Adaptive Fault-Tolerant Control for Smart Grid Applications

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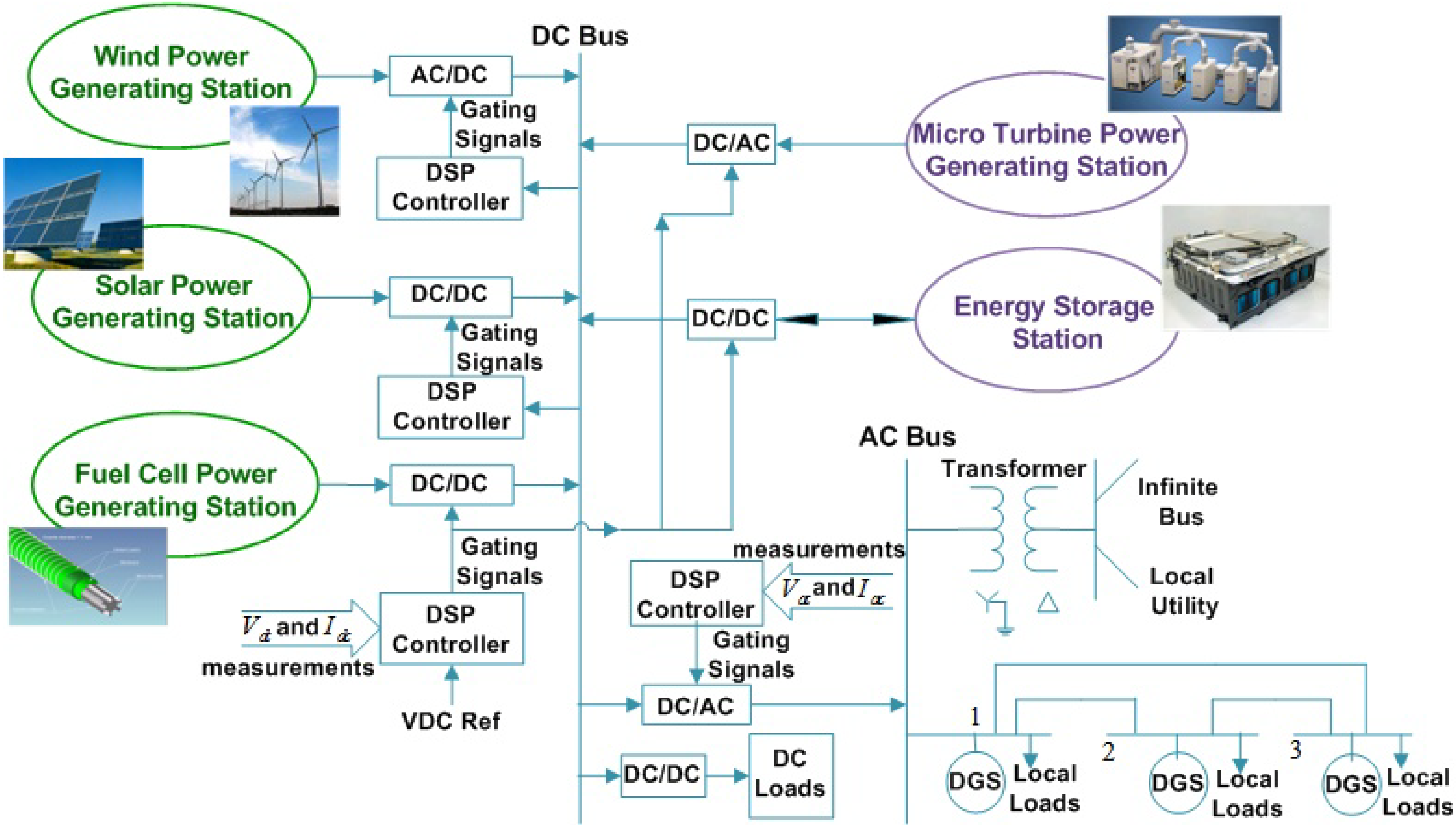
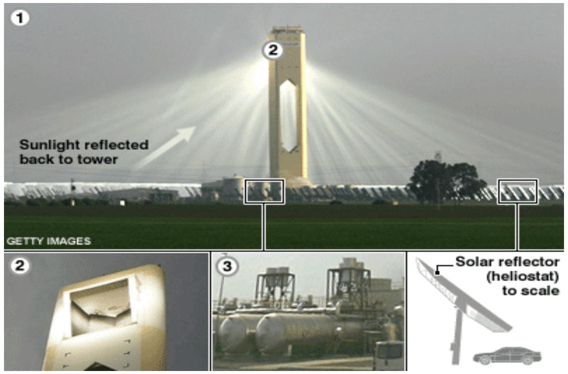
2010 Advanced Energy Conference
Nov. 2010

