A Distributed Control Framework for Smart Grid Development

Jinfeng Liu
Department of Chemical & Materials Engineering
University of Alberta, Canada

Panagiotis D. Christofides
Department of Chemical & Biomolecular Engineering
Department of Electrical Engineering
University of California, Los Angeles, USA

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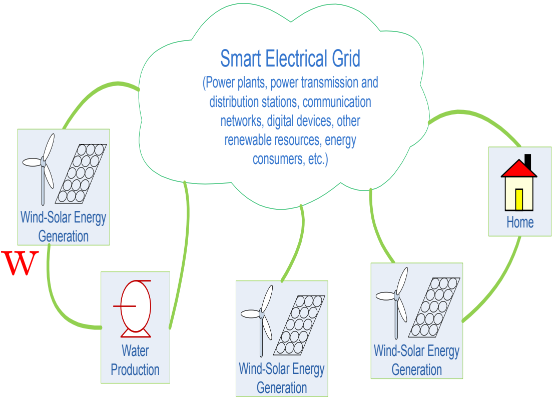
TALK OUTLINE

- Background, motivation and objectives
- Review on different control architectures: Distributed predictive control
- Proposed distributed control architecture for integrating distributed energy resources and loads to the electrical grid
  - ◇ Elements and challenging issues
- Supervisory control of an integrated wind/solar/RO system
  - ◇ Stand-alone operating mode
  - ◇ Electrical grid-connected operating mode
  - ◇ RO is the load of the system (associated with a tank to store ‘energy’)
  - ◇ Simulation results
- Distributed supervisory control of distributed wind and solar systems
  - ◇ Different distributed supervisory controller communication strategies
  - ◇ Simulation results
- Conclusions

INTRODUCTION



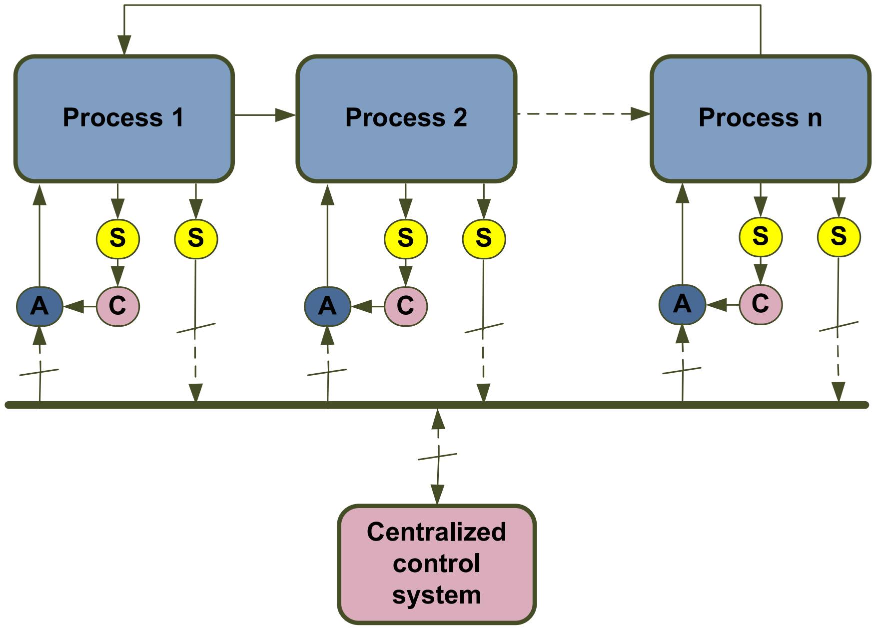
- Traditional electrical grid v.s. smart electrical grid
  - ◇ Centralized power plants with one-directional power flow $v.s.$ distributed power plants with bi-directional power flow
  - ◇ Slow response to power quality issues $v.s.$ real-time, automated, interactive technologies
  - ◇ Difficult for distributed energy resources interconnection $v.s.$ easy to integrate distributed energy resources

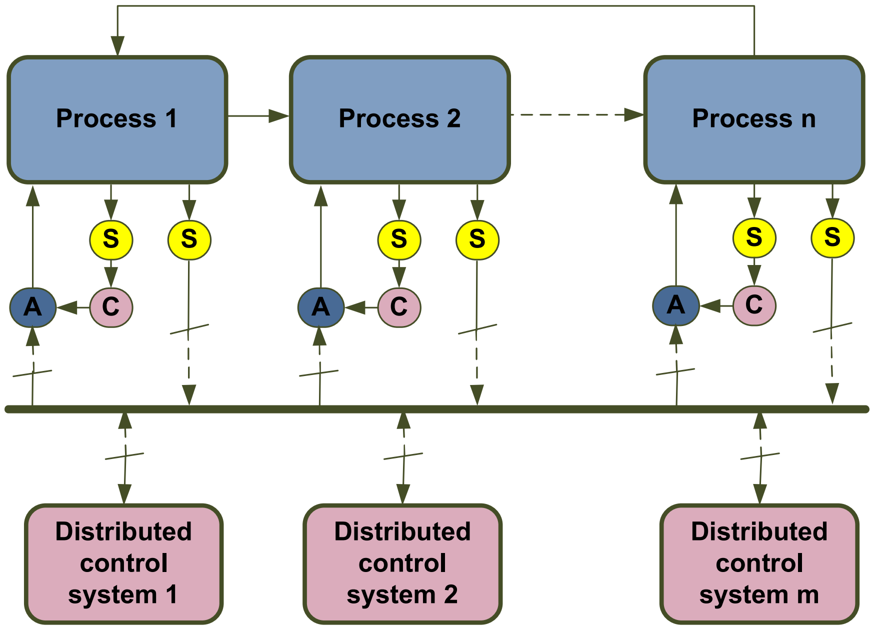
- Renewable energy
  - ◇ Rising rate of energy consumption
  - ◇ Environmental issues
  - ◇ Solar energy and wind energy
    - ▷ Natural resources
    - ▷ No carbon emission
    - ▷ Reduced investment risk
- Distributed predictive control framework for smart grid development

PREVIOUS WORK AND OBJECTIVES

- Previous work on control of wind/solar energy generation systems
  - ◇ Control of wind energy generation (Novak et. al., CSM, 1995; Thiringer and Linders, TEC, 1993; Valenciaga et. al., IJER, 2000; Chinchilla et. al., TEC, 2006)
  - ◇ Control of solar energy generation (Johansen and Storaa, Automatica, 2002; Coito et. al., IJACSP, 1997; Hamrouni et. al., RE, 2008; Yoshida et. al., EPEJ, 2007)
  - ◇ Control of stand-alone hybrid wind/solar energy generation (Valenciaga et. al., CTA, 2000; CTA, 2001; Valenciaga and Puleston, TEC, 2005; Ahmed et. al., EPCS, 2009)
  - ◇ Centralized/distributed supervisory predictive control of wind/solar/RO/grid energy generation systems (Qi et al., TCST, 2011; 2012; JPC, 2011)
- Objectives
  - ◇ Propose a distributed control architecture for integrating distributed energy resources and loads to the electrical grid
  - ◇ Supervisory control of a wind/solar/RO system connected to the grid
  - ◇ Distributed control of distributed wind and solar energy generation system

CENTRALIZED VS. DISTRIBUTED CONTROL

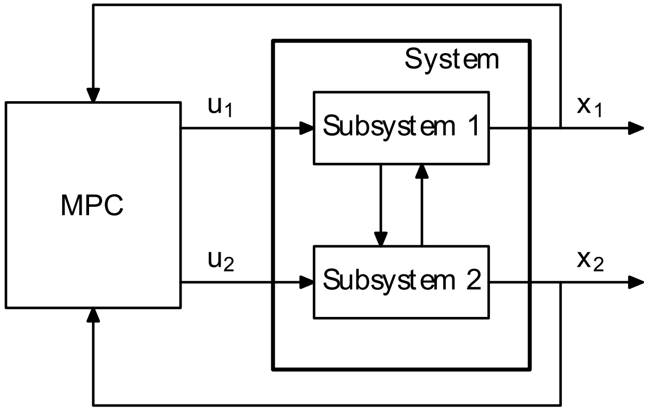




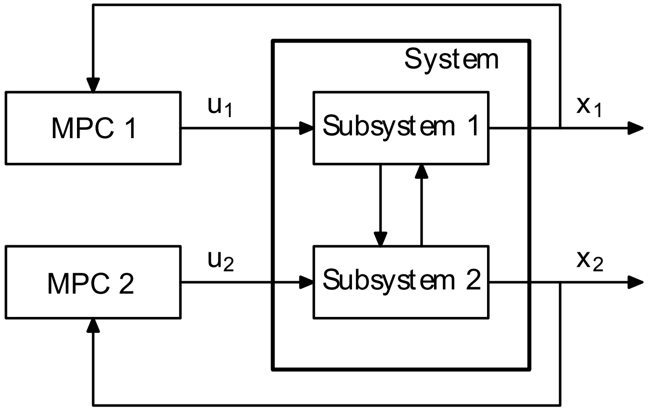
- Centralized process control architecture
    - ◇ Computational complexity
    - ◇ Organization and maintenance
    - ◇ Fault tolerance
- Move towards distributed control architecture
- Issues need to be addressed when moving to distributed control
    - ◇ Coordination of controllers for stability and performance
    - ◇ Communication strategy between distributed controllers
- Model Predictive Control (MPC): a natural framework for distributed control system

CENTRALIZED, DECENTRALIZED AND DISTRIBUTED CONTROL

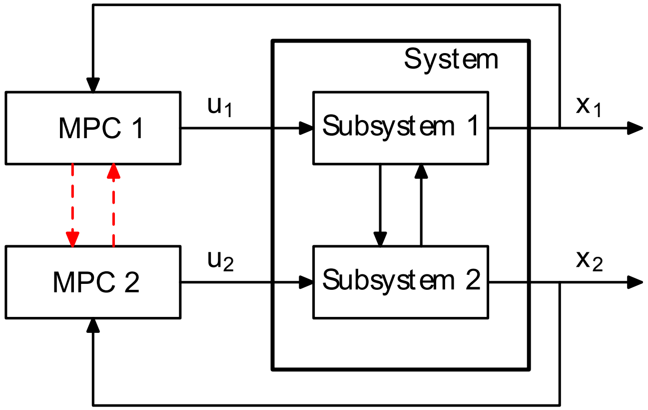
- Different control architectures



Centralized control system



Decentralized control system



Distributed control system

- Classified by communication between different controllers
  - ◇ Decentralized control system
    - ▷ No communication between controllers
  - ◇ Distributed control system
    - ▷ Different controllers exchange information to coordinate their actions
  - ◇ Non-cooperative vs Cooperative distributed control systems
    - ▷ Depending on the cost functions used in the controllers

