Two Control Problems in Wind Energy

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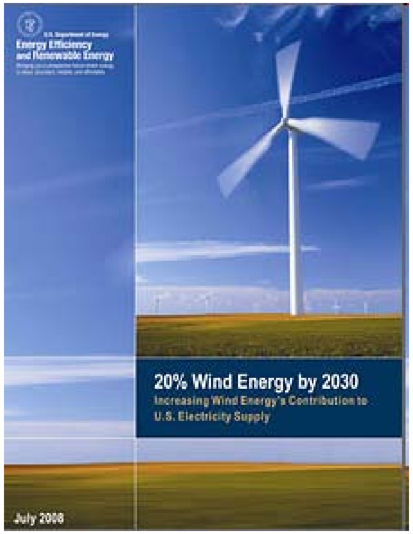
Structural Control of Floating Wind Turbines

Collaboration with Matthew Lackner

The Big Picture

- 20% electricity from wind energy by 2030
  - 37 GW (2010) → 305 GW (2030)
- Critical elements for 2030 scenario*
  - Reduce capital costs (10%)
  - Reduce O&M costs (35%)
  - Improve performance (wind farm)
  - Improve transmission infrastructure
  - Need land and offshore installations
  - Communication & outreach, policy
- Advanced control systems can improve wind turbine reliability and reduce O&M costs



U.S. Department of Energy
Energy Efficiency and Renewable Energy

20% Wind Energy by 2030
Increasing Wind Energy's Contribution to U.S. Electricity Supply

July 2008

* Robinson, ASME Int. Mech. Eng. Educ. Conf., 2009

Offshore Wind Technology ~~Today~~ ~ 3 yrs ago

Robinson, ASME Int. Mech. Eng. Educ. Conf., 2009

Vestas 2.0 MW Turbine Horns Rev, DK

Talisman Energy: Repower 5-MW Beatrice Fields, Scotland

GE 3.6 MW Turbine Arklow Banks

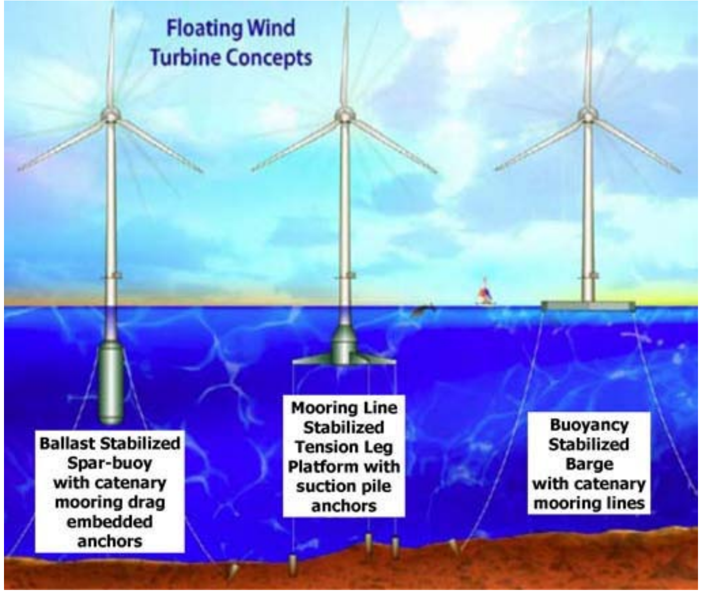
Seimens 2.3 MW Turbines Middlegrunden, DK

Problem we want to solve

- Initial development and demonstration stage; 22 projects, 1135 MW installed
- Fixed bottom shallow water 0-30m depth
- 2 – 5 MW upwind rotor configurations
- 70+ meter tower height on monopoles and gravity bases
- Mature submarine power cable technology
- Existing oil and gas experience is essential
- Reliability problems and turbine shortages have discouraged early boom in development.
- Cost are not well established in the US.

Floating wind turbine technology

- Higher wind speeds and energy capture over deep waters (> 60 m)
  - 60% of U.S. wind resource past 60 m depth
  - Floating systems the only option
- Other incentives of floating systems
  - Site independence, mass production
  - Assembly greatly simplified
  - Lower impact on human activities (and environment)
- Challenges
  - No experience
  - Reduced accessibility
  - Increased motion and mechanical loads due to coupled wind and wave loading

