

Supervisory Optimal Control for Photovoltaics Connected to an Electric Power Grid

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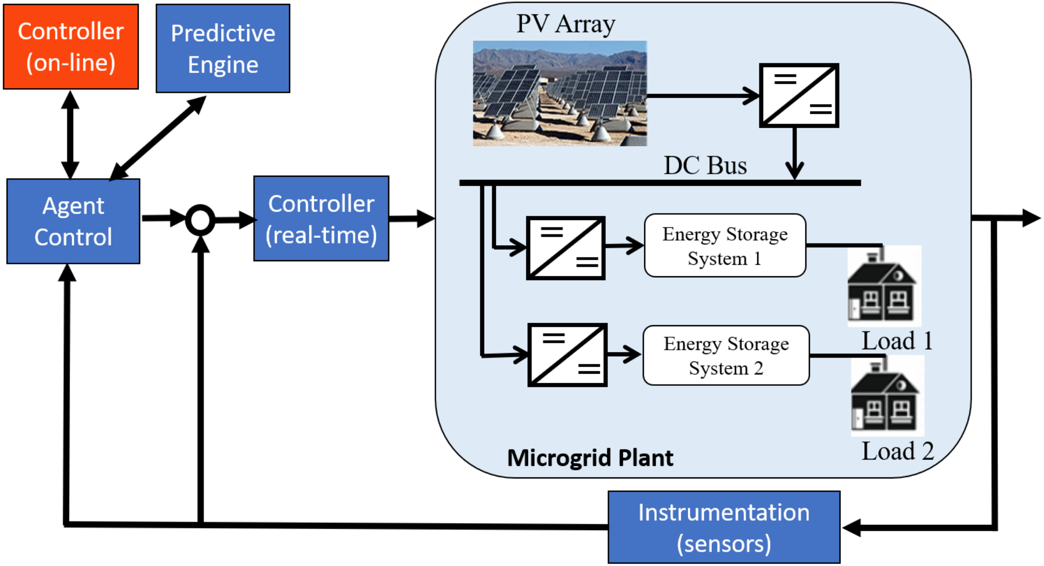
Summary of control design



Summary of control design

- Microgrid - Single or networked power grid
- Agents - Software that coordinates how the different controls operate the microgrid based on information from the sensors and its own internal algorithms
- Sensors - Any instrumentation that provide information about the microgrid
- Real-time Controller - Control that provides fast, subsecond updates
- On-line Controller - Control that provides medium to long term planning
- Predictive Engine - Algorithm that provides long term forecasting for the microgrid

Summary of control design

On-line

- Executes in a variable amount of time
- Solves for new control while the system is in operation

Optimal Control

- Control based on an optimization formulation
- Generally, solution time only deterministic for a linear-quadratic control

Receding Horizon Control

- Behavior of system predicted over a time period called the planning horizon
- Control based on this prediction
- Control executed for as long as the prediction remains accurate, which is called the execution horizon

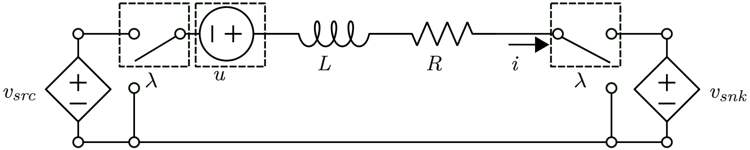
This presentation details an optimal control algorithm based on an on-line optimization engine that solves for a receding-horizon control

High-level view of optimal control

Minimize	Use of storage devices
	Deviation from dispatchable load
Subject to	Series DC component dynamics
	Parallel DC component dynamics

Detail of microgrid components to come next

Series DC components (S)



$$[\lambda]v_{src} + [u] = Li' + Ri + [\lambda]v_{snk}$$

$$i(0) = i_0$$

$$i_{min} \leq i \leq i_{max}$$

$$w' = -ui$$

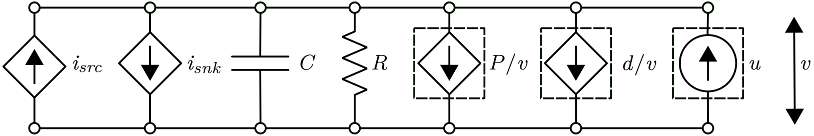
$$w(0) = w_0$$

$$0 \leq w \leq w_{max}$$

$$0 \leq \lambda \leq 1$$

Dotted squares denote optional components

Parallel DC components (P)



$$\sum[\lambda_{src}]i_{src} + [u] = \sum[\lambda_{snk}]i_{snk} + Cv' + \frac{v}{R} + \left[\frac{P}{v}\right] + \left[\frac{d}{v}\right]$$

