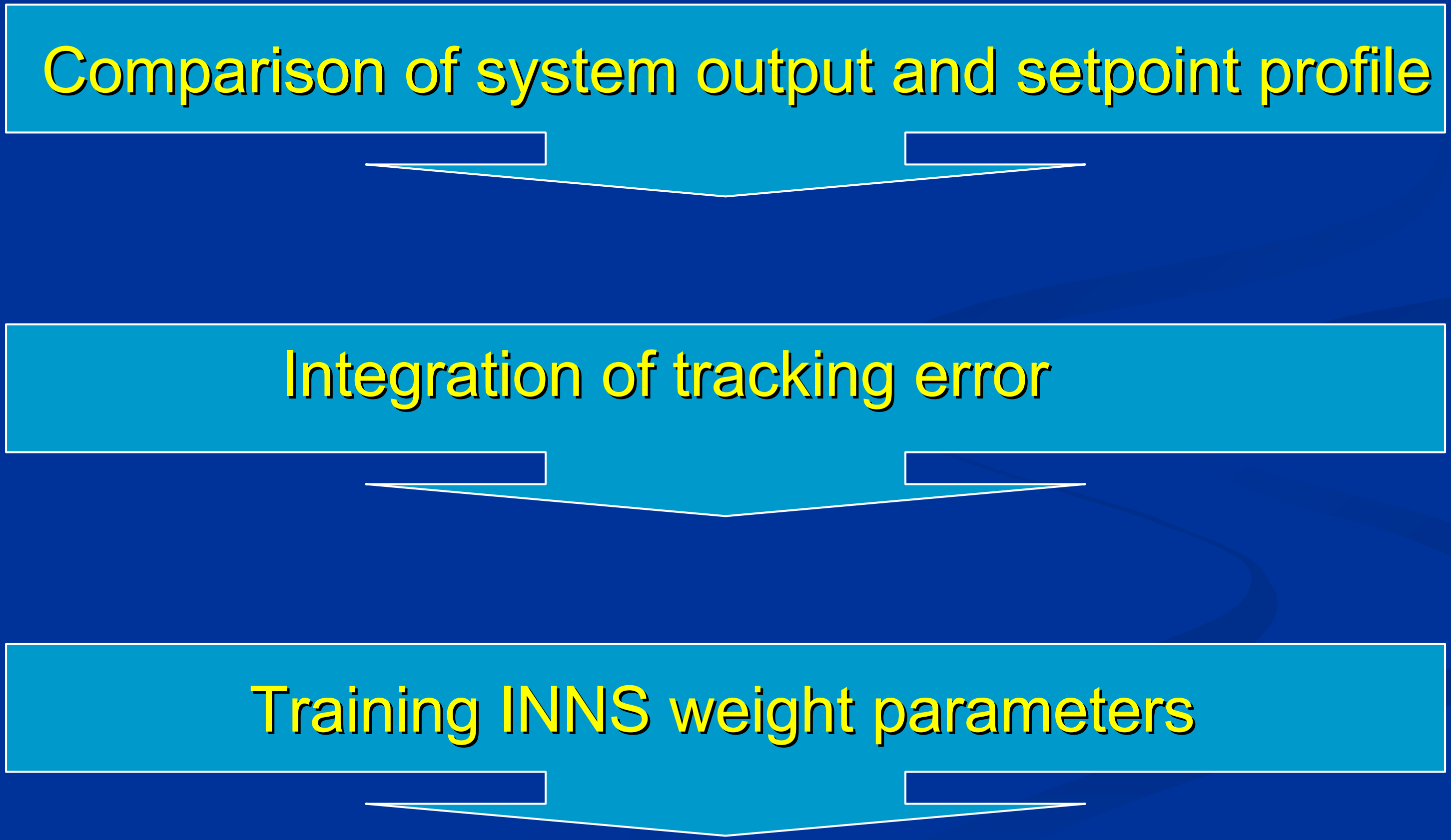
- new concept of intelligent controller
  - INNS = IRG + feedforward controller
- IRG
  - generates setpoints for a given load profile
  - off-line optimizations made by heuristic algorithm
  - adaptive NN learning will be processed for on-line application
- FF controller
  - FF control signals are generated corresponding to the setpoints provided by IRG