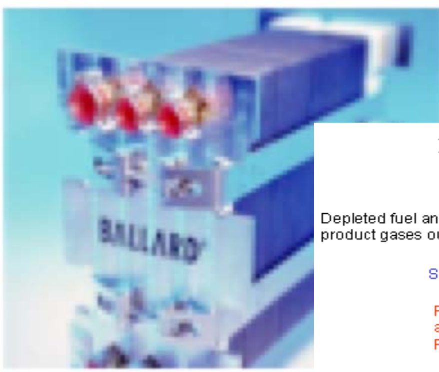
Smart Grid Distributed Generation System (DGS)

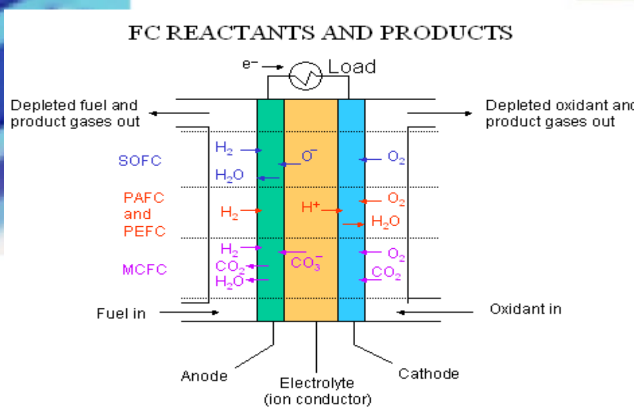


Smart Grid: Power Grid + Local Generation + Cyber (Internet) + Intelligent Fault-Tolerant Distributed Control + Real-Time Pricing

Sustainable Energy Technology







Benefits of DGS: Installation near to local loads; increased efficiency and reliability; peak load shaving; on-site standby power systems during grid outages; modular structure to facilitate system expansion; combined heat and power applications.

Key Research Areas

- Smart Grid Architecture
- Cyber Security
- Modeling and Control
- Smart Metering and Pricing
- Pervasive Monitoring

Challenges

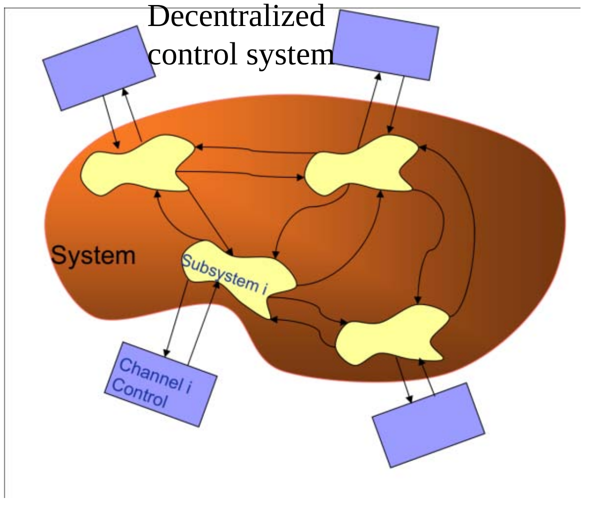
- Highly variable supply patterns … stochastic problem …..storage
- Efficient distributed algorithms required to process massive amounts of data for real-time control
- Adaptive and self-healing control algorithms required for attaining high efficiency, reliability, and security of the large-scale distributed system
- Secure protocols, firewall mechanisms, intrusion prevention

Control Problems

- Control of individual renewable energy, storage, and switching components in microgrid systems
  - Island mode:
    - Microgrid control system should ensure that real and reactive power are matched between local generation and load.
    - Control system should also provide voltage and frequency stability.
    - Load scheduling/shifting and load shedding.
    - Adapting to load changes that could be large relative to total load.
  - Grid-connected mode:
    - Performance principally determined by grid. Microgrid appears as single dispatchable unit.
    - Microgrid control system should ensure that the impact of the distributed generation and any islanding events do not adversely affect grid.
    - Specifically, voltage and current fluctuations, total harmonic distortion. Phase synchronization with the grid should be addressed while transitioning from island to grid-connected mode.
    - Local control mechanisms can improve power quality for loads within microgrid.

Control Problems (Contd.)