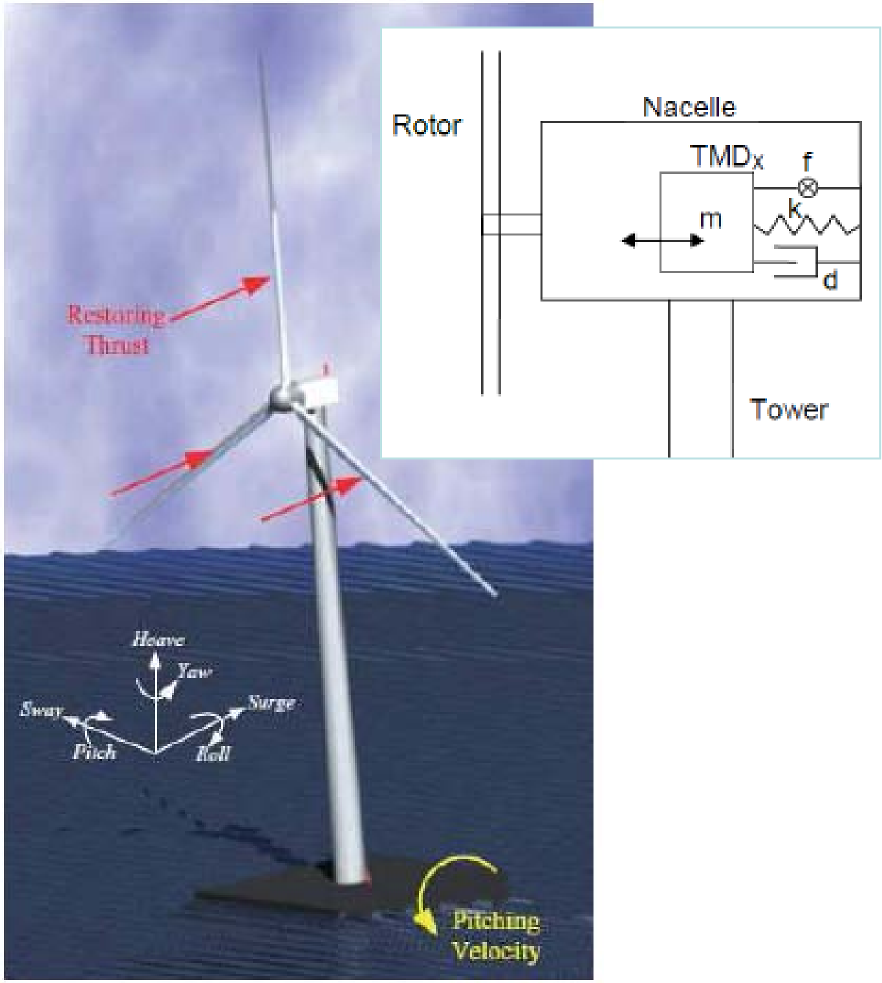


Structural control of floating wind turbines

- Objective
  - Add new control degrees of freedom to reduce motion and mechanical loads
  - Improve reliability, reduce O&M costs
- Approach
  - Develop passive & active systems for managing dynamic loads and motions
  - Incorporate/develop new advances in actuator technology and control theory

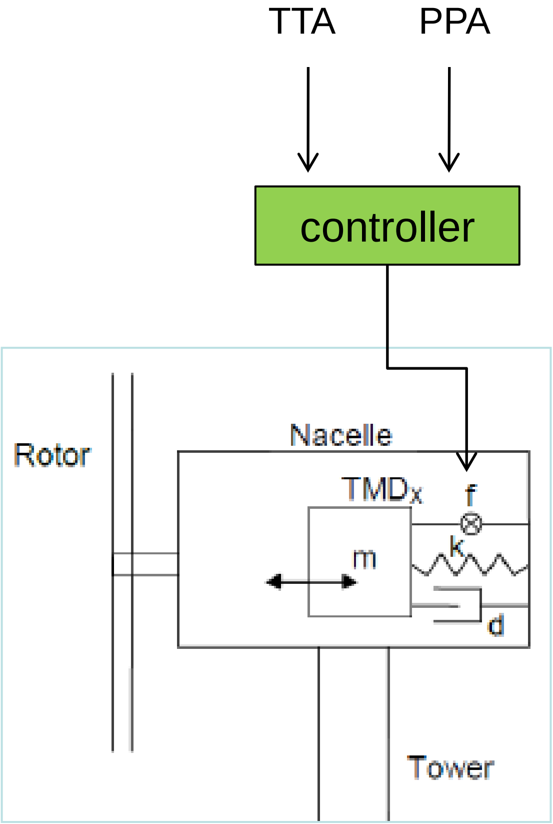
Floating turbine with tuned mass damper

- NREL 5-MW turbine model
  - 3 bladed, upwind, 126 m rotor diameter, 90 m hub height
  - Barge platform
  - FAST-SC: NREL code FAST plus structural control degrees of freedom
- Tuned mass damper (TMD)
  - Mass-spring-damper system in nacelle, fore-aft translation
  - Parameters tuned using FAST-SC to minimize tower fore-aft displacement
  - Reaction on nacelle to external force f serves as control input



Structural control system

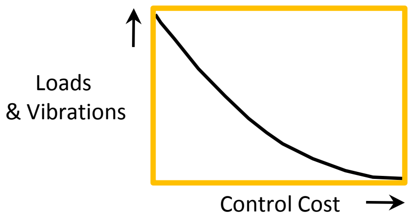
- Sensor signals
  - Tower top acceleration in fore-aft direction (TTA)
  - Platform pitch acceleration (PPA)
- Control signal
  - Force f on nacelle by TMD
- Design process
  - Design model from synthetic data generated with FAST-SC using Matlab's SysID toolbox
    - Design model captures essential dynamics: 1st fore-aft tower bending, platform pitch, TMD
  - Want the tradeoff between load/vibration reduction and the cost of active control



Controller design process

Ideal Process

- Define evaluation criteria to measure loads & vibration reduction and cost of active control
- Determine the set of Pareto optimal controllers for the selected evaluation criteria
- Exact but time consuming

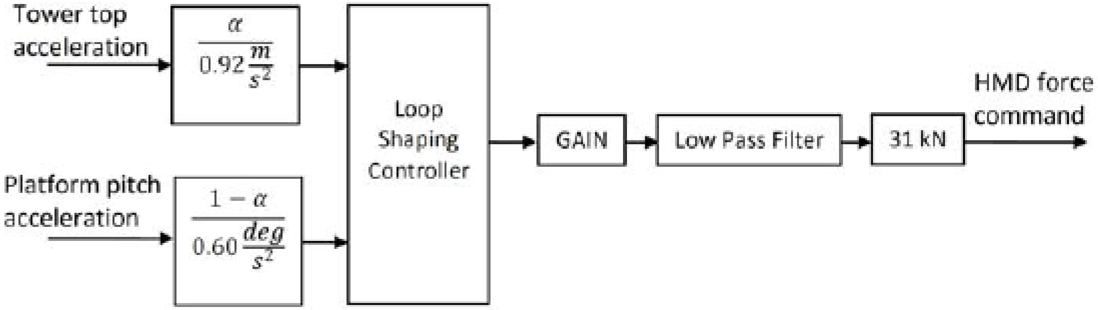


Practical Process

- Select a controller design method known to work well for damping augmentation and disturbance rejection
- Use the chosen method to generate a family of controllers with increasing control authority
- Calculate the evaluation criteria for this controller family
- Approximate but very efficient