NON-COOPERATIVE DMPC

- Non-Cooperative DMPC Review
  - ◇ DMPC for a class of decoupled systems with the distributed controllers evaluated in sequence (Richards and How, International Journal of Control, 2007)
  - ◇ DMPC for a class of discrete-time linear systems (Camponogara et al., IEEE Control Systems Magazine, 2002)
  - ◇ DMPC for systems with dynamically decoupled subsystems (Keviczky et al., Automatica, 2006)
  - ◇ DMPC scheme for linear systems coupled through the state (Jia and Krogh, ACC, 2001)
  - ◇ Application to supply chain optimization (Dunbar and Desa, NMPC, 2005)
  - ◇ Application of iterative DMPC scheme together with a distributed Kalman filter to a quadruple tank system (Mercangoz and Doyle, Journal of Process Control, 2007)

COOPERATIVE DMPC

- Cooperative DMPC Review
  - ◇ Idea of cooperative DMPC was first introduced in 2005 (Venkat et al., CDC, 2005)
  - ◇ Cooperative DMPC of linear systems (Rawlings and Stewart, Journal of Process Control, 2008; Stewart et al., Systems and Control Letters, 2010)
    - ▷ System-wide control objective functions
    - ▷ The closed-loop performance converges to the corresponding centralized control system as the iteration number increases
  - ◇ Lyapunov-based iterative DMPC for nonlinear systems (Liu et al., AIChE Journal, 2009; 2010; Liu et al., Automatica, 2010; TAC, 2012; Christofides et al., Springer, 2011)
    - ▷ Well-characterized regions of closed-loop stability
    - ▷ Accounting for asynchronous and delayed measurements
  - ◇ Coordinator-based DMPC (Cheng et al., Journal of Process Control, 2007; Computers and Chemical Engineering, 2008)

COOPERATIVE DMPC OF NONLINEAR SYSTEMS

(Liu et al., AIChE J., 2009; AIChE J., 2010)

- System description

$$\dot{x}(t) = f(x(t)) + \sum_{i=1}^{m} g_i(x(t))u_i(t) + k(x(t))w(t)$$

  - ◇ $u_i \ (i = 1, \ldots, m)$: m sets of control inputs with $|u_i| \leq u_i^{\max} \ (i = 1, \ldots, m)$
  - ◇ $f(x)$, $g_i(x) \ (i = 1, \ldots, m)$ and $k(x)$: vector functions

- Nonlinear feedback control law, $u = h(x) = [h_1(x) \ldots h_m(x)]^T$

$$\dot{V}(x) = \frac{\partial V(x)}{\partial x}\left(f(x) + \sum_{i=1}^{m} g_i(x)h_i(x)\right) < 0$$

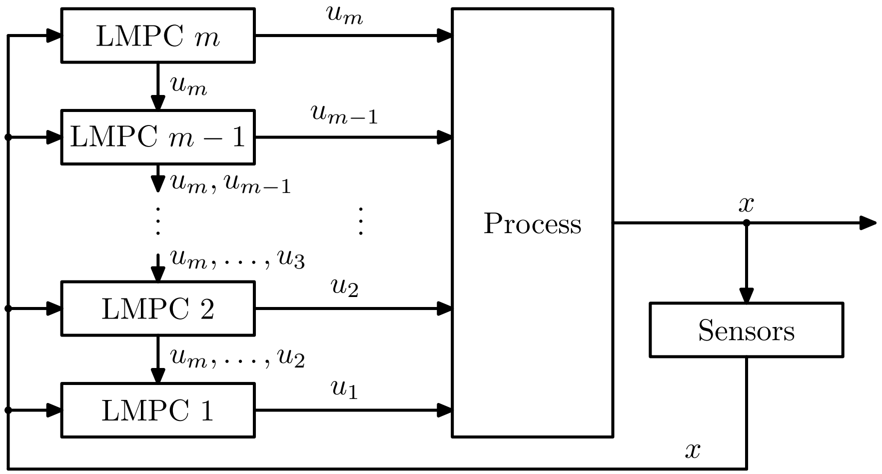
  - ◇ Renders the origin of the nominal system asymptotically stable under the control: $u_i = h_i(x) \ (i = 1, \ldots, m)$
  - ◇ Satisfies the input constraints on $u_i \ (i = 1, \ldots, m)$
  - ◇ Stability region: $\Omega \subset D$ is a compact set containing the origin

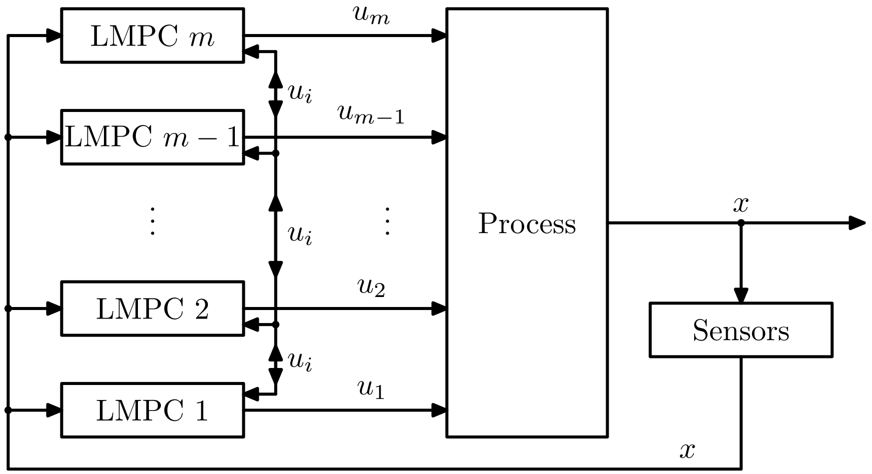
- Distributed model predictive control (DMPC) - each MPC optimizes the same (global) cost function (cooperative, distributed MPC)

COOPERATIVE DMPC ARCHITECTURES

(Liu et al., AIChE J., 2009; AIChE J., 2010)

- m LMPCs will be designed to decide the m sets of control inputs
- Two approaches
  - ◇ Sequential DMPC
  - ◇ Iterative DMPC



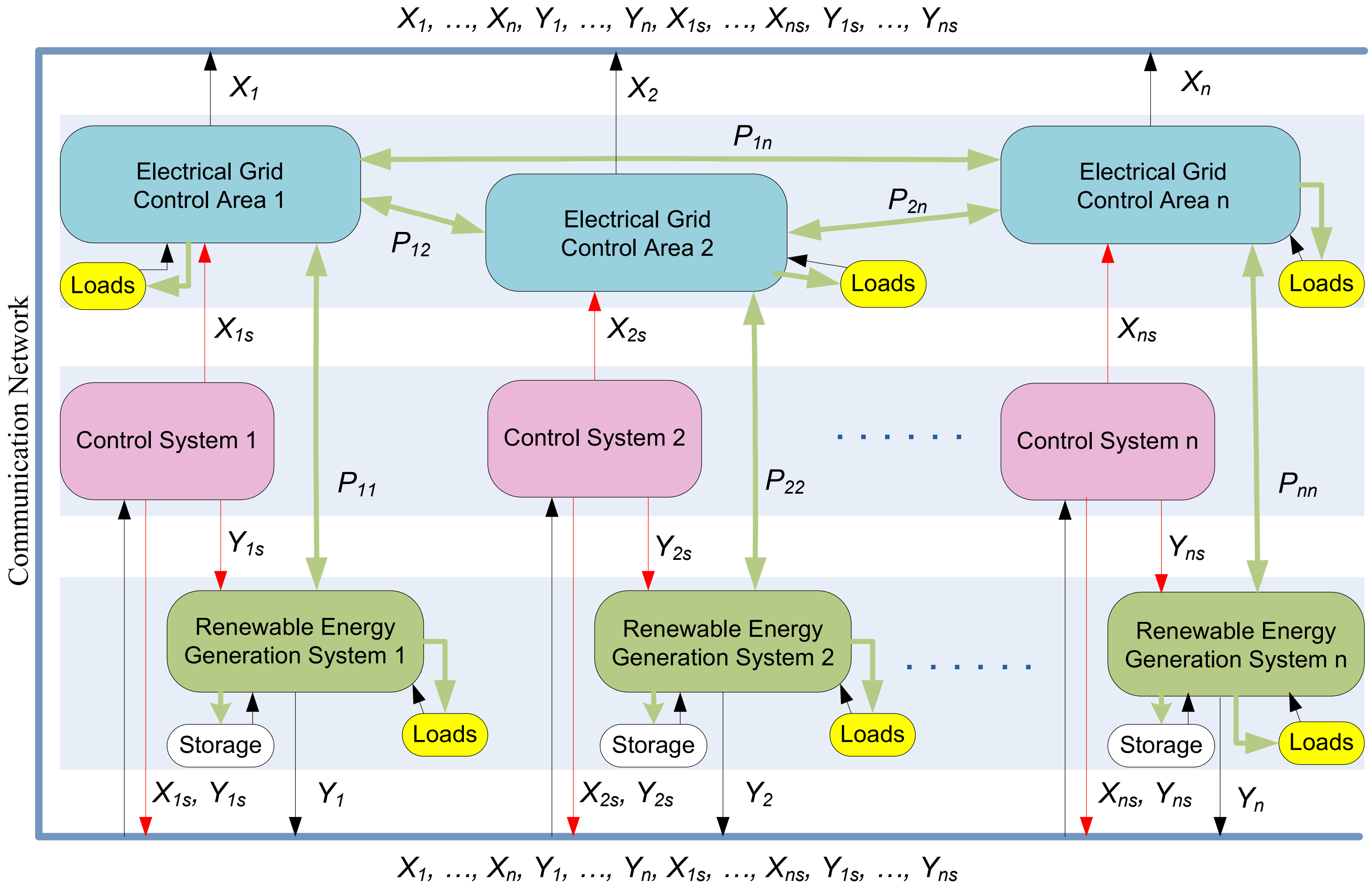


- Sequential DMPC: One-directional communication, each controller is evaluated once at a sampling time
- Iterative DMPC: Bi-directional communication, controllers iterate to achieve convergence at a sampling time

DISTRIBUTED CONTROL ARCHITECTURE

(Qi et al., J. Proc. Contr., 2011)

- Proposed distributed control architecture



$X_1, \ldots, X_n, Y_1, \ldots, Y_n, X_{1s}, \ldots, X_{ns}, Y_{1s}, \ldots, Y_{ns}$

Communication Network

X_1

X_2

X_n

P_{1n}

Electrical Grid Control Area 1

Electrical Grid Control Area 2

Electrical Grid Control Area n

P_{12}

P_{2n}

Loads

Loads

Loads

X_{1s}

X_{2s}

X_{ns}

Control System 1

Control System 2

. . . .

Control System n

P_{11}

P_{22}

P_{nn}

Y_{1s}

Y_{2s}

Y_{ns}

Renewable Energy Generation System 1

Renewable Energy Generation System 2

. . . .