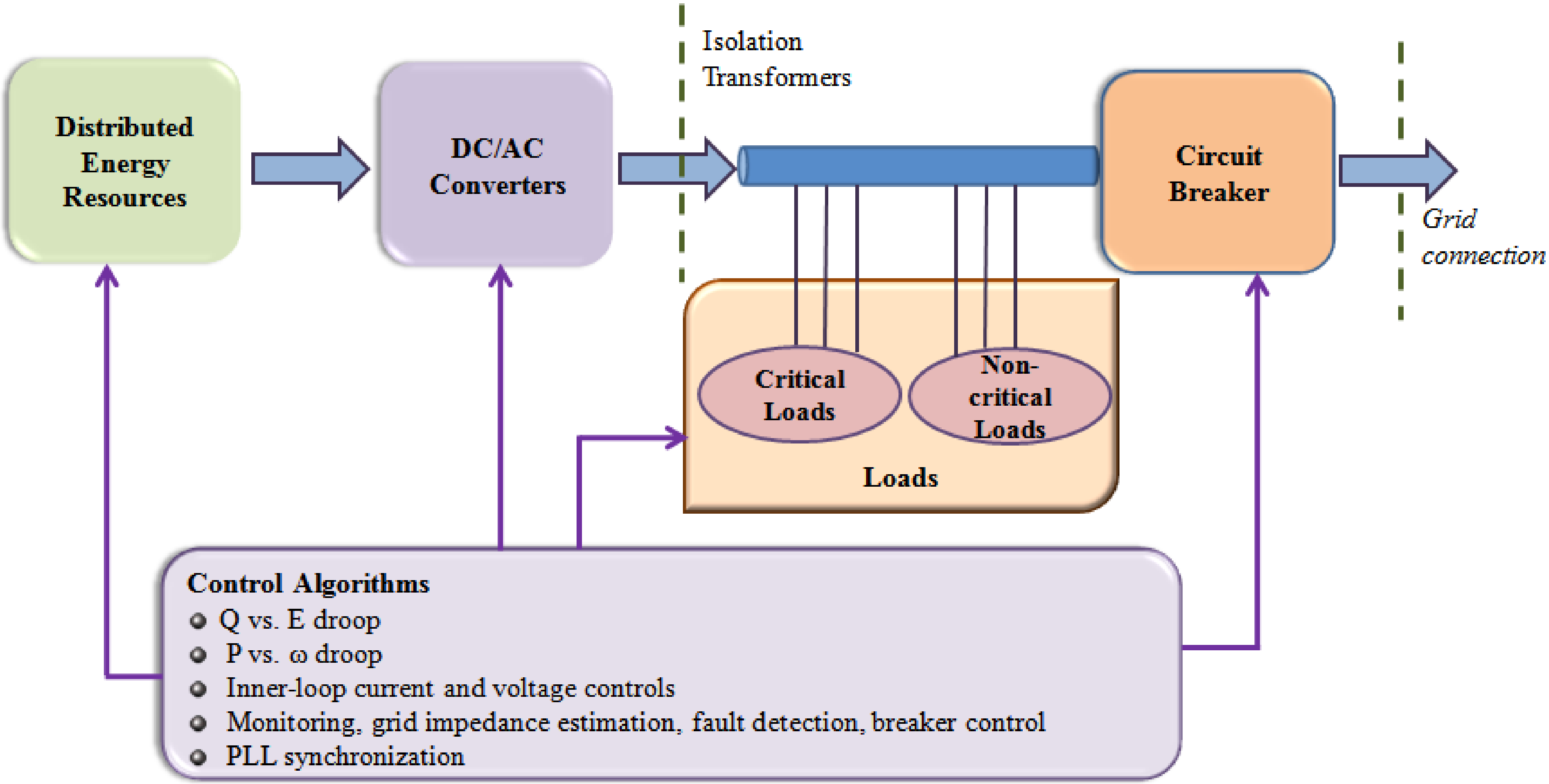
- Transitioning between island and connected modes
  - Monitoring grid conditions and detecting faults
  - Deciding when to disconnect
  - Preserving stability during transients
- Control aspects of the decentralized interconnected system
  - Multi-agent systems
  - Communication requirements and mechanisms
  - Distributed control



Control Objectives and Performance Metrics

- Frequency control … deviation (in Hz) from nominal value
  - Performance expressed as combination of multiple factors such as maximum frequency deviation, interval within which frequency is contained for some percentage of total time, etc. – e.g., within 1 Hz of nominal value 95% of time and within 3 Hz of nominal value always.
- Voltage magnitude control … deviation (as percentage) from nominal value
  - Performance expressed as combination of maximum deviation of voltage magnitude, maximum RMS deviation of sliding-window voltage magnitude signal during some percentage of total time, etc. – e.g. within 10% of nominal value always and RMS deviation of 5 min sliding-window within 15% during 5% of the total time.
- Control of total harmonic distortion (THD) … performance expressed as THD measured over a sliding window of time (e.g., 0.2 s).
- Control of short-term transients (flickers) – response to fast-varying loads; performance expressed as maximum short-term transient voltage deviations, number of deviations in a sliding window of time, and response time for correction. Voltage magnitude and frequency control while switching from grid-connected to island operation.

Microgrid Control Structure



Multi-agent approach with plug-and-play framework and uniform communication protocol: DER control agents, User-side configuration agents, Monitoring and data recording agents, Island/connected transition control agents, Load scheduling agents, etc.