Off-line Training of the INNS



3. Development of Learning System

- Real-time adjustment of INNS

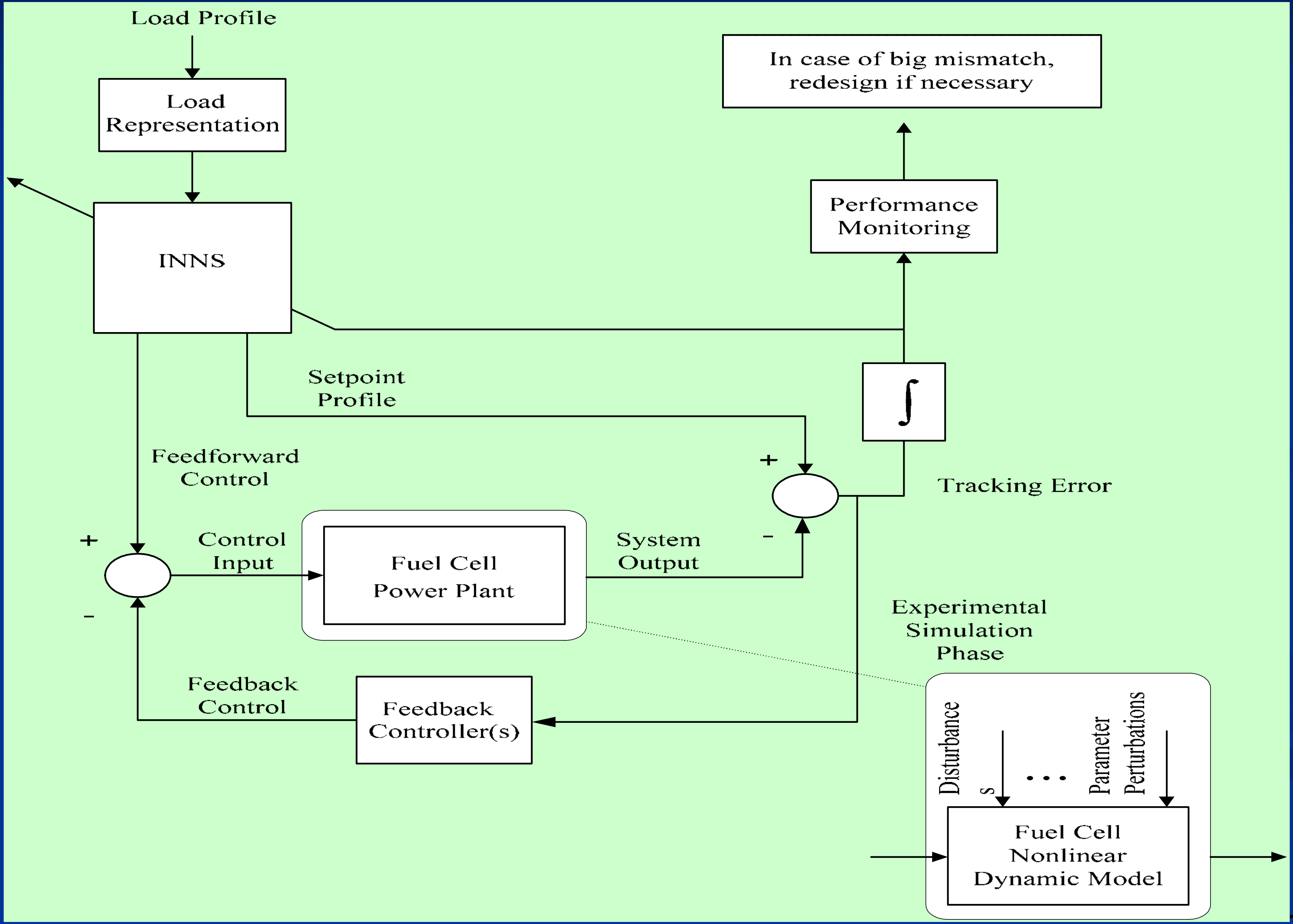


Comparison of system output and setpoint profile

Integration of tracking error

Training INNS weight parameters

Adaptive INNS



4. Development of NN Identifier

- NN Identifier

  - provide system information to controllers