Renewable Energy Generation System n

Storage

Loads

Storage

Loads

Storage

Loads

X_{1s}, Y_{1s}

Y_1

X_{2s}, Y_{2s}

Y_2

X_{ns}, Y_{ns}

Y_n

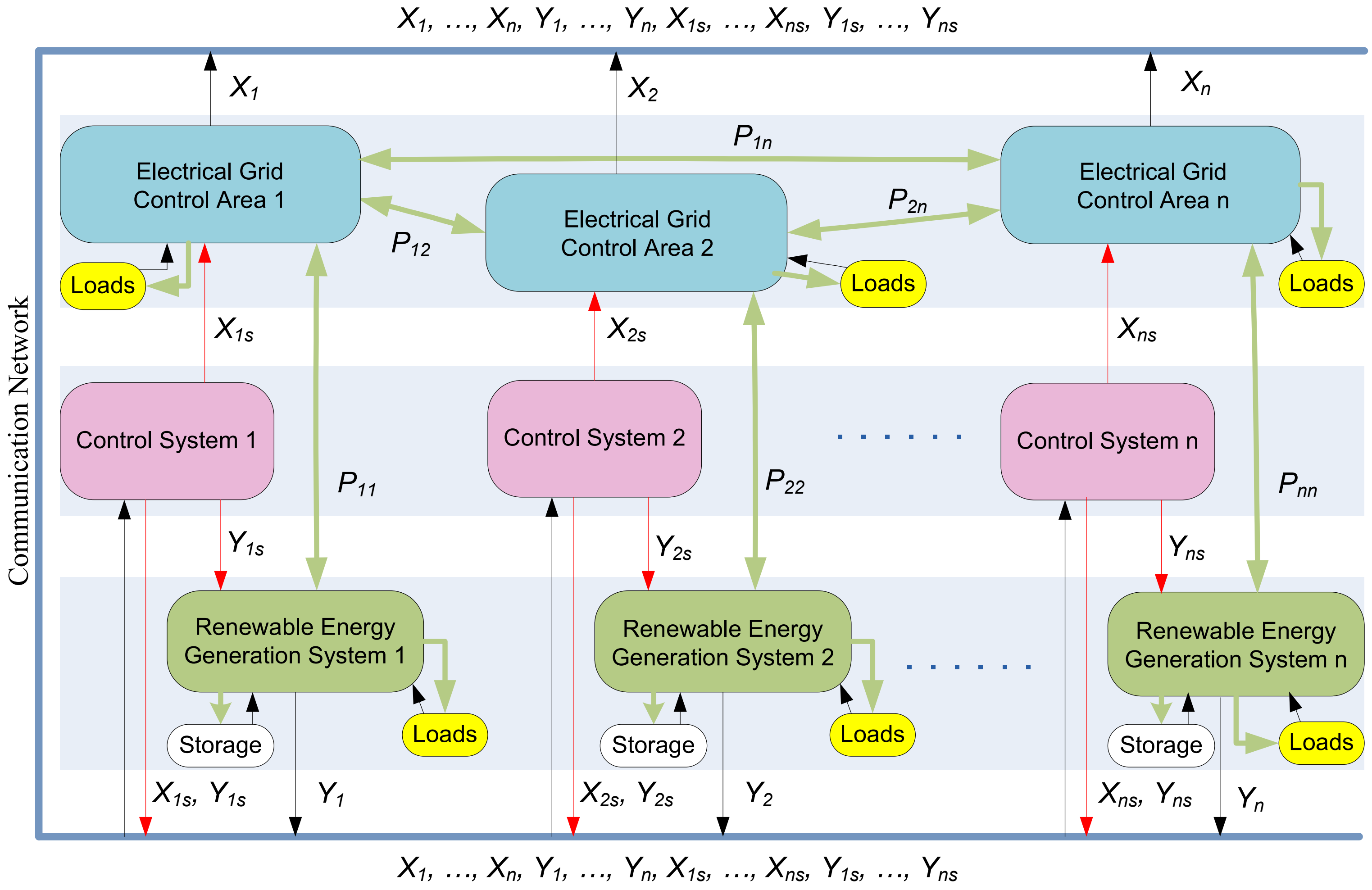
$X_1, \ldots, X_n, Y_1, \ldots, Y_n, X_{1s}, \ldots, X_{ns}, Y_{1s}, \ldots, Y_{ns}$

- ◇ Electrical gird divided into several control areas
- ◇ Distributed renewable energy generation systems
- ◇ Distributed control system
- ◇ Real-time communication network

DISTRIBUTED CONTROL ARCHITECTURE

(Qi et al., J. Proc. Contr., 2011)

- Proposed distributed control architecture

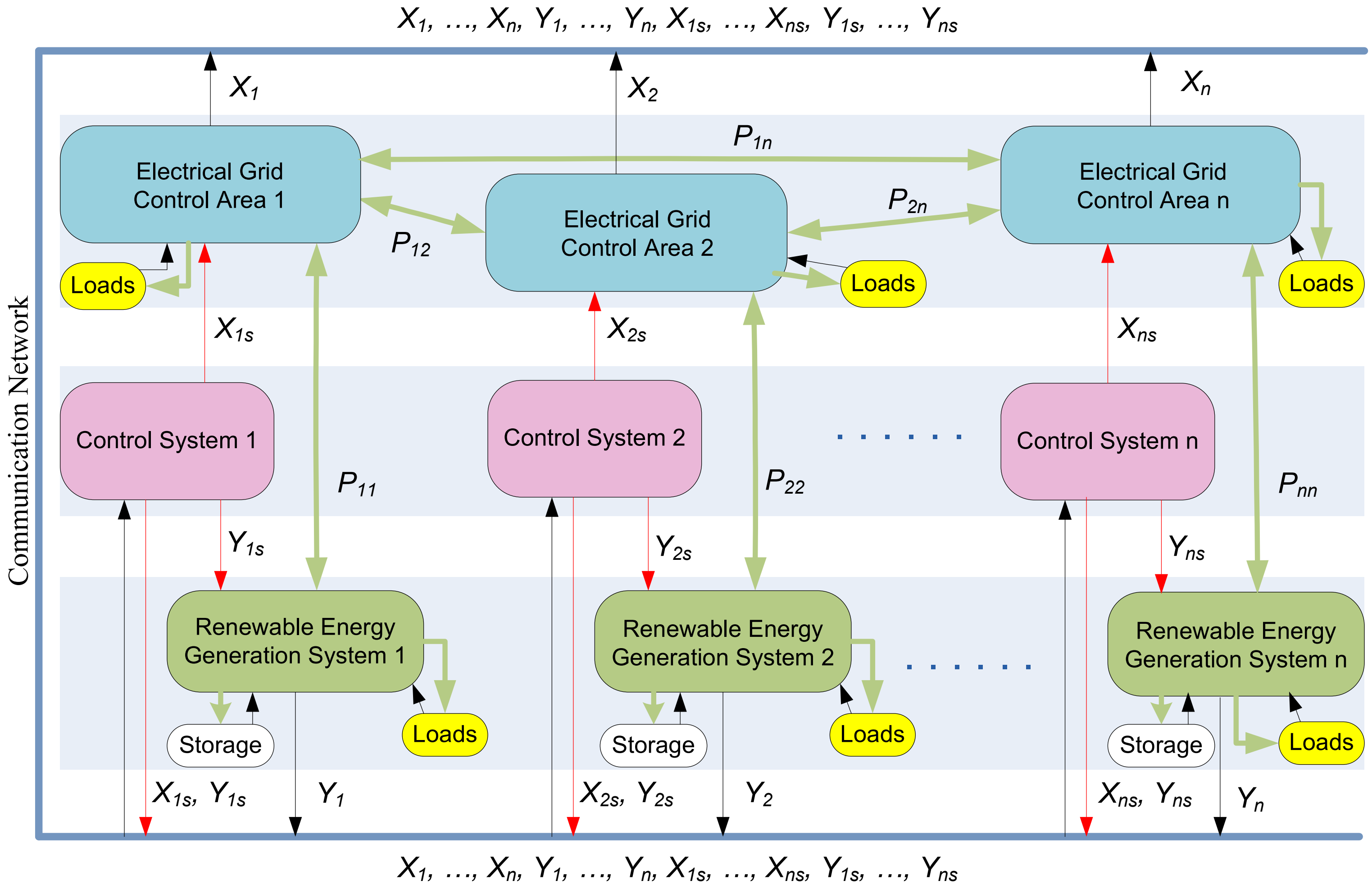


- ◇ Control areas of electrical grid
  - ▷ Different control areas are interconnected through bi-directional power lines
  - ▷ Electrical power can flow between the different control areas bi-directionally

DISTRIBUTED CONTROL ARCHITECTURE

(Qi et al., J. Proc. Contr., 2011)

- Proposed distributed control architecture



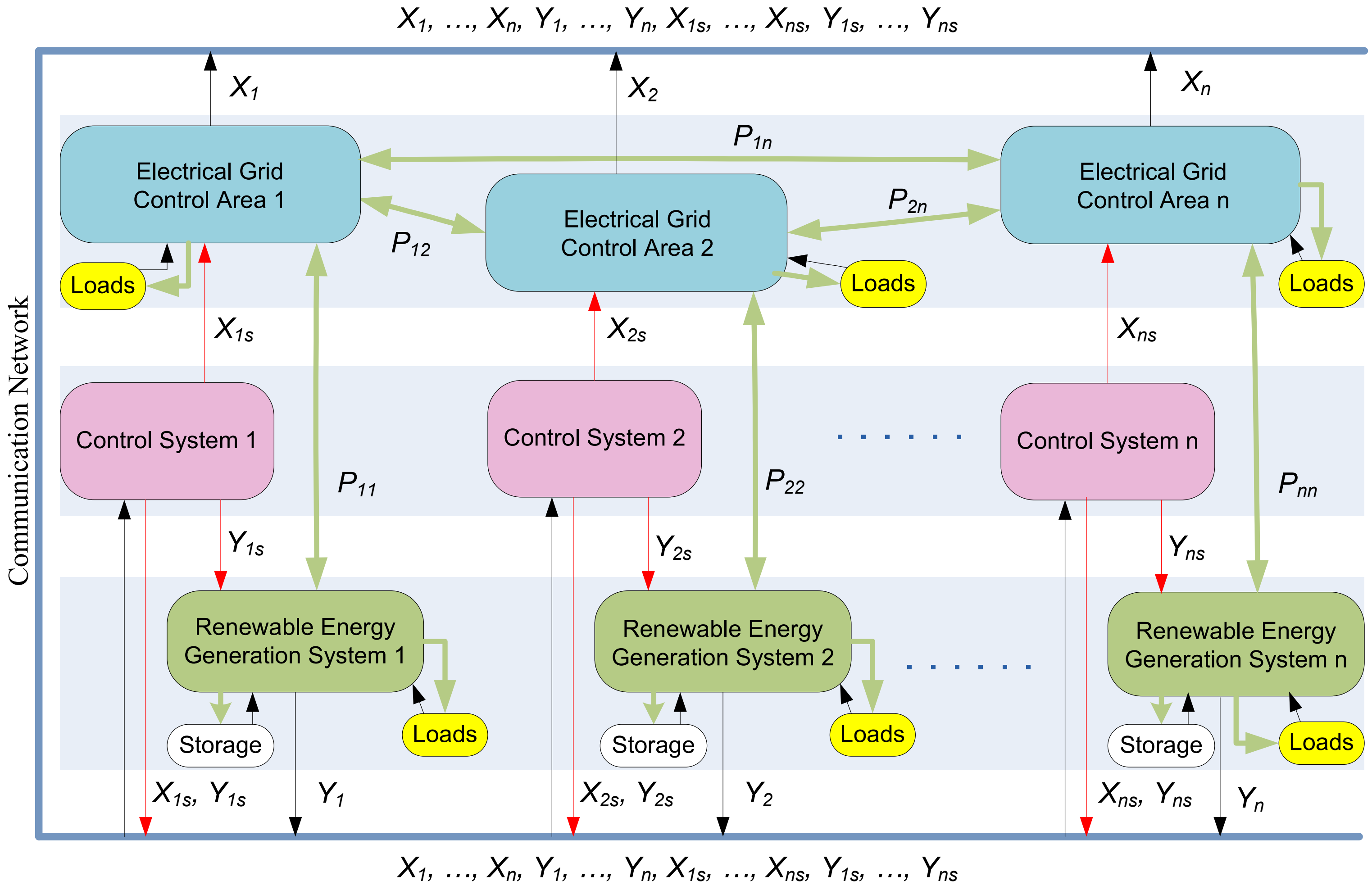
◇ Distributed renewable energy generation systems

