A Distributed Control Framework for Smart Grid Development

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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 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)
    - System-wide control objective functions
    - The closed-loop performance converges to the corresponding centralized control system as the iteration number increases
    - 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)
• 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 \( |u_i| \leq u_{i}^{\text{max}} \) (\( i = 1, \ldots, m \))
- \( f(x), g_i(x) \) (\( i = 1, \ldots, m \)) and \( k(x) \): vector functions

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

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

- 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**: 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
• Proposed distributed control architecture

- Electrical grid 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

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

◊ 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

- RO water desalination system
  - High-pressure pump
  - Water storage tank
  - Solar generation subsystem
  - 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) $s_b = \frac{Q_c}{Q_c^{\text{max}}} = \frac{v_c}{v_c^{\text{max}}}$

- 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:
    \[ P_T = \frac{1}{\eta} \left( P_{\text{sys}} \frac{F_d}{Y} + \frac{F_r^3}{2 Y^3 A_p^2} \rho_w \right) \]

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

\[ J_s(t_k) = \int_{t_k}^{t_k+N} \alpha \left( P_{RO}(\tau) - P_{w}^{ref}(\tau) - P_{s}^{ref}(\tau) \right)^2 d\tau \]

\[ + \int_{t_k}^{t_k+N} \beta P_{s}^{ref}(\tau)^2 d\tau + \int_{t_k}^{t_k+N-1} \zeta (P_{b}(\tau + \Delta) - P_{b}(\tau))^2 d\tau \]

- 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.
Proposed MPC design

\[
\min_{P_w^{\text{ref}}, P_s^{\text{ref}} \in S(\Delta)} J_s(t_k)
\]

\[
\text{s.t. } P_w^{\text{ref}}(\tau) \leq \min_{\tau} \{P_w^{\max}(\tau)\}, \ \tau \in [t_k+j, t_k+j+1)
\]
\[
P_s^{\text{ref}}(\tau) \leq \min_{\tau} \{P_{pv,\text{max}}(\tau)\}, \ \tau \in [t_k+j, t_k+j+1)
\]
\[
P_w^{\text{ref}}(t_k+j+1) - P_w^{\text{ref}}(t_k+j) \leq dP_{w,\text{max}}
\]
\[
P_s^{\text{ref}}(t_k+j+1) - P_s^{\text{ref}}(t_k+j) \leq dP_{s,\text{max}}
\]
\[
\dot{\tilde{x}}(\tau) = f(\tilde{x}(\tau)) + g(\tilde{x}(\tau))u(\tau)
\]
\[
h(\tilde{x}) = 0
\]
\[
\tilde{x}(0) = x(t_k)
\]

- 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

- Power trajectories - \( N = 2, \Delta = 1 \text{ s} \)

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

\[ J_g(t_k) = \gamma \int_{t_k}^{t_{k+N}} d_b(\tau) d\tau + \xi \int_{t_k}^{t_{k+N}} i_b(\tau)^2 d\tau + \zeta \int_{t_k}^{t_{k+N}} p(\tau) P_G(\tau) d\tau \]

\[ + \epsilon \int_{t_k}^{t_{k+N}} |s_t(\tau) - s_{t, opt}| d\tau + \theta \int_{t_k}^{t_{k+N}} P_{RO}(\tau) d\tau \div \int_{t_k}^{t_{k+N}} F_p(\tau) d\tau \]

- 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

\[
\begin{align*}
\min_{i_G^{ref}, v_r^{ref} \in S(\Delta)} & \quad J_g(t_k) \\
\text{s.t.} & \quad P_{RO}(\tau) - P_w(\tau) - P_s(\tau) + i_G^{ref}(\tau)v_b(\tau) + i_b v_b = 0 \\
& \quad F_p^{\min} \leq F_p(\tau) \leq F_p^{\max} \\
& \quad 0 \leq d_b(\tau) \leq d_b^{\max} \\
& \quad s_t^{\min} \leq s_t(\tau) \leq s_t^{\max} \\
& \quad i_b(\tau) \leq i_b^{\max}(s_b(\tau)) \\
\end{align*}
\]

\[
\dot{x}(\tau) = f(\ddot{x}(\tau)) + g(\ddot{x}(\tau))u(\tau) \\
h(\ddot{x}) = 0 \\
\ddot{x}(0) = x(t_k)
\]

- 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
- 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

- Cost function

\[ J = \frac{1}{M_t - M_i + 1} \sum_{i=M_i}^{M_t} \left( \alpha |P_d^{for}(t|t_i) - P_w^{ref}(t|t_i) - P_s^{ref}(t|t_i) + i_{b_1}^{ref}(t|t_i)E_b \right. \\
+ \left. i_{b_2}^{ref}(t|t_i)E_b| + \beta_1 \bar{v}_{b_1}(i)^2 + \beta_2 \bar{v}_{b_2}(i)^2 + \gamma_1 \bar{d}_{b_1}(i)^2 + \gamma_2 \bar{d}_{b_2}(i)^2 + \delta P_s(i) \right) \]
SIMULATION RESULTS

- Sequential distributed supervisory MPC

- 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

<table>
<thead>
<tr>
<th></th>
<th>Insufficient (8 ~ 12 hr &amp; 4 ~ 8 hr)</th>
<th>Balanced (12 ~ 20 hr)</th>
<th>Excessive (20 ~ 4 hr)</th>
<th>Whole day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centralized</td>
<td>581.22</td>
<td>1239.3</td>
<td>752.05</td>
<td>857.54</td>
</tr>
<tr>
<td>Sequential</td>
<td>688.24</td>
<td>1263.5</td>
<td>880.59</td>
<td>944.12</td>
</tr>
<tr>
<td>Sequential (reversed)</td>
<td>736.31</td>
<td>1974.3</td>
<td>1648.2</td>
<td>1453.0</td>
</tr>
<tr>
<td>Iterative (c_{max} = 1)</td>
<td>3337.3</td>
<td>3275.5</td>
<td>4700.7</td>
<td>3771.2</td>
</tr>
<tr>
<td>Iterative (c_{max} = 3)</td>
<td>1487.7</td>
<td>3041.3</td>
<td>2823.6</td>
<td>2450.9</td>
</tr>
<tr>
<td>Iterative (c_{max} = 6)</td>
<td>664.13</td>
<td>1525.9</td>
<td>1280.3</td>
<td>1156.8</td>
</tr>
<tr>
<td>Iterative (c_{max} = 10)</td>
<td>621.92</td>
<td>1414.8</td>
<td>1020.2</td>
<td>1019.0</td>
</tr>
</tbody>
</table>

- 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
REFERENCES