$v = \text{const}$

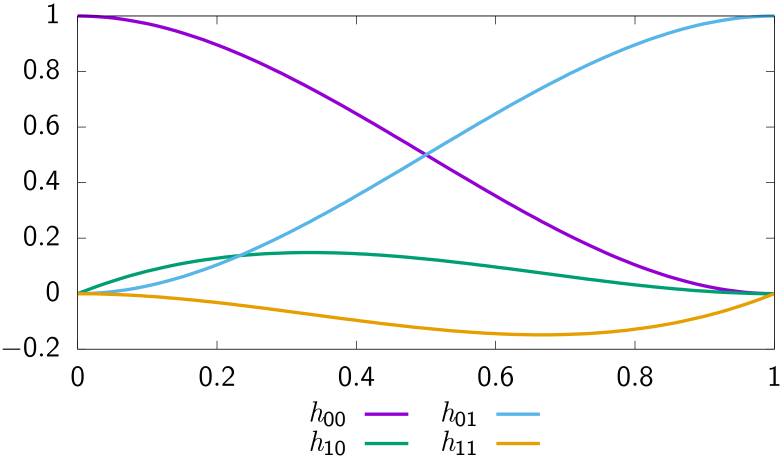
$w' = -vu$

$w(0) = w_0$

$0 \leq w \leq w_{max}$

$0 \leq d$

Hermite cubic splines



$h_{00}(t) = (1 + 2t)(1 - t)^2$

$h_{10}(t) = t(1 - t)^2$

$h_{01}(t) = t^2(3 - 2t)$

$h_{11}(t) = t^2(t - 1)$

Orthogonal spline collocation method (OSCM)

- Represent each function by a Hermite cubic spline
- Satisfy dynamics at Gaussian quadrature (collocation) points
- Practical approach uses evaluation, E, and derivative, D, operators that map spline coefficients to collocation points. Allows differential equation

  $$u' = -u$$

  to be discretized as

  $$D\alpha = -E\alpha$$

  where α represents the spline coefficients
- Convergence rate $O(h^4)$ where h largest interval in mesh

Useful Hermite spline properties

- Constant Bounds - Hermite polynomial

$$p(t) = \alpha_1 h_{00}(t) + \alpha_2 h_{10}(t) + \alpha_3 h_{01}(t) + \alpha_4 h_{11}(t)$$

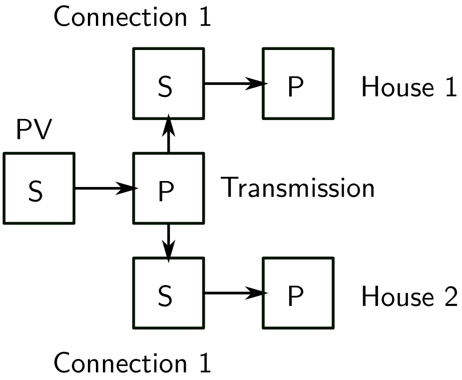
  is bounded between l and u on the interval $[0, 1]$ whenever

$$\begin{aligned} 3l \leq \quad & 3\alpha_1 + \alpha_2 & \leq 3u \\ 3l \leq \quad & 3\alpha_1 - \alpha_2 & \leq 3u \\ 3l \leq \quad & 3\alpha_3 + \alpha_4 & \leq 3u \\ 3l \leq \quad & 3\alpha_3 - \alpha_4 & \leq 3u \end{aligned}$$

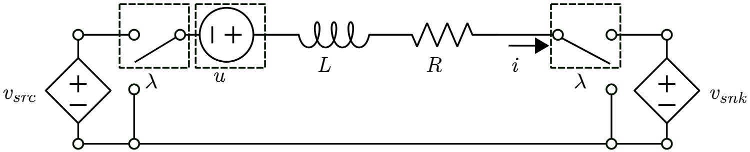
- Nonlinear Bounds - Approximate nonlinear bound with Hermite spline and then bound the difference between the original polynomial and this approximation
- Integration - Given the mesh $\Omega = (t_0, \ldots, t_{\text{nele}})$, spline s, and collocation points C, then

$$\int_{t_0}^{t_{\text{nele}}} s(t)dt = \sum_{k=0}^{\text{nele}-1} (t_{k+1} - t_k)(s(C_{2k+1}) + s(C_{2k+2}))$$

Topology of the microgrid

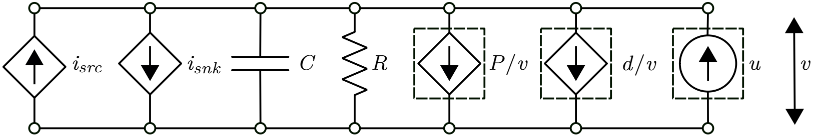


Microgrid parameters (PV)



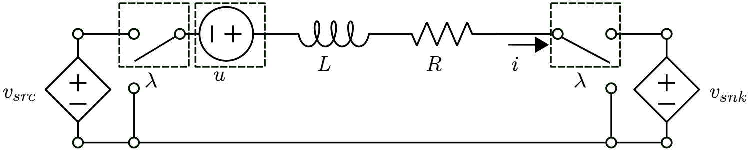
Parameter	Value	Info
v_{src}	110 V	
v_{snk}	v_{trans}	Transmission
$[i_{min}, i_{max}]$	[0,Variable] A	Generation given by the NREL code SAM with 5 kW max power
L	0.001 H	
R	0.121 Ω	250 W parasitic loss @ 5 kW
w_{max}	———	No storage, u

Microgrid parameters (Transmission)