Practical design process

- H_∞ loop-shaping yields nearly Pareto optimal solutions in structural control problems
- H_∞ loop-shaping is amenable to generating a family of controllers with increasing control authority

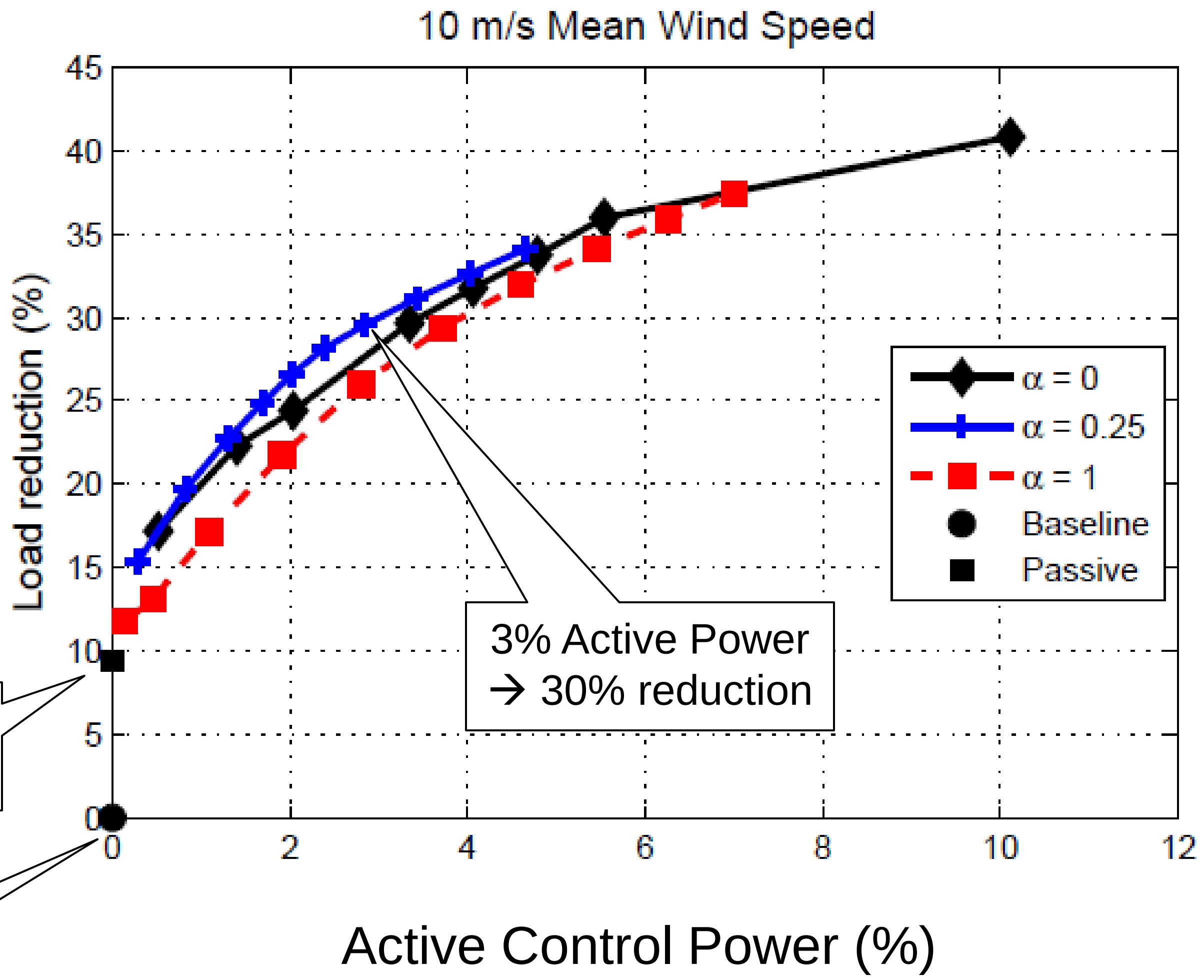


- Controller family obtained by calculating the Loop Shaping Controller for each fixed GAIN
- Estimate tradeoffs by calculating evaluation criteria using detailed FAST-SC simulations for each controller

Evaluation criteria

- Structural
  - Tower base fore-aft damage equivalent load (DEL)
- Active control cost
  - Active control power
  - TMD stroke
- Computed using FAST-SC simulations under realistic wind/wave loading
- Other criteria not shown
  - Tower base side-to-side DEL, Blade root flapwise DEL, power error, peak loads, and pitch actuator usage
  - All criteria improve with active control