Microgrid Control Aspects

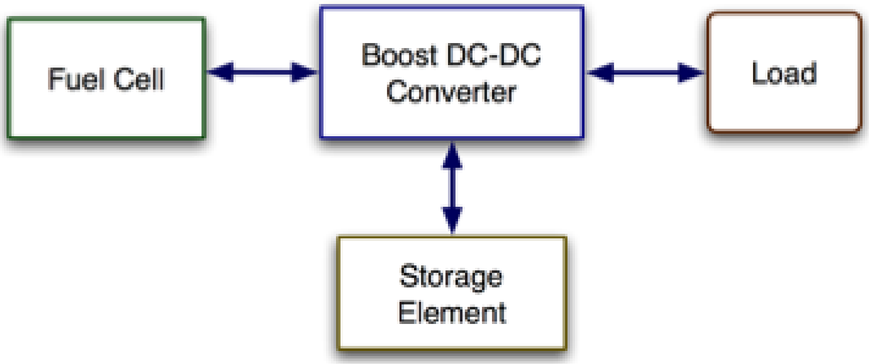
- Adaptive droop control:
  - Real power *P*:
    - Frequency droop (*P* vs. *ω*) : $\omega = \omega^* - \hat{\chi}_\omega (P - P^*)$
    - Angle droop (*P* vs. δ) : $\delta = \delta^* - \hat{\chi}_\delta (P - P^*)$
  - Reactive power *Q*:
    - Amplitude droop (*Q* vs. *E*) : $E = E^* - \hat{\chi}_E (Q - Q^*)$
  - Grid impedance estimation; $\hat{\chi}_\delta, \hat{\chi}_\omega, \hat{\chi}_E$ functions of online adaptation parameters
- Layered control hierarchy:
  - Primary control: *P, Q* droop
  - Secondary control: *ω, E* restoration and synchronization
  - Tertiary control: *P, Q* buy/sell decisions --- economic optimization
- Power sharing among DER microsources and storage elements in microgrid by appropriate droop control and synchronization; agent-based control structure

PEM Fuel Cell Based DG System

- Attractive features of PEM Fuel Cell : high power density, solid electrolyte, low operating temperature (50-1000C), fast start-up, low sensitivity to orientation, favorable power-to-weight ratio, long cell and stack life, and low corrosion
- Analysis of performance and the operating characteristics of stand-alone PEM fuel cell based DG system feeding to time-varying loads.
- Development of dynamic models for PEM fuel cell and its power conditioning unit (dc/dc boost converter, three-phase dc/ac inverter with L-C filter and transformer).
- Development of control techniques to achieve desired performance of the system.
- Determination of energy capacity of storage device that needs to be connected at DC bus

Desired Performance Characteristics of Stand-Alone PEM Fuel Cell Based DG System

- Provide output voltage to loads at magnitude 208 V(L-L)/120 V (L-N) and at 60 Hz frequency up to its rated value.
- Provide power during peak load demand and during load transients.
- Output voltage of the system must have low load regulation (< 5 %) - system must be able to maintain steady-state output voltage independent of load conditions up to its rated value.
- Provide output voltages with low total harmonic distortion (THD) – (Reduction in 5^{th} and 7^{th} harmonic)
- Protect itself from overload conditions such as short circuit faults.
- Maximize life of fuel cell and battery.



Modeling and System Identification of Fuel Cell Based DGS Unit

- Equations of operation based on physical principles; State space description of the system dynamics. System description contains:
  - Parametric uncertainties -- *estimated via Maximum Likelihood Estimation (MLE)*
  - Functional uncertainties --- *estimated via Neural Network (NN) modeling*

- Reaction at anode: $2H_2 \longrightarrow 4H^+ + 4e^-$
- Reaction at cathode: $O_2 + 4e^- + 4H^+ \longrightarrow 2H_20$
- Open-circuit output voltage:

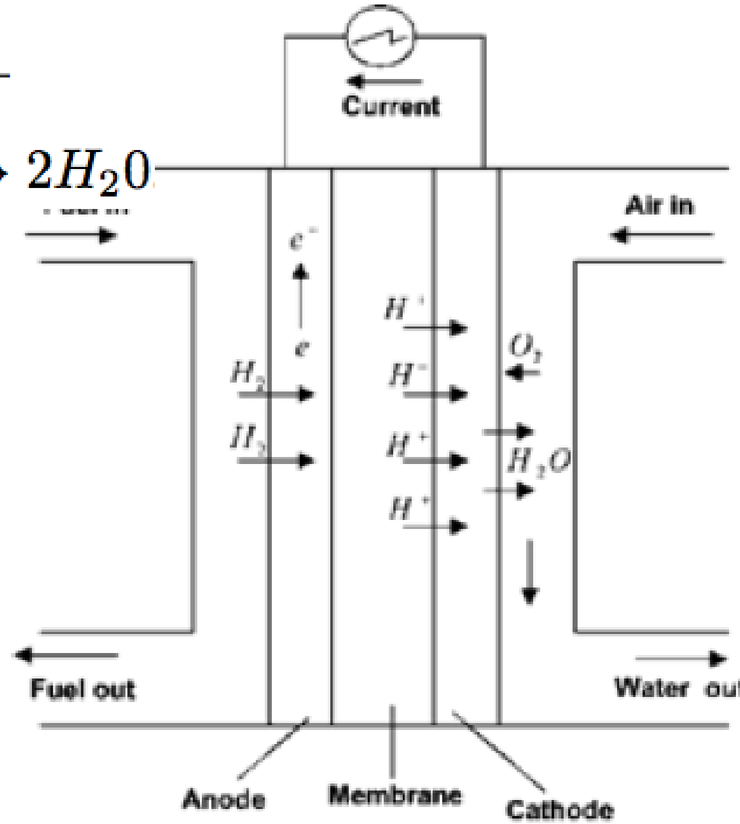
$$V_{O,FC} = n_s E_0^{Cell} + \frac{n_s RT}{2F} \ln \left[\frac{P_{H_2}(P_{O_2})^{0.5}}{P_{H_2O}} \right]$$