▷ Each control area may connect with many different types of renewable energy generation systems

DISTRIBUTED CONTROL ARCHITECTURE

(Qi et al., J. Proc. Contr., 2011)

- Proposed distributed control architecture

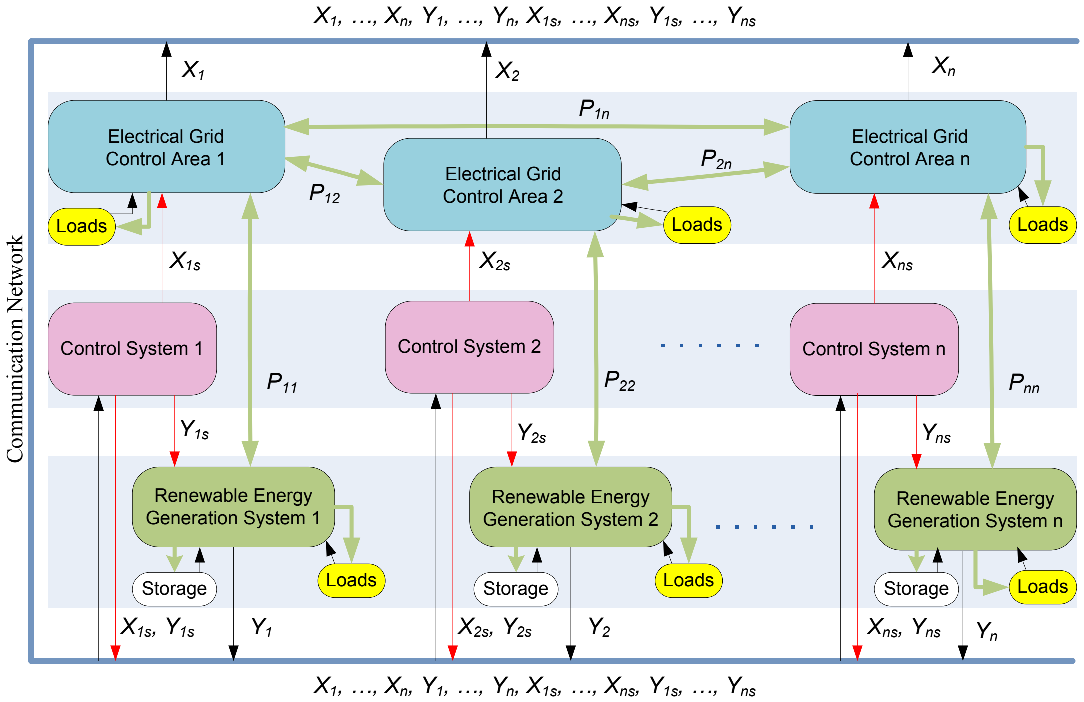


◇ Distributed control system

  ▷ Calculates the operating set-points for the control area and the renewable energy generation system - DMPC is particularly suited

DISTRIBUTED CONTROL ARCHITECTURE

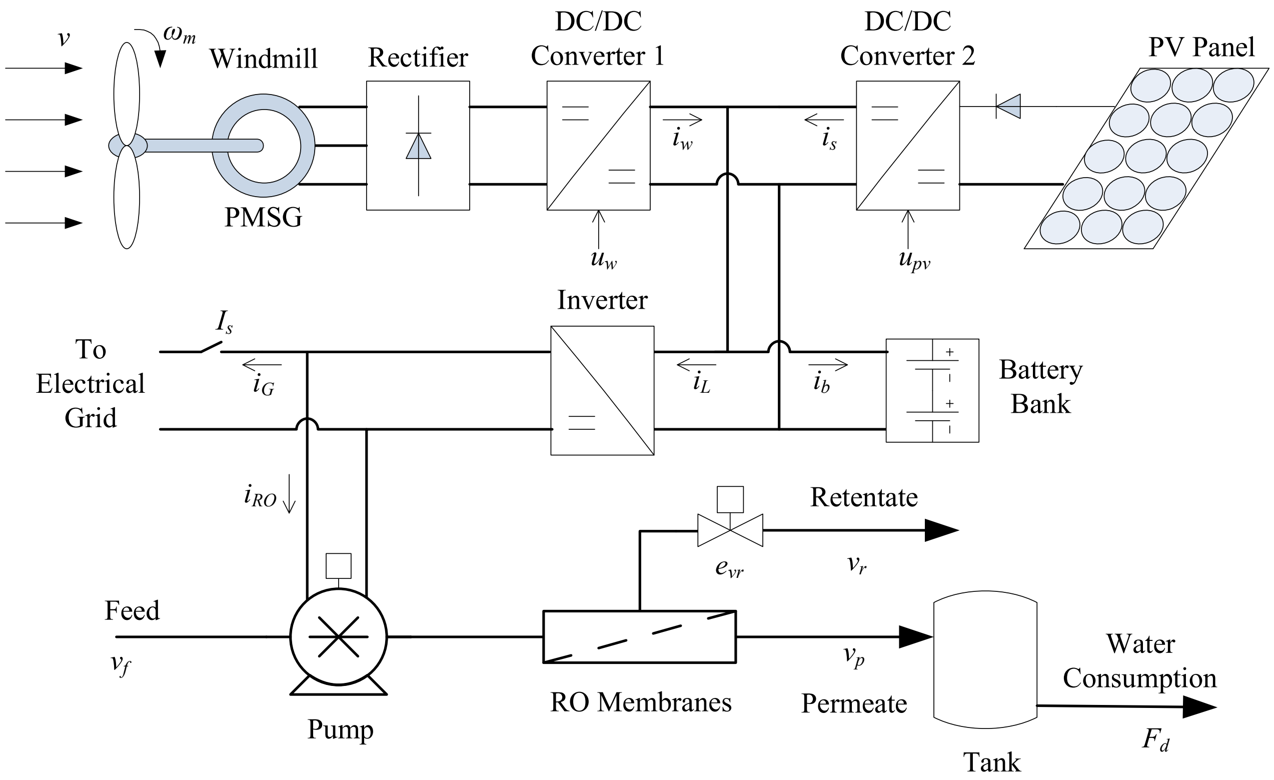
- Proposed distributed control architecture



- Challenging issues
  - ◇ Predictive control of different renewables-based energy generation systems
  - ◇ Coordination of a renewables-based energy generation system with the electrical grid and loads
  - ◇ Cooperation between different control systems
- Integrated wind/solar energy generation system connected to an RO water desalination system and the electrical grid (addressing first two issues)
- Distributed control of distributed wind and solar energy generation system

INTEGRATED WIND/SOLAR AND RO SYSTEM

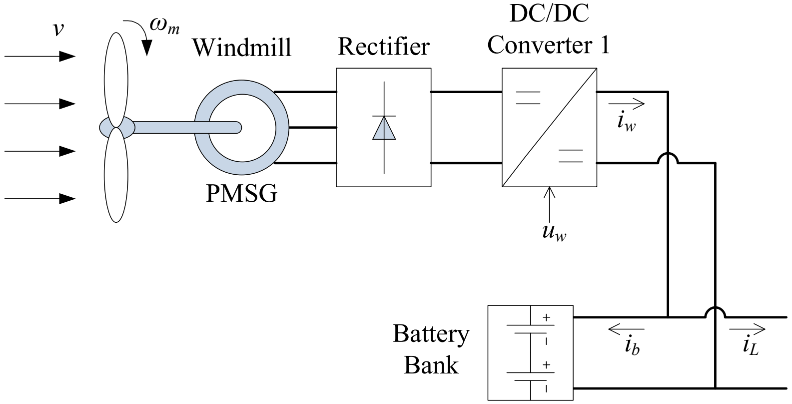
- System description



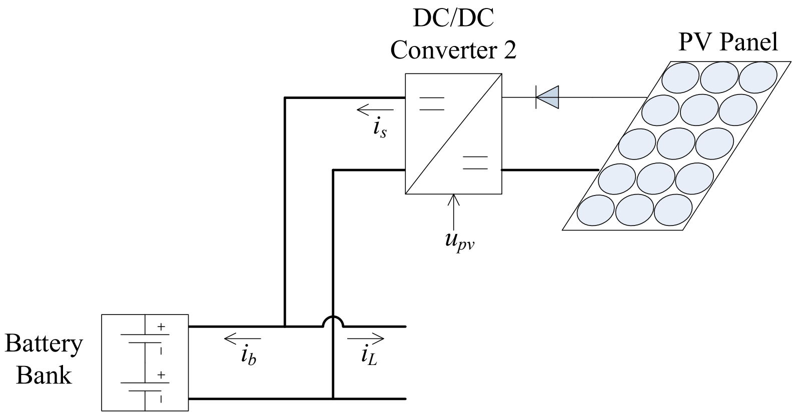
- ◇ Energy generation system
  - ▷ Wind generation subsystem
  - ▷ Battery bank
  - ▷ Solar generation subsystem
- ◇ RO water desalination system
  - ▷ High-pressure pump
  - ▷ Water storage tank
  - ▷ RO membrane module

SYSTEM MODELING

- Wind subsystem modeling
  - ◇ Three nonlinear ODEs
  - ◇ Quadrature current i_q, direct current i_d and electrical angular speed w_e
  - ◇ Manipulated input is a function of the duty cycle of the converter u_w
  - ◇ Power generated $P_w = v_b \frac{\pi}{2\sqrt{3}} \sqrt{i_q^2 + i_d^2} u_w$