Tower fore-aft DEL reduction



3% Active Power
→ 30% reduction

Passive TMD
→ 10% reduction

Baseline

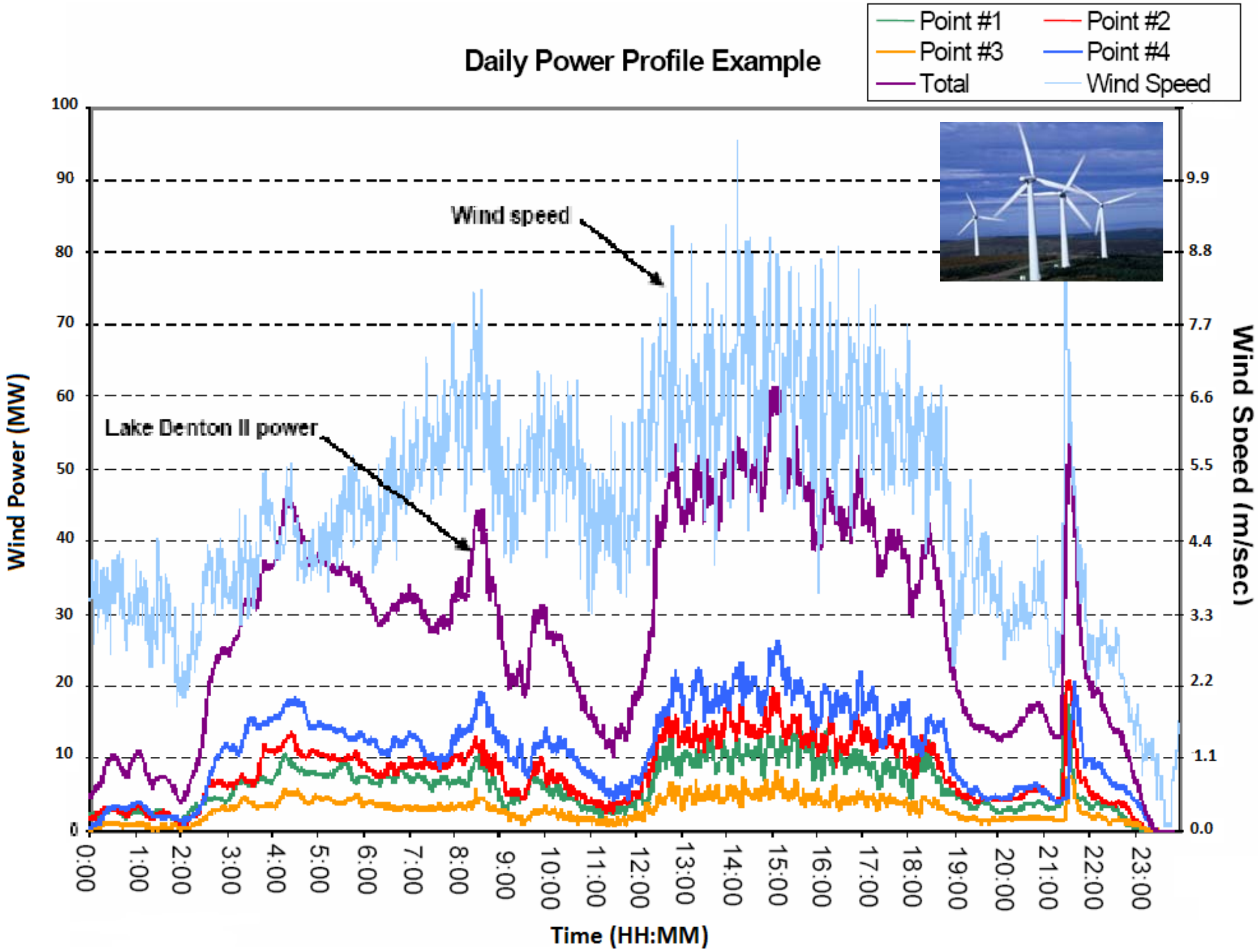
Remarks

- Active or passive structural control
  - Reduce mechanical loads in wind turbines
  - Do not require transfer of power or data to the blade reference frame
  - Power for active control obtained from excess power when wind speed is high (region 3)
  - Conventional active systems may have large stroke requirements
- Impact
  - More reliable wind turbine → reduced O&M
  - Lighter wind turbine?
- To probe further
  - Lackner & Rotea, Passive structural control of offshore wind turbines, *Wind Energy* , Vol. 14, No. 3, 2011
  - Lackner & Rotea, Structural control of floating wind turbines, *Mechatronics,* Vol. 21, No. 4, *Special Issue on past, present and future modeling and control of wind turbines*, 2011

Control of Battery Storage Systems for Wind Energy Applications

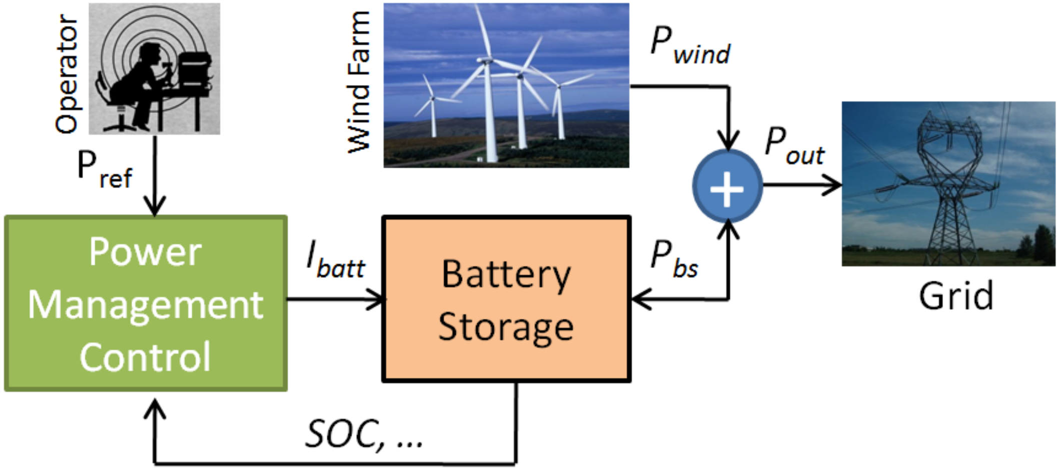
Collaboration with Ali Borhan
and Daniel Viassolo