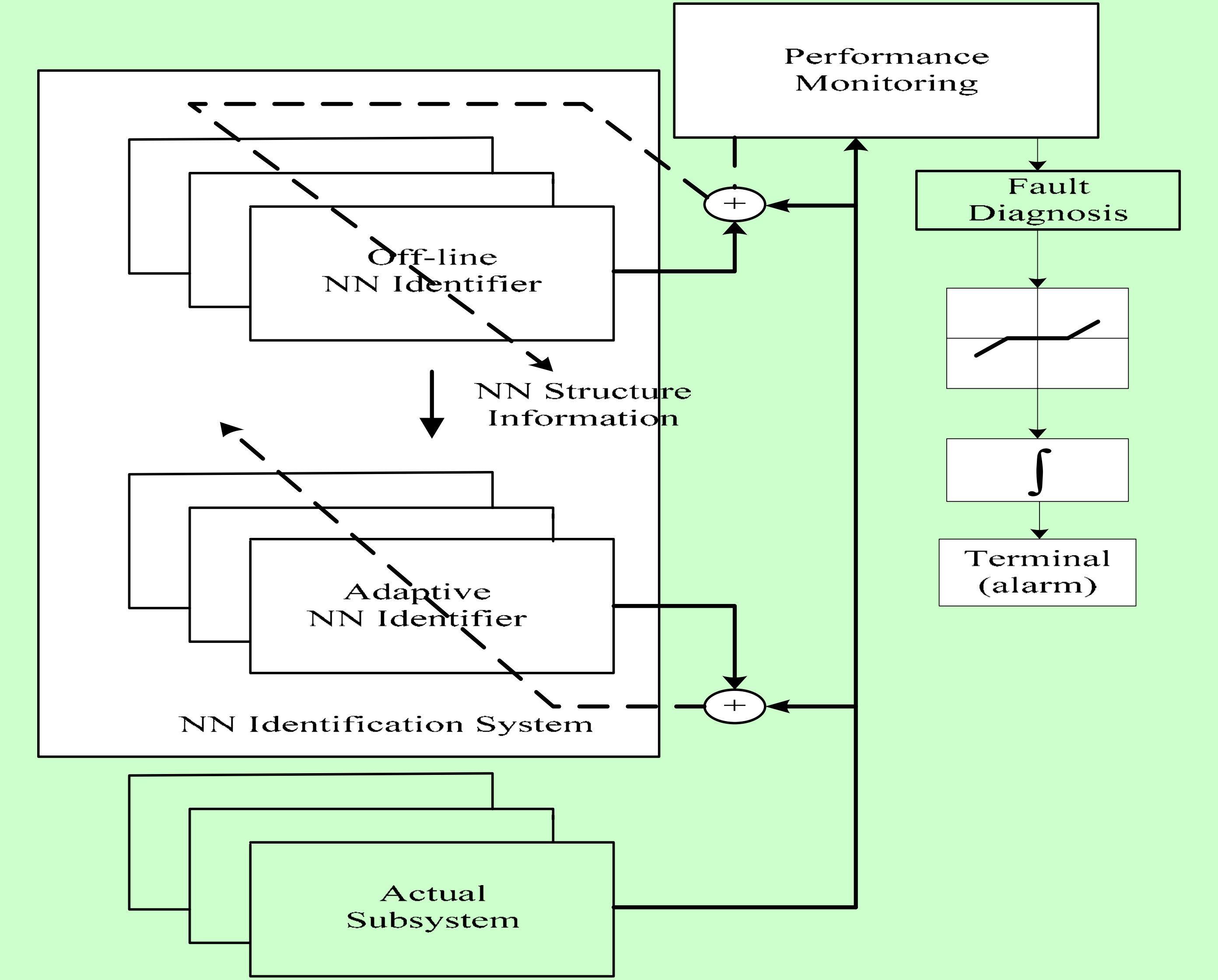
- Off-line NN Identifier

  - complete learning cycle for system identification
  - obtain nominal subsystem model for fault-diagnosis

- Adaptive NN Identifier

  - initialize NN using off-line NN structure
  - update NN weights with I/O data of actual plant
  - informations will be used for PI control gain tuning to provide optimal operation and preserve stability