- Output voltage:

$$V_{fc} = V_{O,FC} - n_S(V_{loss}^{Act} + V_{loss}^{O} + V_{loss}^{Conc})$$

$$\Longrightarrow V_{fc} = n_s E_0^{cell} + \frac{n_S RT}{2F} \ln \left(\frac{x_5 \sqrt{x_6}}{x_7} \right)$$

$$-n_S(a_0 + aT) - n_S x_{11} - n_S R^0 I$$



PEM Fuel Cell Modeling: State Space

$$\dot{x}(t) = A(\theta)x(t) + B(\theta)u(t) + G(\theta)w(t)$$

$$x = [(m_{O_2})_{net}, (m_{H_2})_{net}, (m_{H_2O})_{net}, T, P_{H_2}, P_{O_2}, P_{H_2O}, Q_C, Q_E, Q_L, V_C]^T$$

$$u = [u_{P_A}, u_{P_C}, u_{T_R}]^T \quad ; \quad w = [I] \qquad y = \theta_7(x_4, x_5, x_6, x_7)$$

$$\theta = [\theta_1(x_4), \theta_2(x_4), \theta_3(x_4), \theta_4(x_4), \theta_5(x_7), \theta_6(x_4, x_5, x_6, x_7), \theta_7(x_4, x_5, x_6, x_7), \theta_8(x_4, x_5, x_6, x_7)]^T$$

$$A = \begin{bmatrix} -\frac{1}{\lambda_C} & 0 & 0 & 0 & 0 & 0 & 0_{1\times4} & 0 \\ 0 & -\frac{1}{\lambda_A} & 0 & 0 & 0 & 0 & 0_{1\times4} & 0 \\ 0 & 0 & -\frac{1}{\lambda_C} & 0 & 0 & 0 & 0_{1\times4} & 0 \\ 0 & 0 & 0 & \frac{-h_S n_S A_S}{M_{fc} C_{fc}} & 0 & 0 & 0_{1\times4} & 0 \\ 0 & 0 & 0 & 0 & -2\theta_1(x_4) & 0 & 0_{1\times4} & 0 \\ 0 & 0 & 0 & 0 & 0 & -2\theta_3(x_4) & 0_{1\times4} & 0 \\ 0 & 0 & 0 & 2\theta_5(x_7) & 0 & 0 & 0_{1\times4} & 0 \\ 0_{2\times1} & 0_{2\times1} & 0_{2\times1} & 0_{2\times1} & 0_{2\times1} & 0_{2\times1} & 0_{2\times4} & 0_{2\times1} \\ 0 & 0 & 0 & h_S n_S A_S & 0 & 0 & 0_{1\times4} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0_{1\times4} & \frac{-1}{C(R^{Act}+R^{Conc})} \end{bmatrix}$$

$$B = \begin{bmatrix} 0_{3\times1} & 0_{3\times1} & 0_{3\times1} \\ 0 & 0 & \frac{h_S n_S A_S}{M_{fc} C_{fc}} \\ 2\theta_1(x_4) & 0 & 0 \\ 0 & 2\theta_3(x_4) & 0 \\ 0_{3\times1} & 0_{3\times1} & 0_{3\times1} \\ 0 & 0 & -h_S n_S A_S \\ 0 & 0 & 0 \end{bmatrix}$$

$$G = \left[\left(\frac{1}{4\lambda_C F}\right), \left(\frac{1}{2\lambda_A F}\right), \left(\frac{1}{2\lambda_C F}\right), -\theta_8, -\theta_2, -\theta_4, 2\theta_4, \theta_6, \theta_7, 0, \frac{1}{C}\right]^T$$