Intermittency Issue



Example: 24-Hr Output From NREL Monitoring at Buffalo Ridge Sub, Lake Benton, MN

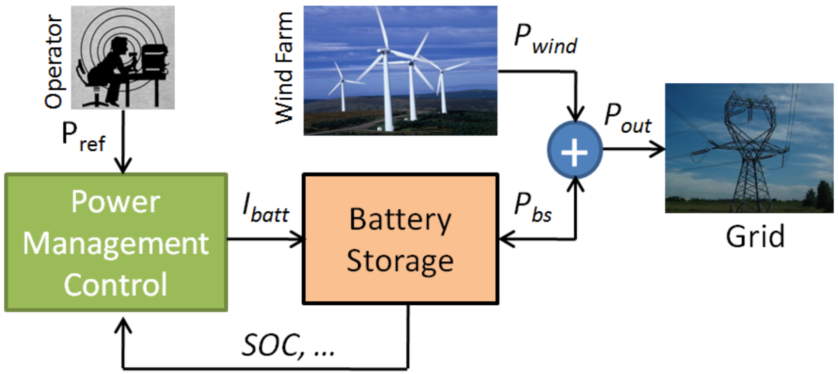
Wind Farm with Battery Storage

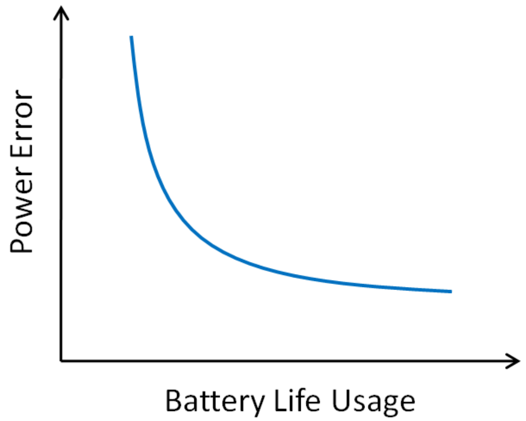


- The combined power of the wind farm and the BSS goes to the grid
- BSS is charged/discharged to deliver an operator reference power with appropriate battery usage
- BSS is controlled by commanding the battery current

Control Objectives

- Power error objective
  - To minimize the error between the output power of the system and an operator reference power over an Optimization horizon *H*
  - Minimization is subject to battery constraints (SOC, current, …)
- Battery life objective
  - To minimize the loss of battery life in order to reduce the O&M and replacement costs





Models for Control Objectives

Power error objective

$$P_{error} = \frac{1}{H} \int_{t}^{t+H} \left| P_{out}(\tau) - P_{ref}(\tau) \right| d\tau$$

$$with$$

$$P_{out}(\tau) = P_{wind}(\tau) + P_{bs}(\tau)$$

$$P_{bs}(\tau) = n_{batt} V_{batt}(\tau) I_{batt}(\tau)$$

Battery dynamics and constraints*

$$\frac{dSOC}{d\tau} = \frac{I_{batt}(\tau)}{C_{batt}}$$

$$I_{batt,\min} \le I_{batt}(\tau) \le I_{batt,\max}$$

$$SOC_{\min} \le SOC(\tau) \le SOC_{\max}$$

** Note that the battery parameters can be function of battery operating conditions*

Models for Control Objectives (continued)

Battery life objective

- Weighted Amp-hr throughput model for the battery life consumption over *H*
- Weight factors to model the irregular operating conditions
- *Life objective*: terminal weighted Amp-hr throughput over *H*

$$\frac{dwAh_{batt}}{d\tau} = \begin{cases} \prod_i \; f_i(\tau)\cdot I_{batt}(\tau) & if \;\; I_{batt}(\tau)\geq 0 \\ 0 & if \;\; I_{batt}(\tau)<0 \end{cases}$$

Life Objective: $wAh_{batt}(t+H)$

$$f_{SOC}(t) = 1 + (c_{SOC,0} + c_{SOC,\min}\cdot(1-SOC_{\min}(t)\,|_{t_0}^{t})) \times\sqrt{\frac{I_{ref}}{I}}\Delta t_{SOC}(t)$$

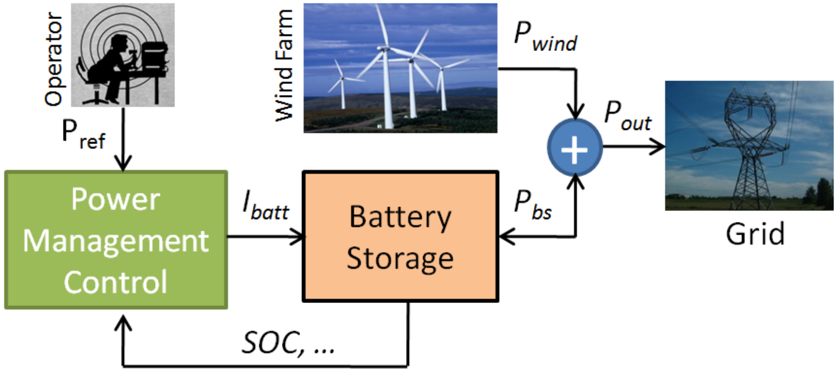
Control Problem

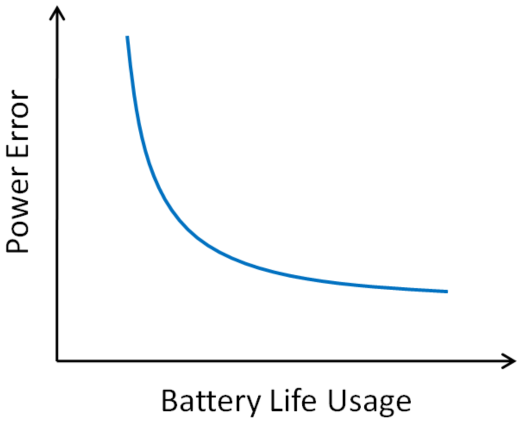
Given

- P_{ref}: reference power demand from operator over an optimization horizon H
- P_{wind}: an estimate of the wind power over H
- Current state of BS (e.g., *SOC*,…)