Structure of NN Identification System



V. Interface to the Utility System

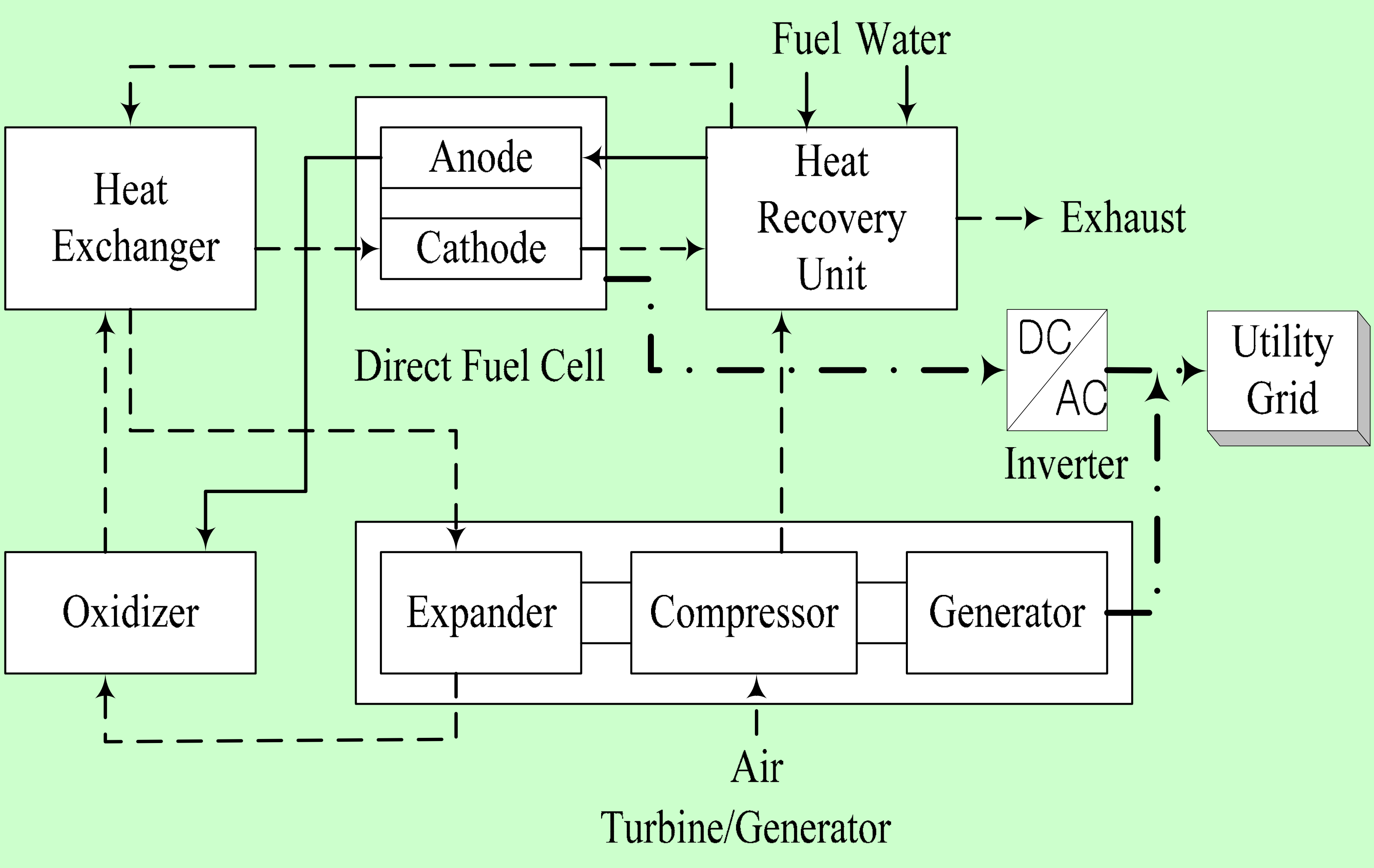
1. Hybrid Power Plant

- Hybrid Power plant = MCFC + gas turbine
  - achieve high efficiency: 50~60 % ⇨ 85%
- Key features of hybrid power plant
  - independence of gas turbine and FC pressure
  - integration of atmospheric pressure with gas turbine
  - by recovering FC byproduct heat