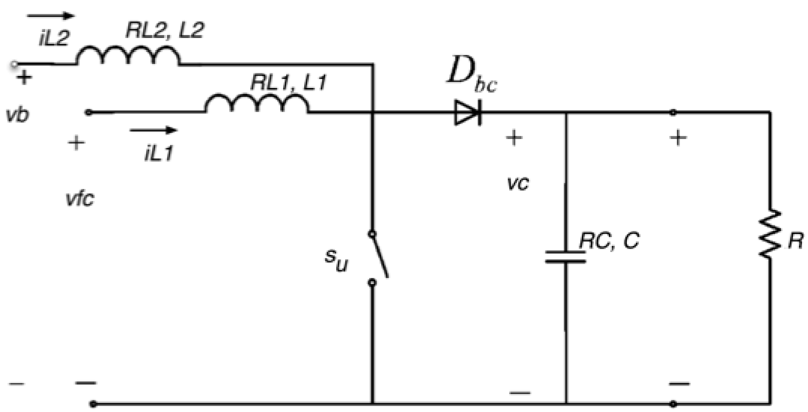
Modeling of Storage Element and DC-DC Boost Converter

Storage Element: Lead-Acid Battery

$$\dot{b} = i_b$$
$$v_b = E_b - i_b R_b$$
$$E_b = E_{b0} - K_b \frac{Q_b}{Q_b - b} + A_b \exp(-B_b * b)$$

v_b : output voltage at the battery terminals
i_b : current supplied by the battery
E_b: no-load (open-circuit) voltage of the battery

Boost DC-DC Converter: Time-averaging to capture dynamic models for switch-closed and switch-open conditions



$$\dot{i}_{L_1} = \frac{1}{L_1} v_{fc} - \frac{R_{L_1}}{L_1} i_{L_1} + (1 - D_s)\Big[- \frac{R}{(R+R_C)L_1} v_C - \frac{R R_C}{(R+R_C)L_1}(i_{L_1} + i_{L_2})\Big]$$

$$\dot{i}_{L_2} = \frac{1}{L_2} v_b - \frac{R_{L_2}}{L_2} i_{L_2} + (1 - D_s)\Big[- \frac{R}{(R+R_C)L_2} v_C - \frac{R R_C}{(R+R_C)L_2}(i_{L_1} + i_{L_2})\Big]$$

$$\dot{v}_C = -\frac{1}{(R+R_C)C} v_C + (1 - D_s)\frac{R}{(R+R_C)C}(i_{L_1} + i_{L_2})$$

D_s : duty cycle of the switching input s_u

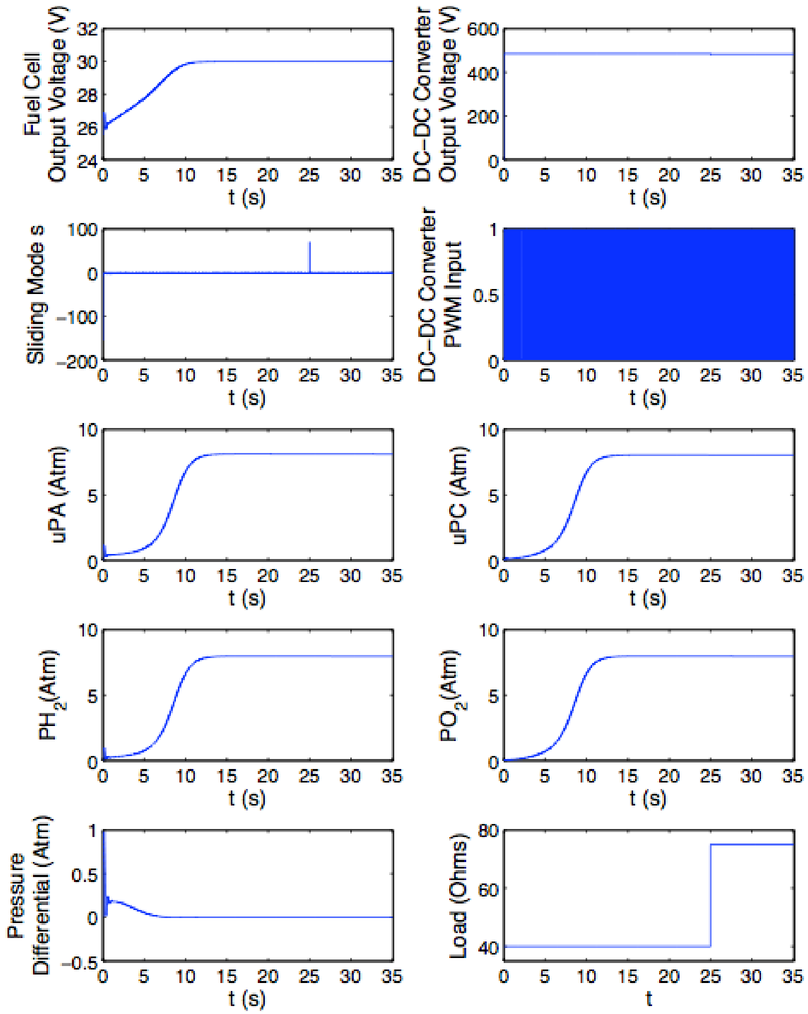
Control Objectives for PEM Fuel Cell Based DG System