Find the command current I_{batt} over the optimization horizon H to *jointly* minimize the power and battery life objectives:

$$J = w_{error} \cdot P_{error} + w_{life} \cdot wAh_{batt}(t+H)$$



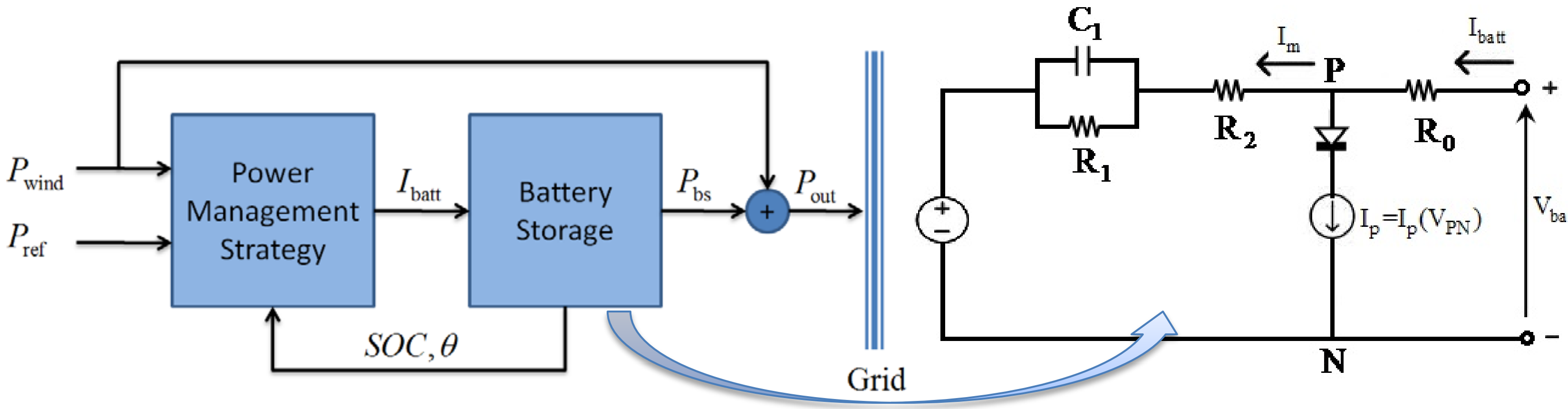


Solution to Control Problem

- Problem is decomposed into three stages
- Stage 1 (performance)
  - Find family of current profiles that minimize power error subject to terminal SOC constraints
- Stage 2 (battery life analysis)
  - Calculate the terminal weighted Amp-hr throughput for each current profile
- Stage 3 (find best compromise)

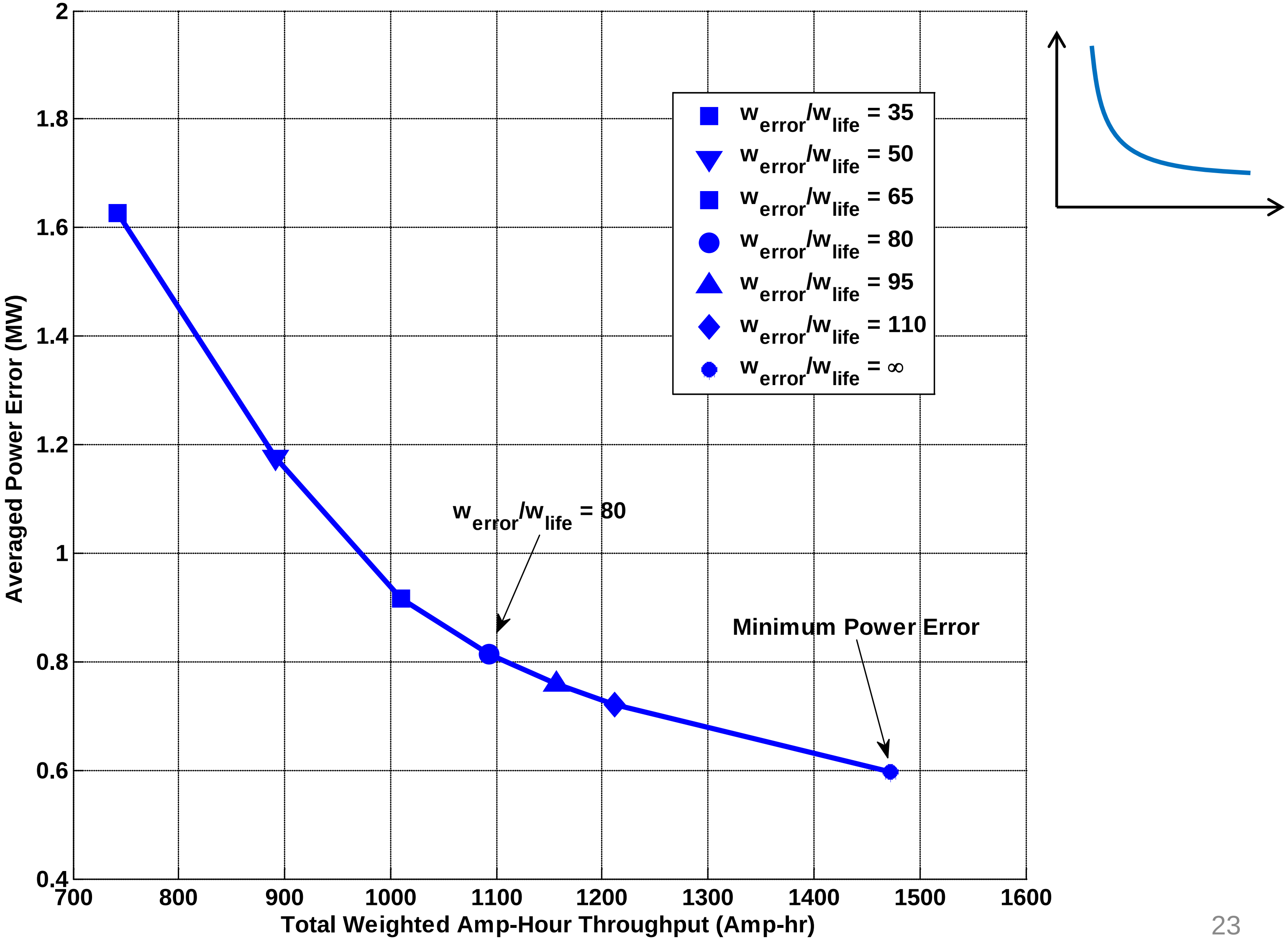
$$\boxed{\begin{aligned} J_n^* &= w_{error} \cdot P_{error,n}^* + w_{life} \cdot wAh_{batt,n}^* \\ n &= 1 \cdots L \\ I_{batt,opt}^*(\tau) &= \arg \min_{\{I_{batt,1}^*, \ldots, I_{batt,L}^*\}} \{J_1^*, \ldots, J_L^*\} \end{aligned}}$$