  ⇨ generation of additional power

  ⇨ provide air for FC operation

Fuel cell/turbine hybrid system



2. Interface Technologies

- Synchronous Machines

  - DC field for excitation

  - produce real and reactive power

- Asynchronous Machines

  - induction motors drives faster than synchronous speed

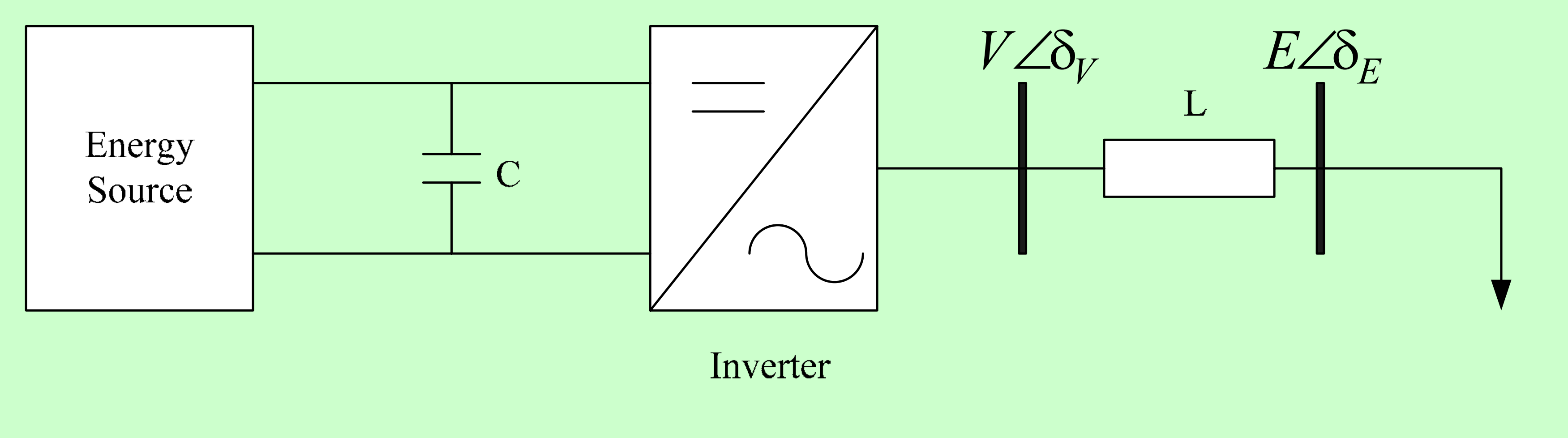
  - produce real power only

- Power Electronic Inverters

  - convert DC to AC at a desired voltage and frequency

3. Inverter Interfaced FC Power Plant

1. Control Schemes for Inverter Interfaced FC power plant



- FC energy source: constant voltage source
- DC link capacitor: energy balance

  - discharge: higher load demand than energy supply

  - charge: lower load demand than energy supply

  - transient stability

  ► battery storage: appropriate for long term stability

2. Theoretical Considerations on PQ Control

- Basic requirement of Voltage Source Inverter

  - real & reactive power flow control between FC & AC power system

- Mathematical relations for P&Q magnitudes

$$P = \frac{VE}{X}\sin(\delta_V - \delta_E),$$

$$Q = \frac{V^2}{X} - \frac{VE}{X}\cos(\delta_V - \delta_E) = \frac{V}{X}[V - E\cos(\delta_V - \delta_E)]$$