- *DC-DC voltage tracking objective*: Given a desired output voltage trajectory $V_{DC,des}(t)$, the output of the DC-DC converter should track $V_{DC,des}(t)$.
- *Fuel cell voltage tracking objective*: The output of the PEM fuel cell should track a (nominally constant) desired voltage V_{des} — typically chosen to be equal to the constant nominal voltage of the storage element.
- *Pressure differential minimization objective*: The signal $|P_{H_2}(t) - P_{O_2}(t)|$ should be minimized. This helps in reducing membrane degradation effects.

Available Control Inputs: Switching command signal to the DC-DC converter and the channel pressures of hydrogen and oxygen being supplied to the fuel cell

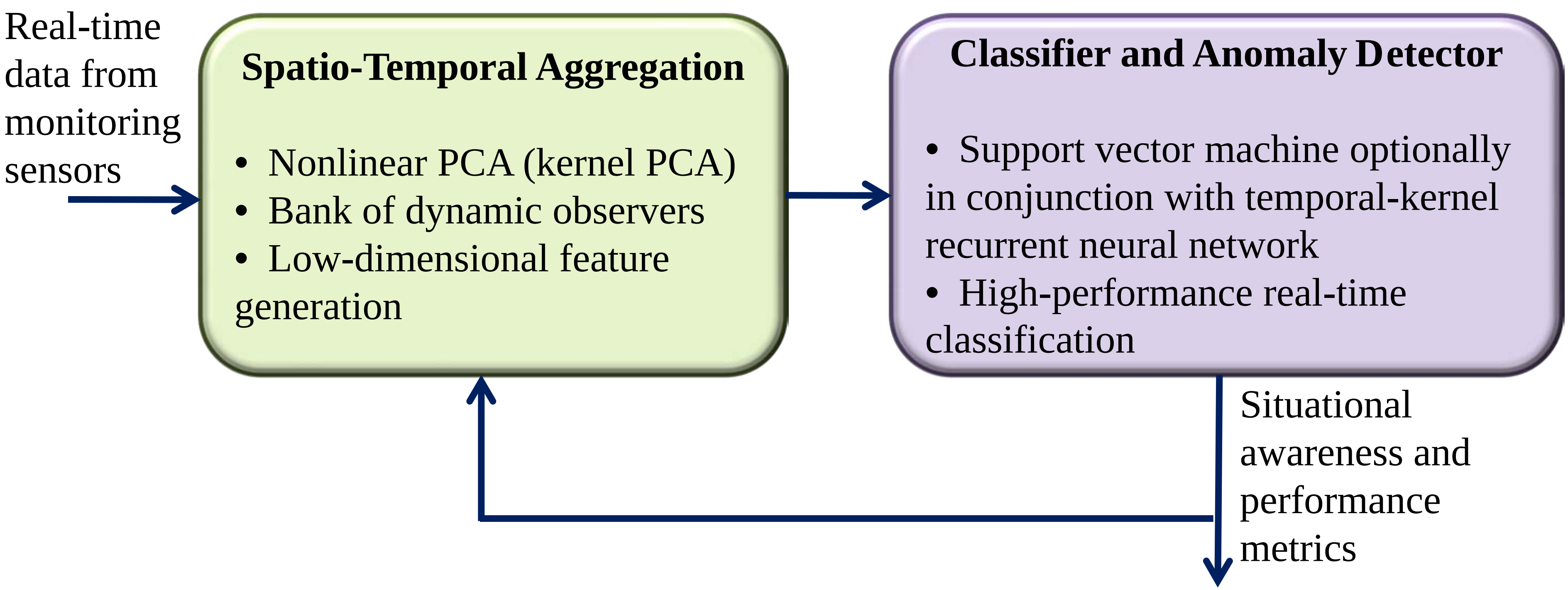
Control Design for PEM Fuel Cell Based DG System

- Lyapunov-based adaptive control design technique for fuel cell
  - Robust to parametric and functional uncertainties in system dynamics
- 9 x 1 parameter vector for adaptation
- Simultaneously addresses voltage tracking and pressure differential minimization
- Sliding mode control design for DC/DC boost converter … alternatively, PI controller + PWM switching