Simulation Conditions

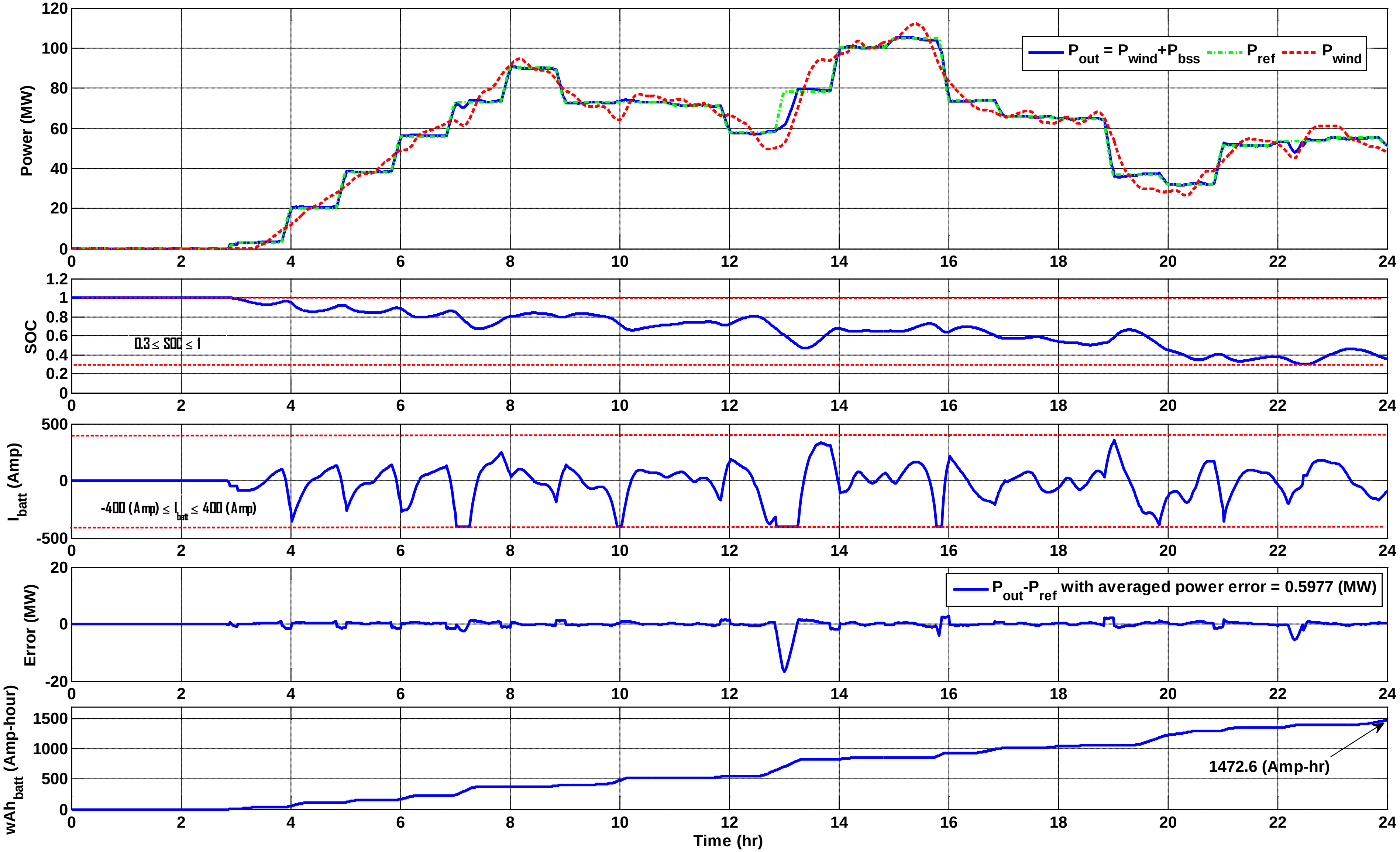


- Actual wind farm data from a 150 MW wind farm in Texas
- One-hour power dispatching scenario over a 24 hour simulation time
- Control sampling time = 1 minute; Prediction horizon *H* = 10 minutes
- 10 pre-defined terminal SOC's
- Constraints: $SOC_{max} = 1.0$, $SOC_{min} = 0.3$, $I_{batt,max} = -I_{batt,min} = 400$ A
- Nominal battery storage specifications: 18 (MW) maximum power with 18 MW-hr capacity (12% of the wind farm maximum power)
- Single battery specifications: A lead acid battery with nominal capacity of 500 Ah and the equivalent circuit model verified in "*M. Ceraolo. IEEE Transactions on Power Systems, Vol. 15, No. 4, November 2000*"