- For small changes in angle

  - P is dependent on the power angle difference $(\delta_V - \delta_E)$

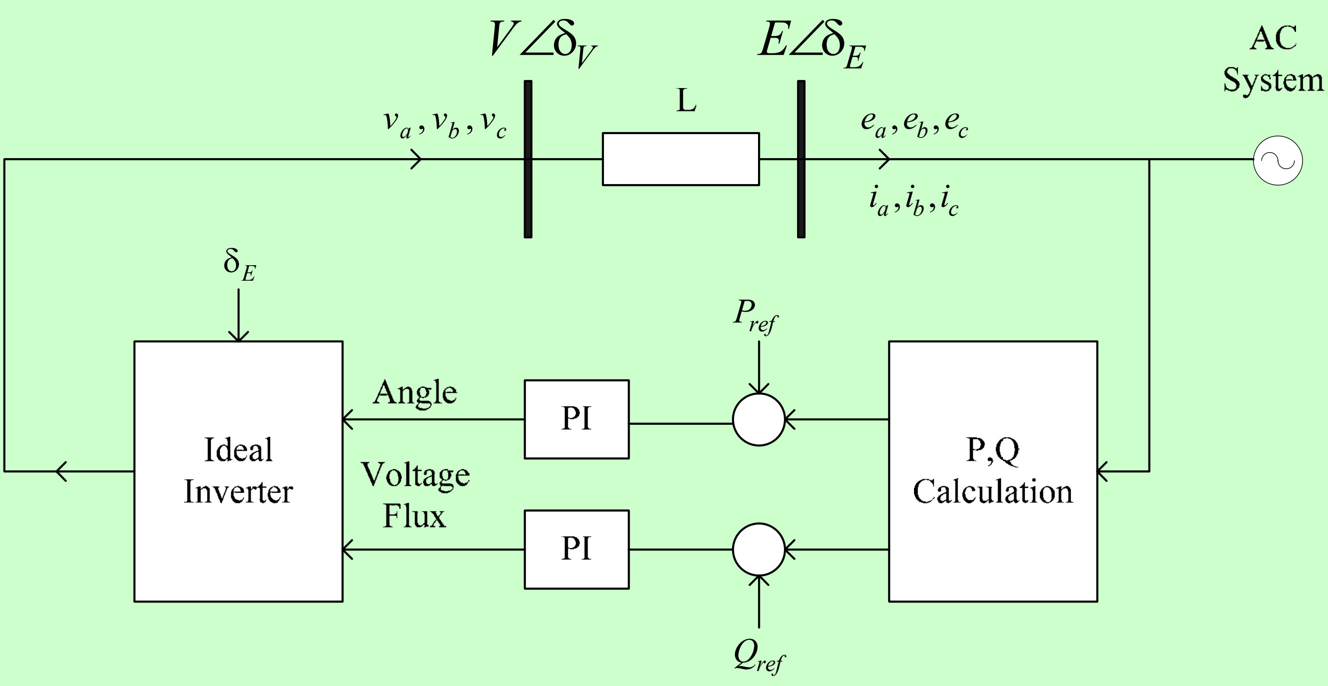
  - Q is dependent on the voltage magnitude difference (V-E).