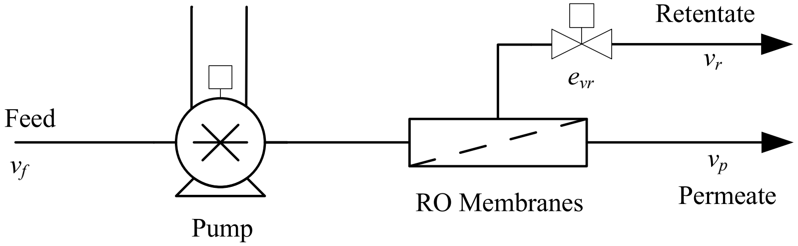


- Solar subsystem modeling
  - ◇ Two nonlinear ODEs and one algebraic equation
  - ◇ Voltage level on the PV panel terminal v_{pv} and the current injected to the DC bus i_s
  - ◇ Manipulated input is duty cycle of the converter u_{pv}
  - ◇ Power generated $P_s = i_s v_b$



SYSTEM MODELING

- Modeling of the battery bank
  - A voltage source E_b connected in series with a resistance R_b and a capacitor C_b $v_b = E_b + v_c + i_b R_b$
  - State of charge (SOC) $s_b = \dfrac{Q_c}{Q_c^{\max}} = \dfrac{v_c}{v_c^{\max}}$
- RO subsystem modeling
  - One ODE and two algebraic equations
  - Retentate stream velocity v_r
  - Manipulated input is the valve resistance e_{vr}
  - Power needed for the water desalination system: $P_T = \dfrac{1}{\eta}\left(P_{sys}\frac{F_d}{Y} + \frac{1}{2}\frac{F_r^3}{Y^3 A_p^2}\rho_w\right)$



- Dynamics of the water storage tank level
  - $\dot{h}_l = \dfrac{F_s}{A_s} = \dfrac{A_p}{A_s}(v_f - v_r) - \dfrac{F_d}{A_s}$
  - State of storage (SOS) $s_t = \dfrac{h_l}{h_l^{\max}}$

TWO-TIME-SCALE BEHAVIOR AND CONTROL TASKS

- Two-time-scale behavior of the integrated system dynamics
  - ◇ Fast dynamics: i_q, i_d, w_e, v_{pv}, i_s, v_r
    - ▷ Dynamics of the wind, solar and water subsystems
  - ◇ Slow dynamics: v_c, h_l
    - ▷ States reflecting the interaction of the different subsystems
- Control tasks
  - ◇ Short-term supervisory predictive control of the integrated system
    - ▷ Standalone mode, $I_s = 0$
  - ◇ Long-term supervisory predictive control of the integrated system
    - ▷ Connected to the electrical grid, $I_s = 1$
    - ▷ Two-time-scale behavior is taken into account in the design of the supervisory control system

SHORT-TERM SUPERVISORY PREDICTIVE CONTROL

(Qi et al., IEEE Contr. Syst. Tech.,2011)

- Control objectives
  - ◇ Primary control objective is to coordinate the wind and solar as well as battery to provide enough energy to the RO subsystem to satisfy scheduled water production
  - ◇ Secondary control objective is to optimize the operation - reduce battery short-term charge-discharge cycles
- Design of the cost function

$$\begin{aligned} J_s(t_k) &= \int_{t_k}^{t_{k+N}} \alpha \left(P_{RO}(\tau) - P_w^{ref}(\tau) - P_s^{ref}(\tau) \right)^2 d\tau \\ &+ \int_{t_k}^{t_{k+N}} \beta P_s^{ref}(\tau)^2 d\tau + \int_{t_k}^{t_{k+N-1}} \zeta \left(P_b(\tau + \Delta) - P_b(\tau) \right)^2 d\tau \end{aligned}$$

  - ◇ The first term penalizes the difference between the power generated by the wind and solar subsystems and the total power demand
  - ◇ The second term makes the wind subsystem as the primary generation subsystem
  - ◇ The third term penalized the change of the power provided by the battery

SUPERVISORY CONTROL SYSTEM DESIGN

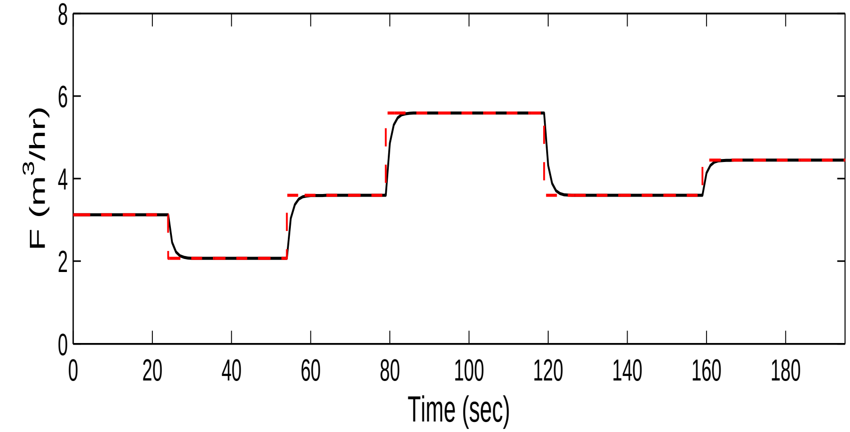
- Proposed MPC design

$$
\begin{aligned}
\min_{P_w^{ref}, P_s^{ref} \in S(\Delta)} \quad & J_s(t_k) \\
\text{s.t.} \quad & P_w^{ref}(\tau) \le \min_{\tau}\{P_w^{\max}(\tau)\},\ \tau \in [t_{k+j}, t_{k+j+1}) \\
& P_s^{ref}(\tau) \le \min_{\tau}\{P_{pv,\max}(\tau)\},\ \tau \in [t_{k+j}, t_{k+j+1}) \\
& P_w^{ref}(t_{k+j+1}) - P_w^{ref}(t_{k+j}) \le dP_{w,\max} \\
& P_s^{ref}(t_{k+j+1}) - P_s^{ref}(t_{k+j}) \le dP_{s,\max} \\
& \dot{\tilde{x}}(\tau) = f(\tilde{x}(\tau)) + g(\tilde{x}(\tau))u(\tau) \\
& h(\tilde{x}) = 0 \\
& \tilde{x}(0) = x(t_k)
\end{aligned}
$$

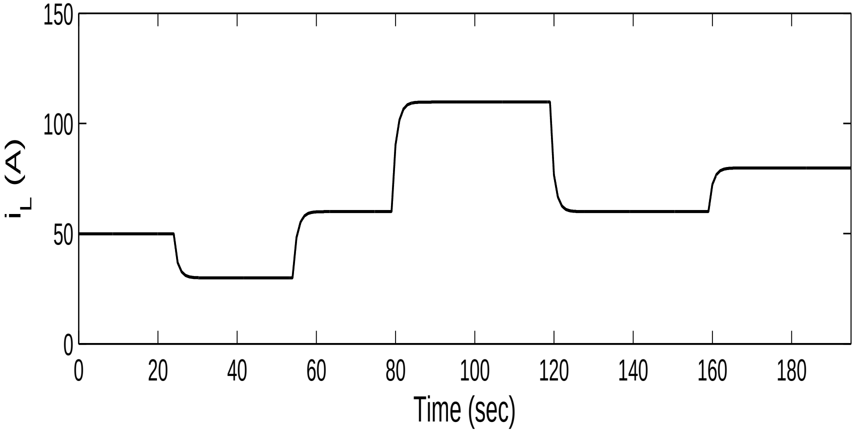
  - ◇ The first two constraints make sure the power references of the wind and solar subsystems are achievable
  - ◇ The third and fourth restrict the change value of the generated power in two consecutive sampling times
  - ◇ The last three equations are system model

SIMULATION RESULTS

- Water production demand

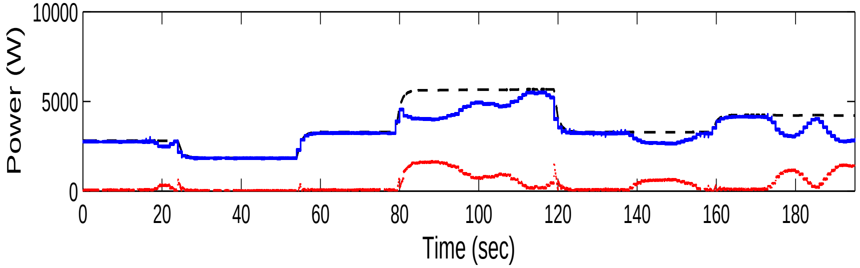


(a)

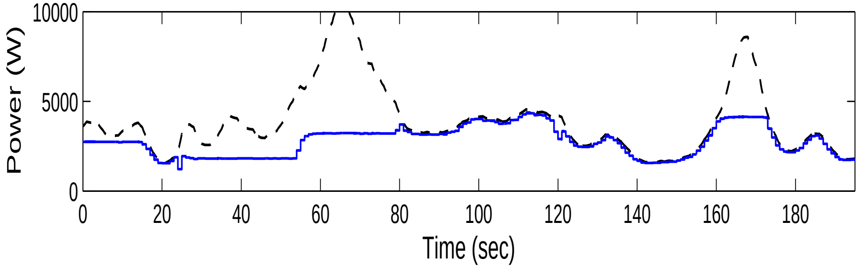


(b)

- Power trajectories - $N = 2$, $\Delta = 1\ s$



(a)



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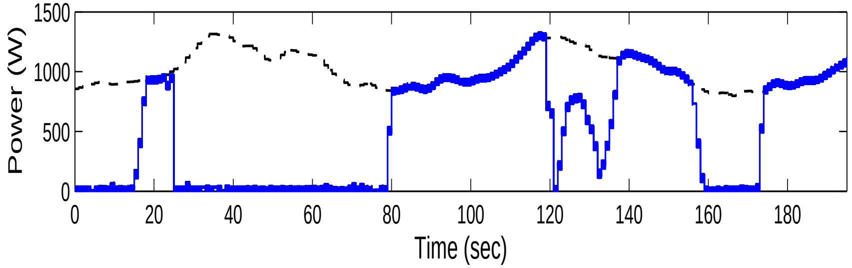


(c)

- The proposed control system coordinates wind/solar/battery to satisfy the energy demand of water production

LONG-TERM SUPERVISORY PREDICTIVE CONTROL

(Qi et al., IEEE Contr. Syst. Tech.,2012)

- Control objectives
  - ◇ Primary control objective is to regulate the integrated system to provide enough energy to the RO subsystem to satisfy scheduled water production
  - ◇ Secondary control objective is to optimize the operation - battery maintenance and time-varying electric power pricing
- Design of the cost function

$$\begin{aligned} J_g(t_k) &= \gamma \int_{t_k}^{t_{k+N}} d_b(\tau) d\tau + \xi \int_{t_k}^{t_{k+N}} i_b(\tau)^2 d\tau + \zeta \int_{t_k}^{t_{k+N}} p(\tau) P_G(\tau) d\tau \\ &\quad + \epsilon \int_{t_k}^{t_{k+N}} \left| s_t(\tau) - s_t^{opt} \right| d\tau + \theta \int_{t_k}^{t_{k+N}} P_{RO}(\tau) d\tau \div \int_{t_k}^{t_{k+N}} F_p(\tau) d\tau \end{aligned}$$