- Dynamic Programming to solve the optimization problem in stage 1

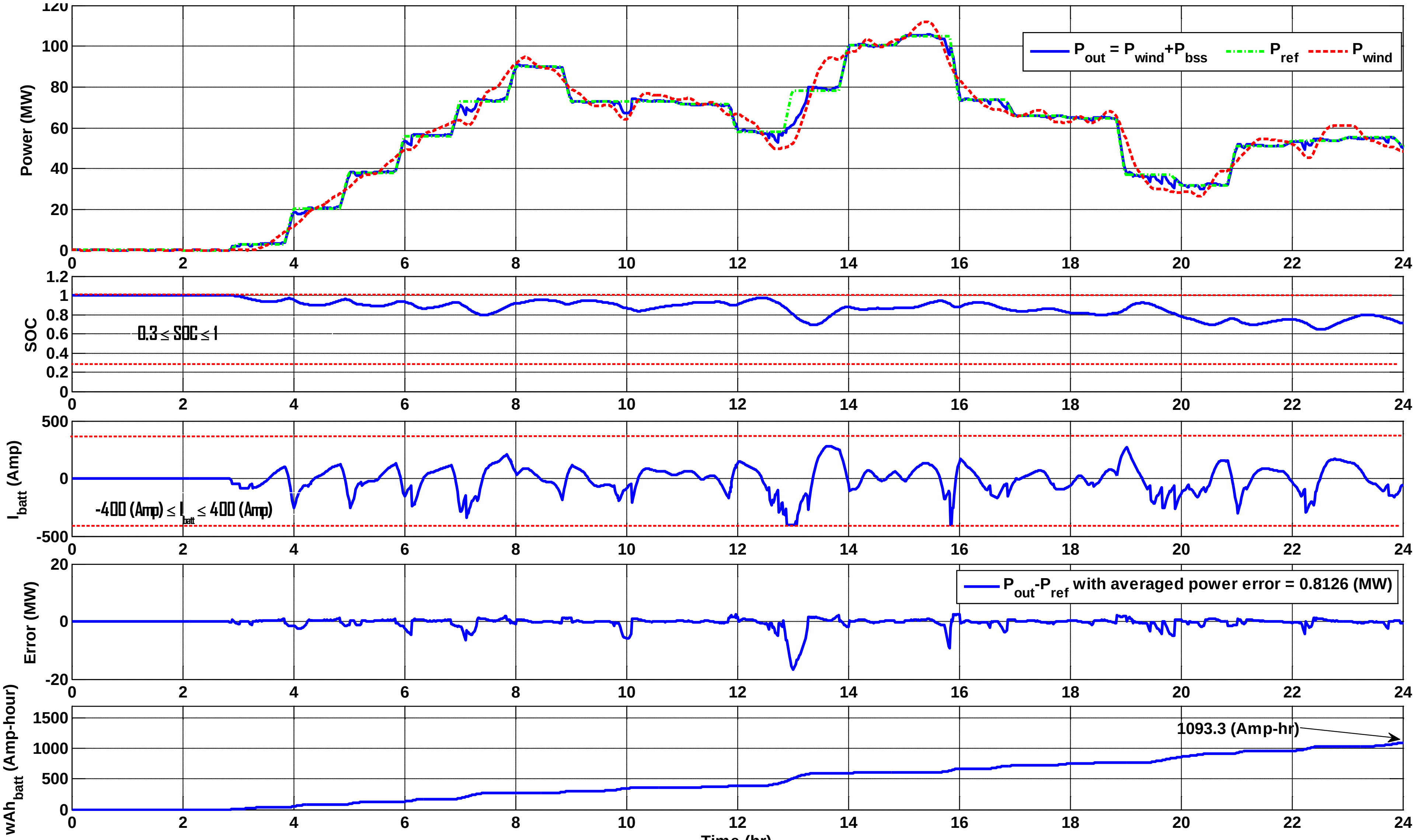
Simulation results



Solution for Minimum Power Error



Solution for $w_{error}/w_{life} = 80$



Remarks

- Developed a real-time optimization-based strategy to reduce both the power error and the loss of the battery life
- The strategy is modular
  - More elaborate models can be used for the battery life without more complex optimization solvers
- To probe further
  - Borhan, Rotea, Viassolo, “Optimization-based power management of a wind farm with battery storage,” submitted to Wind Energy

Message

- Control technology will
  - Improve the reliability of wind turbines
  - Improve the efficiency of wind farms
  - Enable the integration of wind energy and storage systems