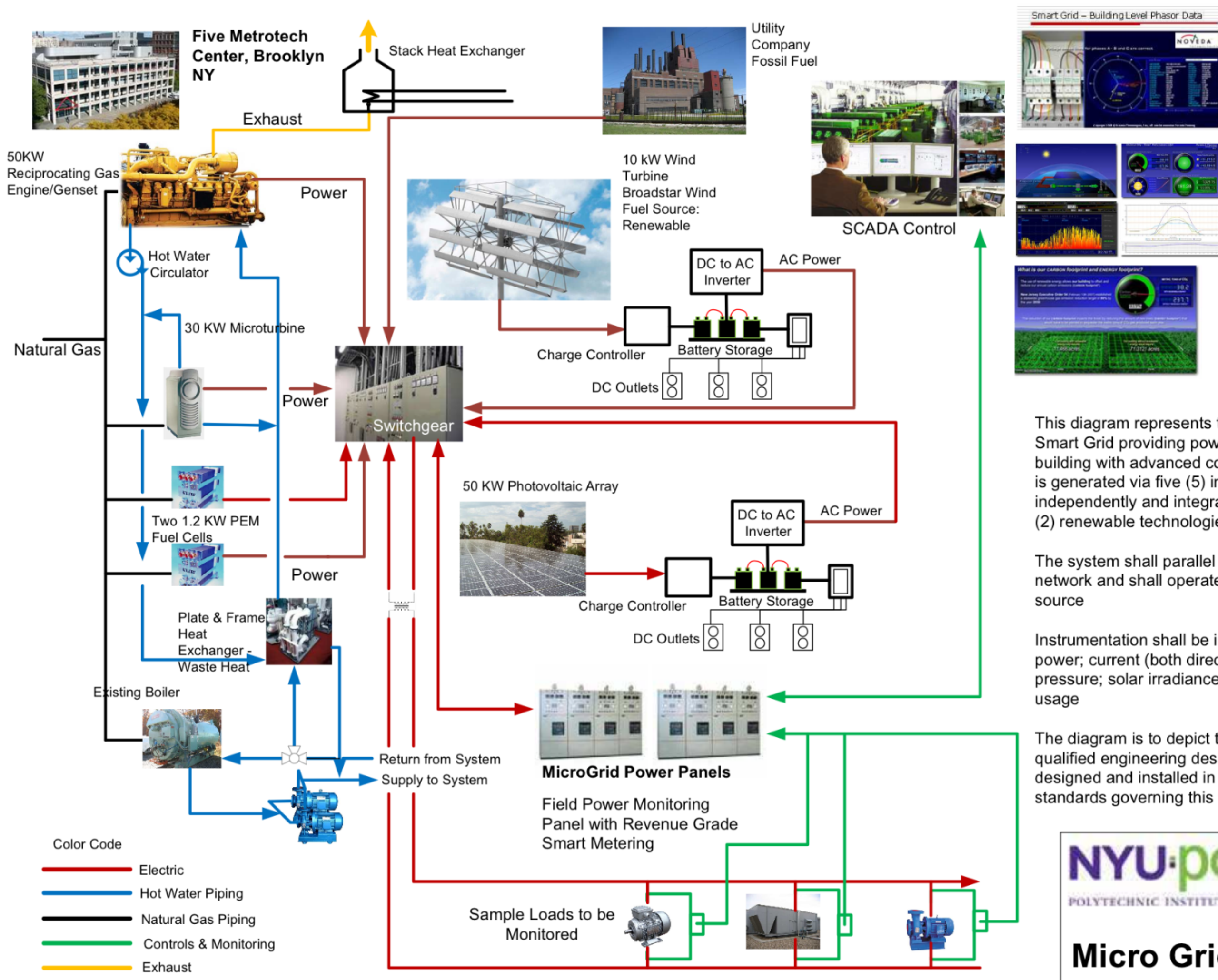


- *48 stack PEM fuel cell*
- *Desired output voltage of fuel cell and DC-DC converter = 30 V and 480 V, respectively*
- *Step load change at t = 25 s*

Smart Grid Monitoring and Anomaly Detection



Cyber-Controlled Smart Grid



Noveda web-based, real-time monitoring & visualization suite

- Extend Smart Grid to building level
- Maintain high performance building
- Demand Control
- Demand Response
- Real-time energy monitoring & analysis
- Carbon Footprint reductions
- Document compliance with energy goals, certifications and mandates
- Building Disclosure
- Comprehensive assessment of each technology using advanced monitoring and instrumentation both on an integrated and stand-alone basis

This diagram represents the architecture of a distributed generation Smart Grid providing power and thermal energy on micro level to one building with advanced controls and monitoring technology. The power is generated via five (5) independent prime movers acting both independently and integrally with storage capacity for power on the two (2) renewable technologies.

The system shall parallel with the local electric utility's distribution network and shall operate during blackout conditions as a backup power source

Instrumentation shall be installed throughout the system to monitor power; current (both direct and alternating); thermal energy; differential pressure; solar irradiance; emissions and emission offsets and fuel usage

The diagram is to depict the concept and should not be used as a qualified engineering design of the system. The actual system shall be designed and installed in accordance with all pertinent codes and standards governing this type of installation

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Micro Grid Demonstration Project