  - ◇ The first term implies that the battery should be charged
  - ◇ The second term means small charging currents are preferred
  - ◇ The third term considers the economics by selling/buying power to/from the grid ($P_G = -i_G v_b$)
  - ◇ The fourth term is used to maintain the water level around the optimal value
  - ◇ The fifth term penalized the energy consumption in producing water

SUPERVISORY CONTROL SYSTEM DESIGN

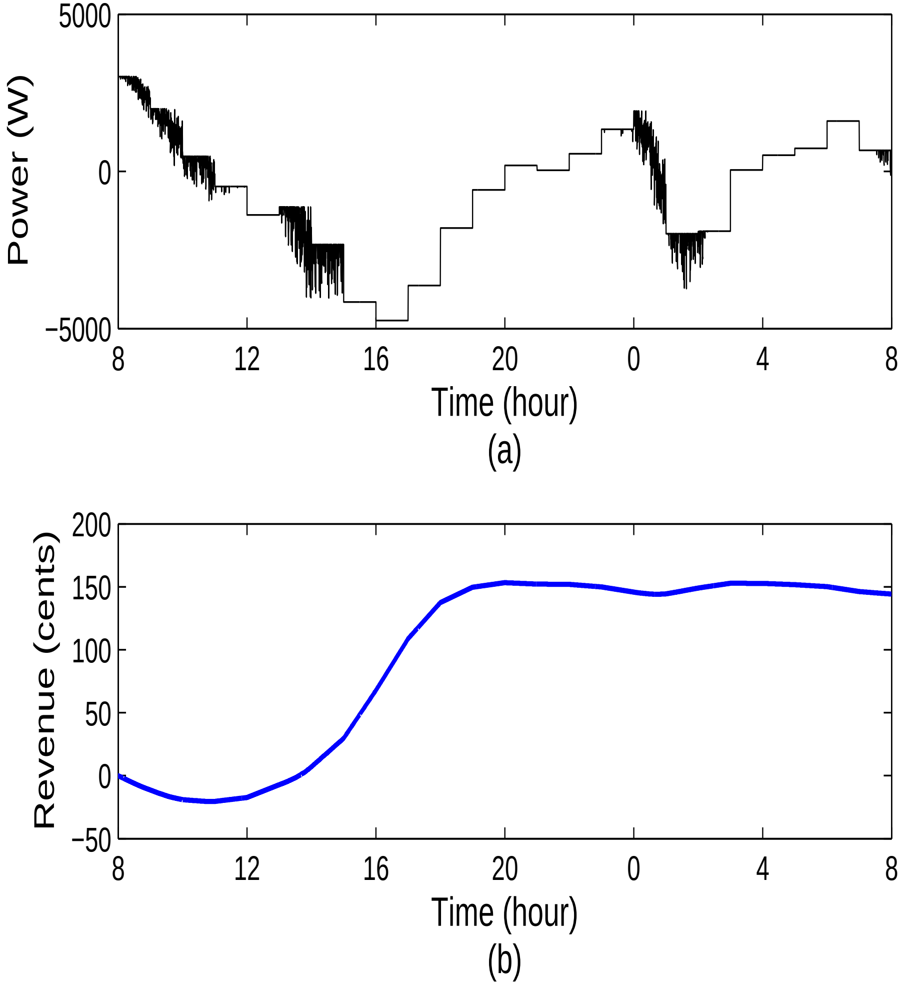
- Proposed MPC design

$$
\begin{aligned}
&\min_{i_G^{ref},\, v_r^{ref} \in S(\Delta)} \quad J_g(t_k) \\
\text{s.t.} \quad & P_{RO}(\tau) - P_w(\tau) - P_s(\tau) + i_G^{ref}(\tau) v_b(\tau) + i_b v_b = 0 \\
& F_p^{\min} \leq F_p(\tau) \leq F_p^{\max} \\
& 0 \leq d_b(\tau) \leq d_b^{\max} \\
& s_t^{\min} \leq s_t(\tau) \leq s_t^{\max} \\
& i_b(\tau) \leq i_b^{\max}(s_b(\tau)) \\
& \dot{\tilde{x}}(\tau) = f(\tilde{x}(\tau)) + g(\tilde{x}(\tau)) u(\tau) \\
& h(\tilde{x}) = 0 \\
& \tilde{x}(0) = x(t_k)
\end{aligned}
$$

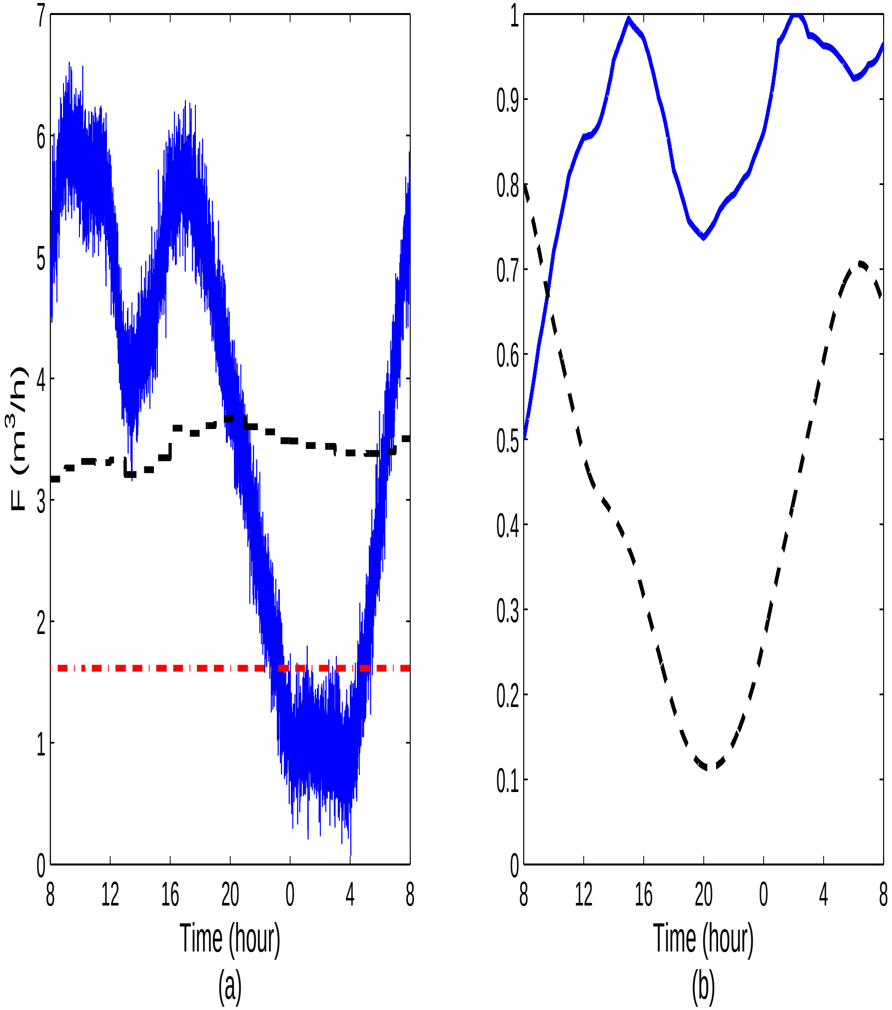
- ◇ The first constraint is an energy balance between different subsystems
- ◇ The second to the fifth constraints are constraints on system operation
- ◇ The last three equations are system model accounting for the two-time-scale behavior

SIMULATION RESULTS

- Power trading profile



- Process trajectories

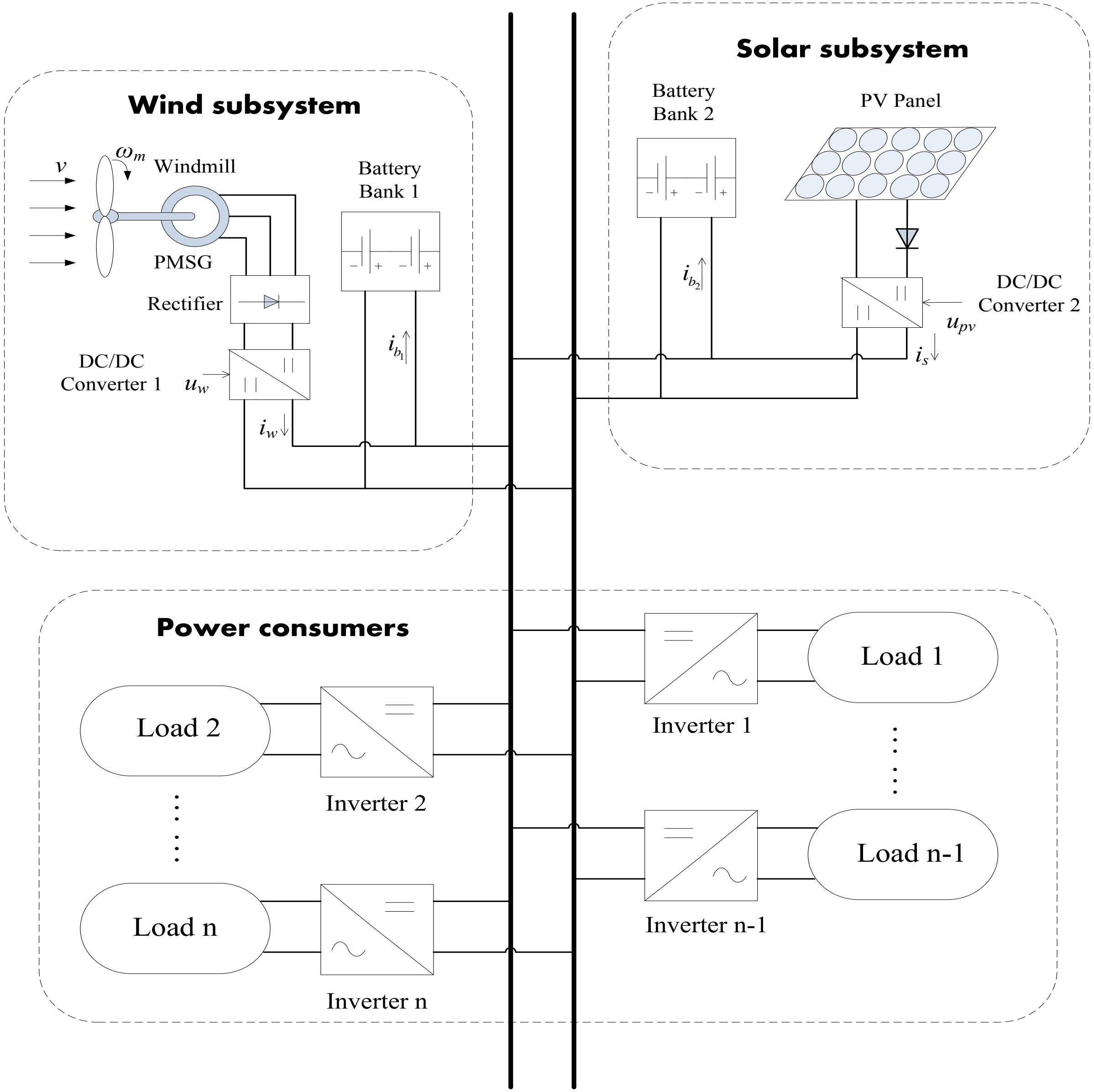


- Efficiently coordinates wind/solar/battery/RO subsystems and optimally provides power to the electrical grid