3. Voltage Source Inverter Model

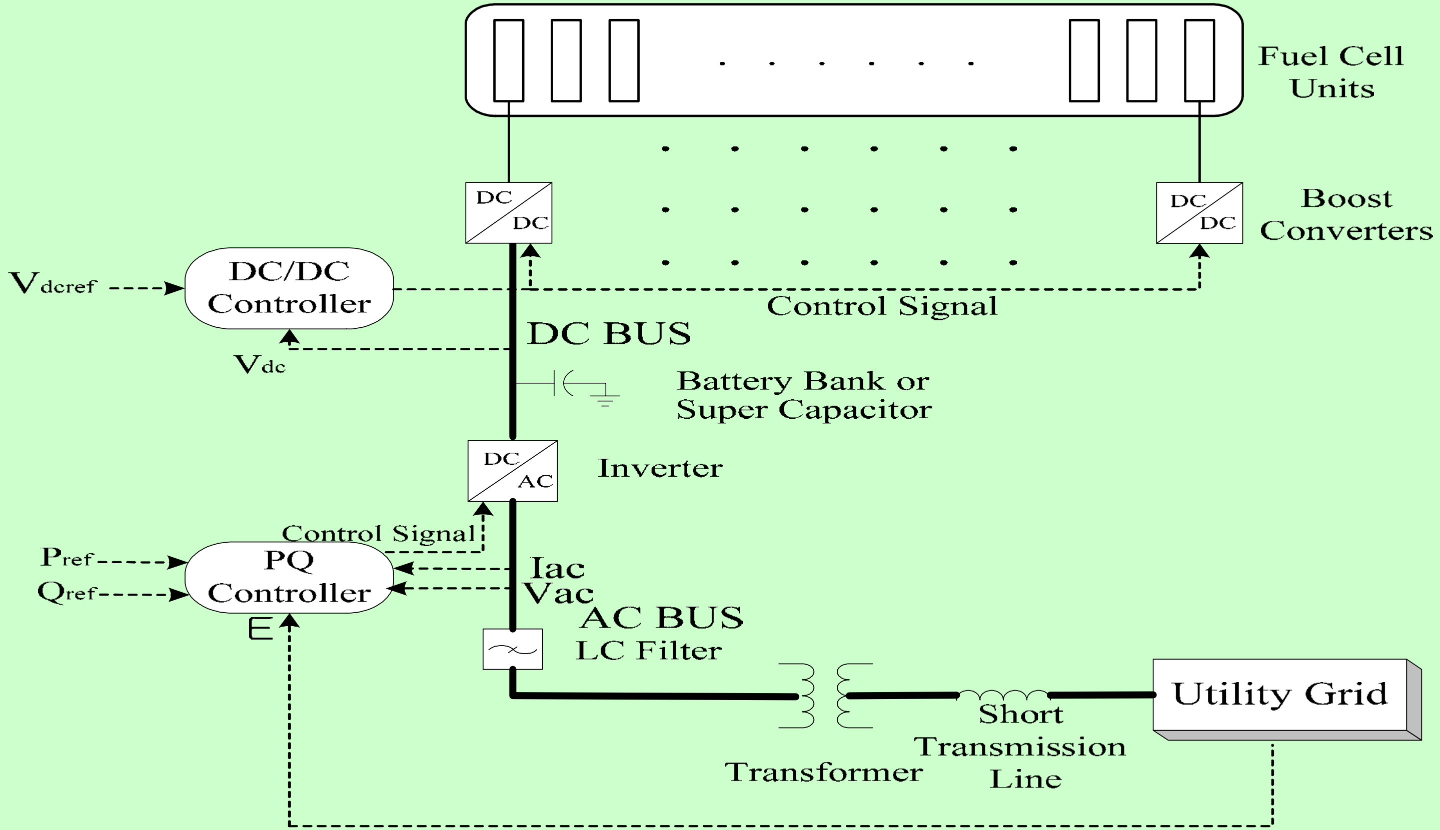
- Control variables: V, δ_V

$$v_a = \sqrt{2}\ V\sin(wt+\delta_V),$$
$$v_b = \sqrt{2}\ V\sin(wt+\delta_V - 2\pi/3),$$
$$v_c = \sqrt{2}\ V\sin(wt+\delta_V + 2\pi/3).$$

4. Basic Structure of VSI PQ Controller



5. Inverter-based Interface to the utility Grid



- ❑ Boost DC/DC converter: control DC output voltage level, noise isolation
- ❑ Super capacitor: improve performance under transient disturbances
- ❑ LC band pass filter: eliminate undesired harmonics

4. Operating Conflicts

- ☐ Fault Clearing
  - ⇨ DG protection devices need to separate the fault, coordinating normal fault-clearing process of utility
- ☐ Reclosing
  - ⇨ DG needs to disconnect early in the reclosing interval to allow successful reclose
- ☐ Interface with Relaying
  - ⇨ Due to opposite current flow, the reach of relay is shortened, leaving high impedance fault undetected.
- ☐ Islanding
  - ⇨ When utility breaker opened, a portion of utility system remains energized while isolated from the remainder of utility system, resulting in injuries to the public and utility personnel.
- ☐ Ferroresonance
  - ⇨ When DG is disconnected by a fault, transformer (L) and cable (C) constitute the ferroresonance condition.

5. Power Quality Issues

- ☐ Sustained Interruptions
  - ⇨ In case of power interruption, instantaneous reclosing and DG breakers need to cooperate.
- ☐ Voltage Regulation
  - ⇨ DG need to work properly with utility voltage regulating equipments.
- ☐ Voltage Flicker
  - ⇨ Abrupt load change in FC can cause a Voltage flicker.
- ☐ Voltage Sags
  - ⇨ Inverter-based PQ controller need to provide reactive power to compensate the voltage sag.
- ☐ Harmonics
  - ⇨ inverter using IGBT using PWM can prevent harmonics.

* IGBT: Insulated Gate Bipolar Transistor, PWM: Pulse Width Modulator

VI. Future Work

1. Intelligent Control of FC Power Plant

- Development of Intelligent Reference Governor
  - setpoints for a given load profile
  - heuristic optimization technique ⇨ optimal setpoint
- Development of Intelligent NN Supervisor
  - setpoints of the load dependent control variables
  - feedforward control signals for the plant
- Development of NN Identifier
  - adaptive NN identifier: PI control gain tuning
  - off-line NN identifier: identification of all subsystems
- Development of Learning System
  - real-time adjustment to achieve performance objectives