DISTRIBUTED ENERGY GENERATION SYSTEM INTEGRATED INTO A DC POWER GRID

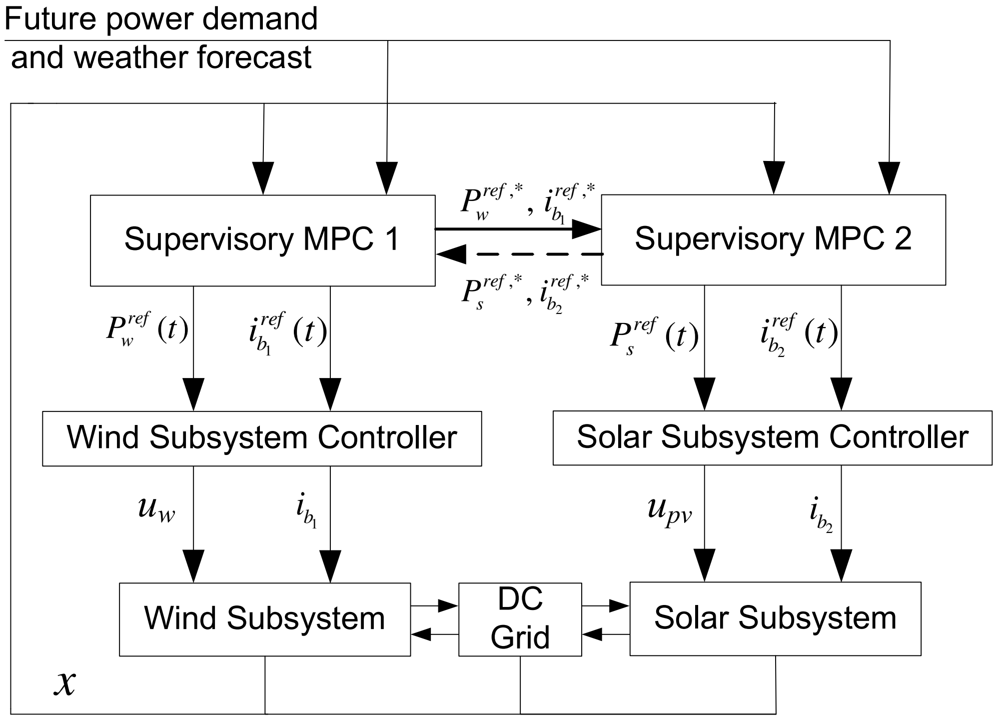
(Qi et al., IEEE Contr. Syst. Tech., in press)

- System description
  - ◇ Wind subsystem
  - ◇ Solar subsystem
  - ◇ Loads of the system
  - ◇ DC bus



DISTRIBUTED CONTROL PROBLEM FORMULATION

- Distributed supervisory control system

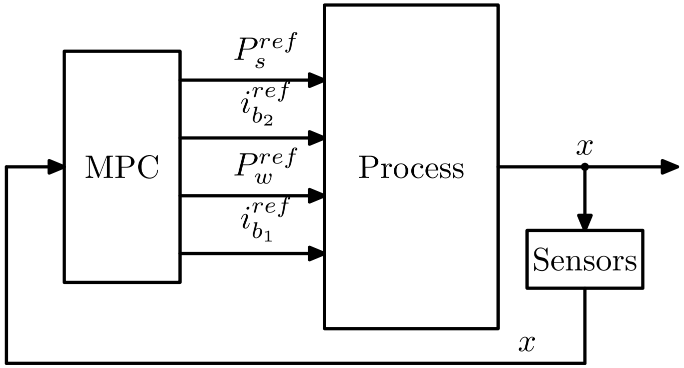


  - ◇ One supervisory MPC for wind subsystem and one for solar subsystem
  - ◇ Supervisory MPCs coordinate and calculate the operating references for the subsystems
  - ◇ Local controllers operate the subsystems to track the references

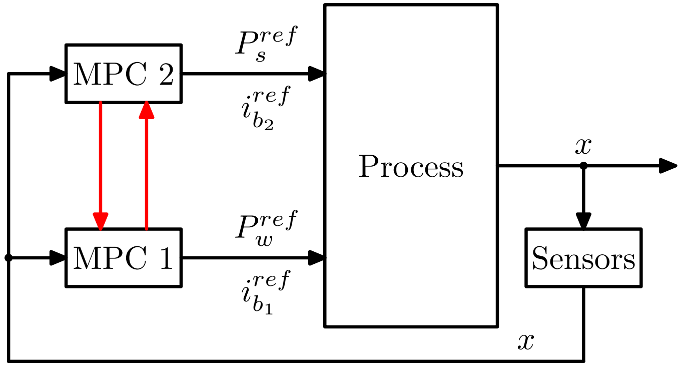
- Control objective is to coordinate the wind and solar subsystem as well as batteries to meet total power demand

CONTROL STRATEGIES

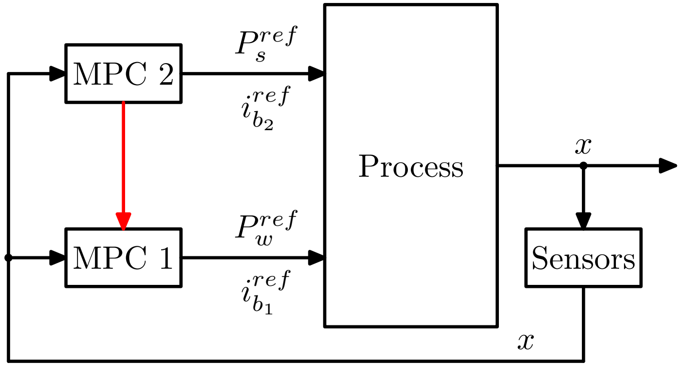
- Four control strategies



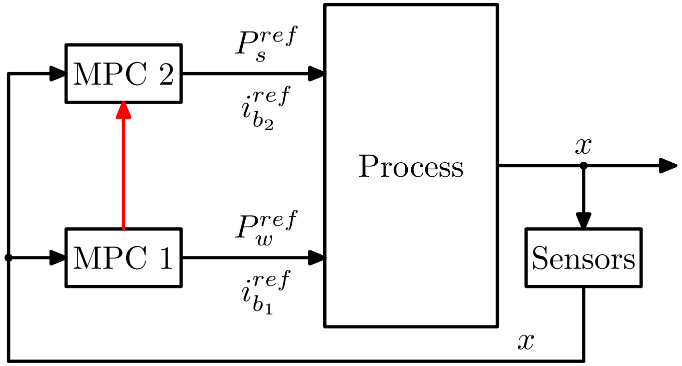
Centralized control



Iterative DMPC



Sequential DMPC (2→1)



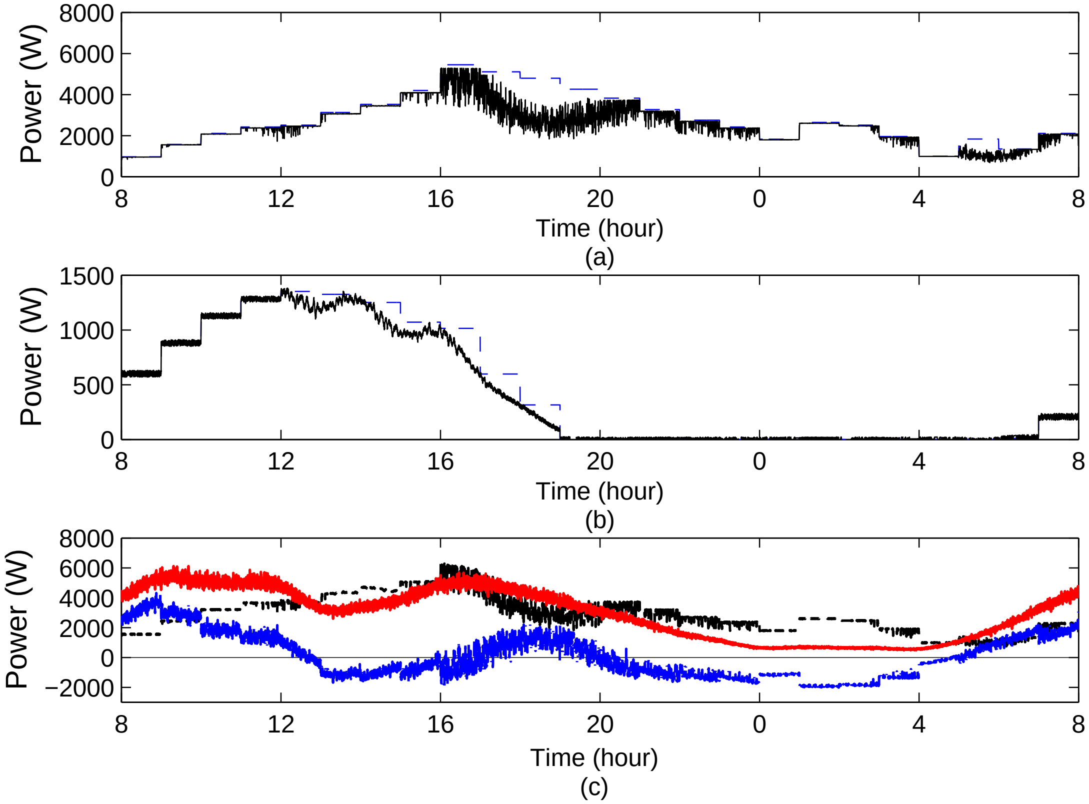
Sequential DMPC (1→2)

- Cost function

$$J = \frac{1}{M_t - M_i + 1} \sum_{i=M_i}^{M_t} (\alpha |P_d^{for}(t|t_i) - P_w^{ref}(t|t_i) - P_s^{ref}(t|t_i) + i_{b_1}^{ref}(t|t_i) E_b$$
$$+ i_{b_2}^{ref}(t|t_i) E_b| + \beta_1 \bar{i}_{b_1}(i)^2 + \beta_2 \bar{i}_{b_2}(i)^2 + \gamma_1 \bar{d}_{b_1}(i)^2 + \gamma_2 \bar{d}_{b_2}(i)^2 + \delta \bar{P}_s(i))$$

SIMULATION RESULTS

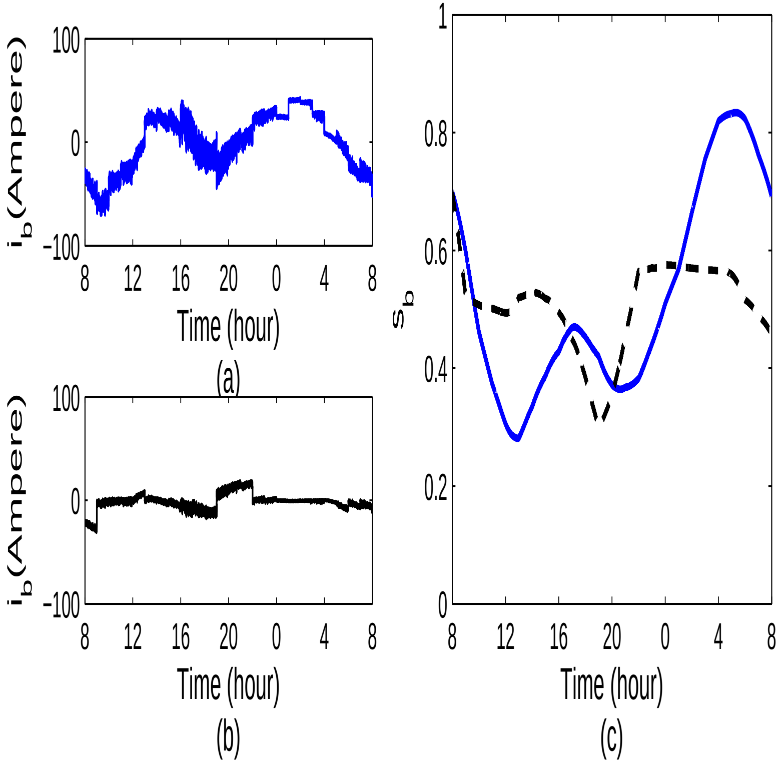
- Sequential distributed supervisory MPC



(a)

(b)

(c)



(a)

(b)

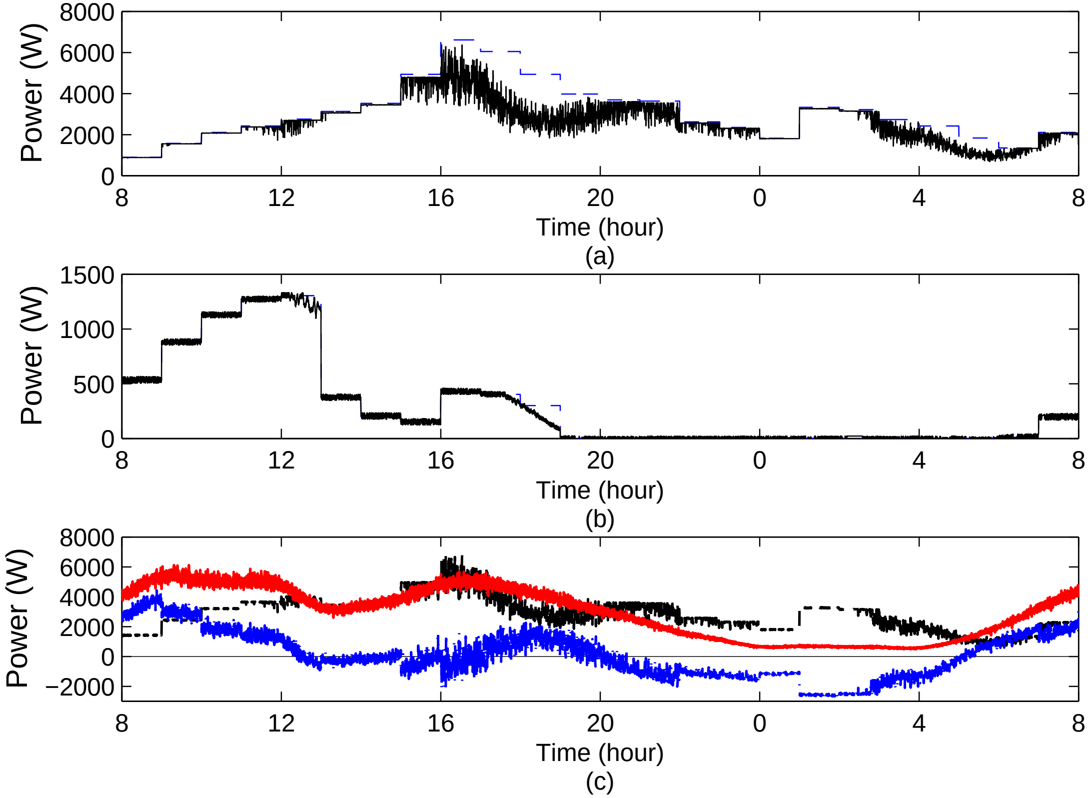
(c)

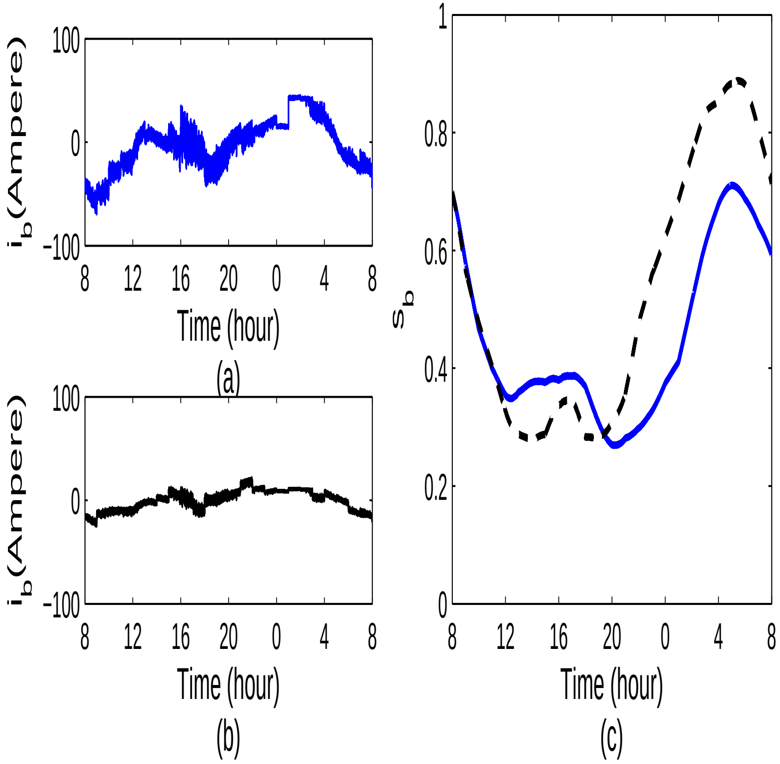
◇ The sequential distributed supervisory MPC coordinates different parts of the system to satisfy the total power demand

◇ Batteries make up the energy shortage

SIMULATION RESULTS

- Iterative distributed supervisory MPC





◇ The iterative distributed supervisory MPC is also able to coordinate different parts to satisfy the total power demand

◇ Similar evolution of system states

SIMULATION RESULTS

- Mean performance of each hour under different power generation conditions

	Insufficient ($8 \sim 12\ hr$ & $4 \sim 8\ hr$)	Balanced ($12 \sim 20\ hr$)	Excessive ($20 \sim 4\ hr$)	Whole day
Centralized	581.22	1239.3	752.05	857.54
Sequential	688.24	1263.5	880.59	944.12
Sequential (reversed)	736.31	1974.3	1648.2	1453.0
Iterative ($c_{max} = 1$)	3337.3	3275.5	4700.7	3771.2
Iterative ($c_{max} = 3$)	1487.7	3041.3	2823.6	2450.9
Iterative ($c_{max} = 6$)	664.13	1525.9	1280.3	1156.8
Iterative ($c_{max} = 10$)	621.92	1414.8	1020.2	1019.0

- Centralized control has the smallest cost and the cost of the iterative DMPC decreases as iteration number increases

CONCLUSIONS

- Review on different control architectures
  - ◇ Distributed predictive control is favorable for large-scale systems
  - ◇ Computational complexity, organization, fault tolerance
- Distributed control architecture for integrating distributed energy resources and loads to the electrical grid
  - ◇ Elements: control areas, distributed energy systems, distributed control
  - ◇ Coordinating different renewable generation systems, grid, loads
- Supervisory control of an integrated wind/solar/RO system
  - ◇ Integrated system modeling
  - ◇ Short-term supervisory control of the integrated system in standalone mode
  - ◇ Long-term operation of the integrated system connected to the electrical grid
- Distributed supervisory control of wind and solar energy generation system
  - ◇ Compared four different control strategies from a performance point of view

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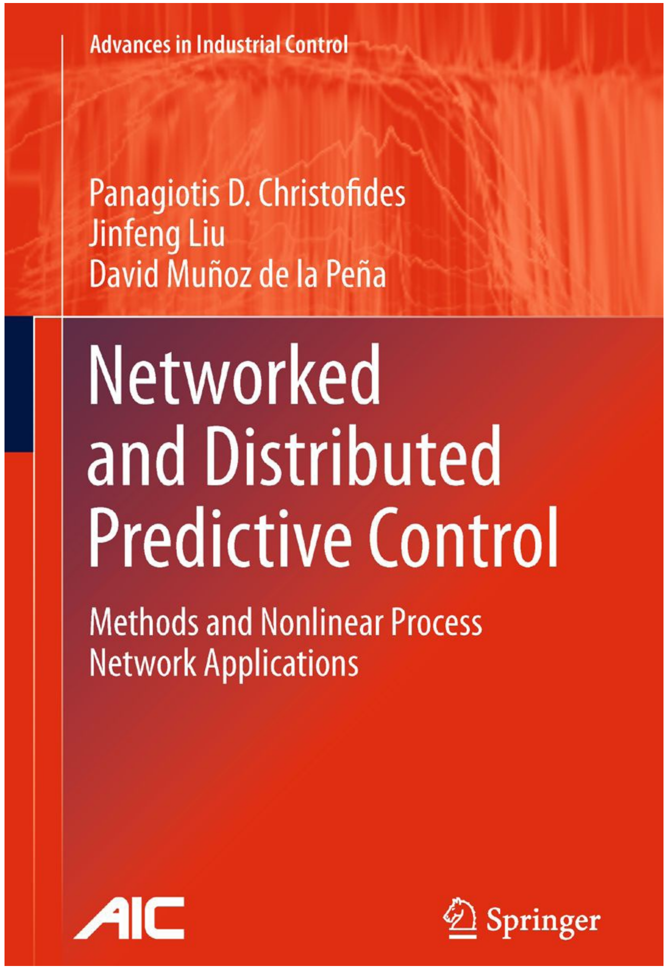

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