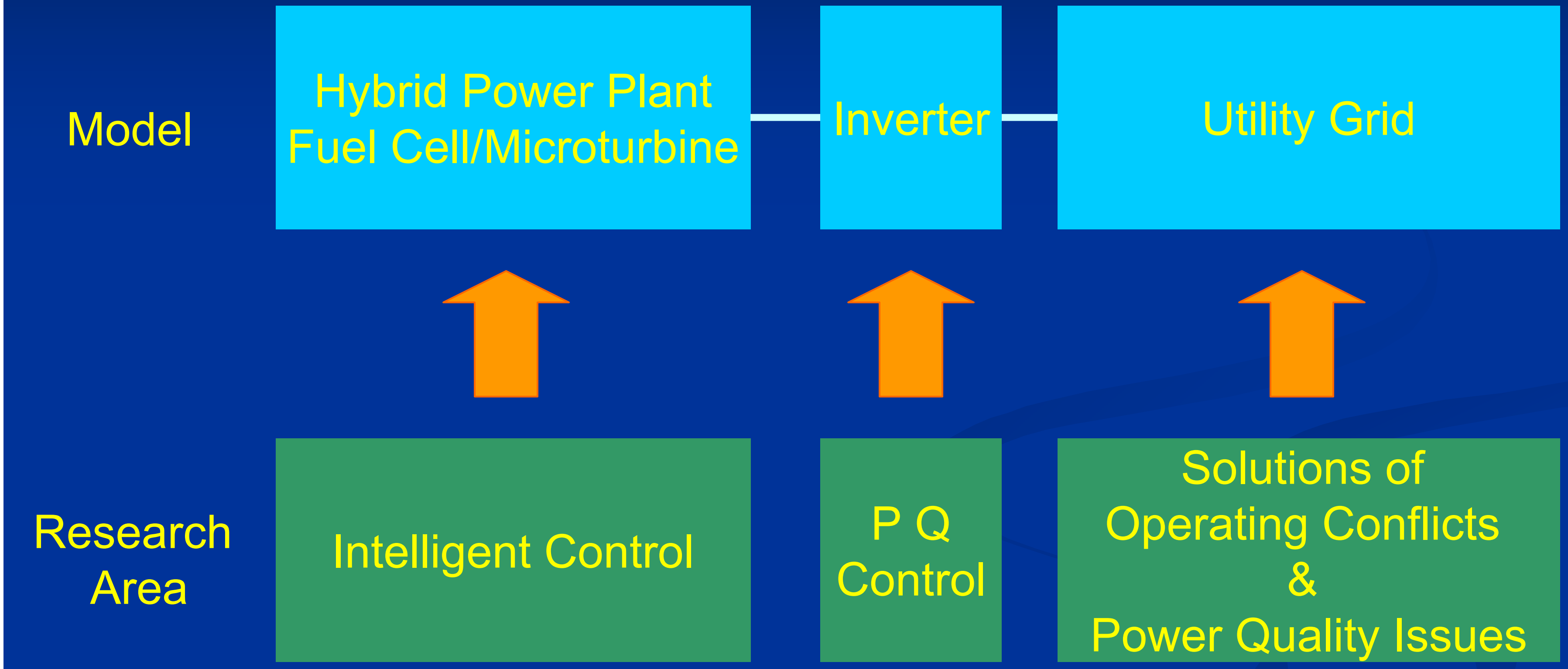
2. Interface to the Utility System

- Development of Hybrid Power Plant Model
  - modeling of gas turbine
  - intelligent control concept will be extended to hybrid power plant
- Development of VSI PQ controller Model
  - control schemes for Voltage Source Inverter PQ controller
  - Matlab/Simulink model will be simulated for case studies
- Development of Inverter-based Interface Model
  - boost DC/DC converter: control output DC voltage level
  - DC link capacitor: energy balancing
  - LC band pass filter: eliminate harmonics

3. Operating Conflicts and Power Quality Issues

- Recommendation of operational standards to the utility and DG provider
  - to solve the problem of fault clearing, reclosing, and the interface with relaying
- Recommendation of construction standards to the utility
  - to prevent harmonics through grounding arrangements
- Development of remote control system for DG breakers, switches and transformers
  - monitoring of islanding, voltage regulation and DG protection devices
- Development of inverter-based PQ control system model
  - case studies to prevent voltage flicker and voltage sags will be performed through the simulation of matlab/simulink model

Integration of Hybrid Power Plant Interface Model



Model

Hybrid Power Plant
Fuel Cell/Microturbine

Inverter

Utility Grid

Research Area

Intelligent Control

P Q Control

Solutions of
Operating Conflicts
&
Power Quality Issues

➡ **Commercialization of Hybrid Power Plant**

Thank you !