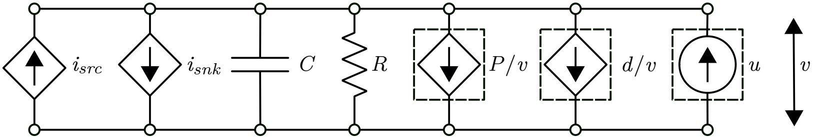
Parameter	Value	Info
i_{src}	i_{pv}	PV
i_{snk}	$i_{conn\ 1\ and\ 2}$	Connection
v	200 V	
C	________	Constant voltage
R	160 Ω	250 W parasitic loss
P	________	None
D	________	None
w_{max}	________	No storage, u

Microgrid parameters (Connection)



Parameter	Value	Info
v_{src}	v_{trans}	Transmission
v_{snk}	$v_{house\ 1\ or\ 2}$	House
$[i_{min}, i_{max}]$	———	No bounds on power transfer
L	0.001 H	
R	0.05 Ω	
w_{max}	———	No storage, u

Microgrid parameters (House)



Parameter	Value	Info
i_{src}	$i_{conn\ 1\ and\ 2}$	Connection
i_{snk}	————	None
v	220 V	
C	————	Constant voltage
R	193.6 Ω	250 W parasitic loss
P	Variable	Load profile taken from sampled data collected from houses in Albuquerque, NM
D	————	None
w_{max}	3 or 4 MJ	Local storage at each house, 0.83 kW h for house 1 and 1.11 kW h for house 2

Scenario overview

Goal

- Meet demand when combined loads exceed generation capacity
- Coordinate use of storage to minimize storage use and keep storage 90% full

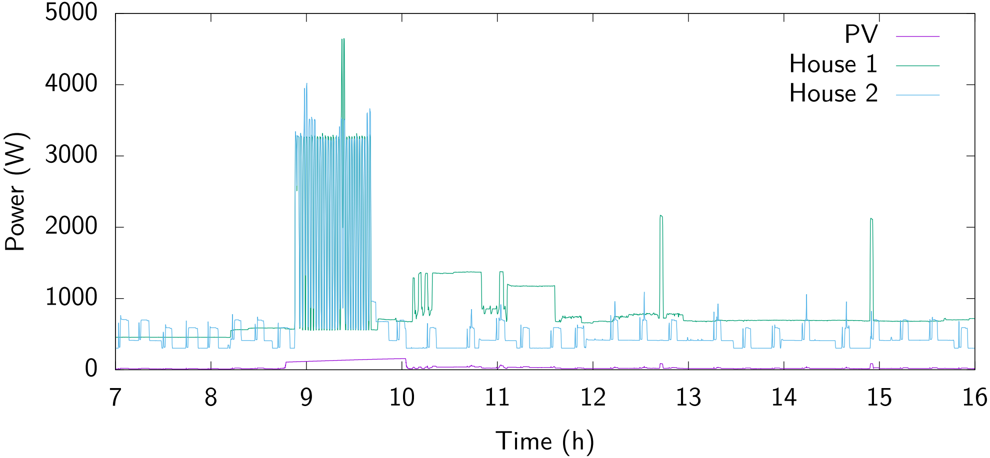
Setup

- Scenario lasts for 9 h, 0700-1600
- Generation capacity estimated using the NREL code SAM with 5 kW max generation using averaged historical weather information for Albuquerque, NM on a typical May 1
- Load sampled directly from two houses in Albuquerque, NM in 1 s intervals and averaged over 15 s intervals
- Storage devices located at houses

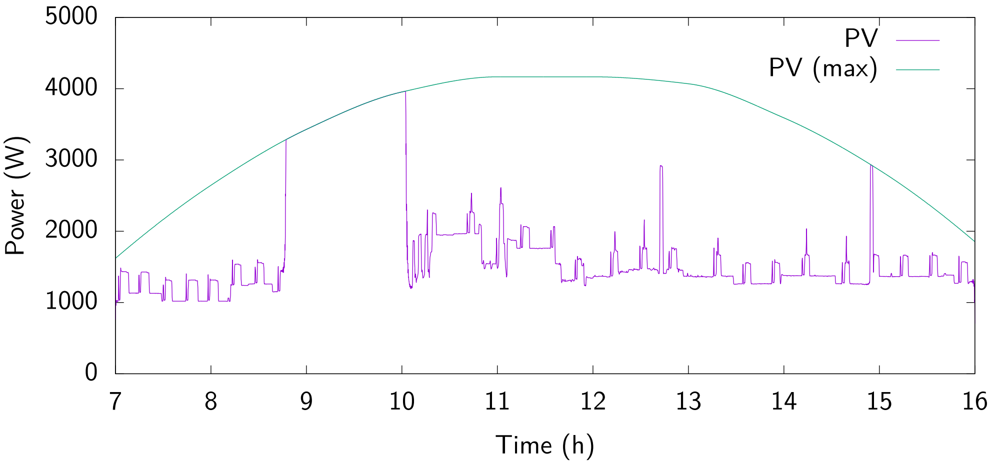
Results

- Load demands met
- Storage only used when generation exceeded demand

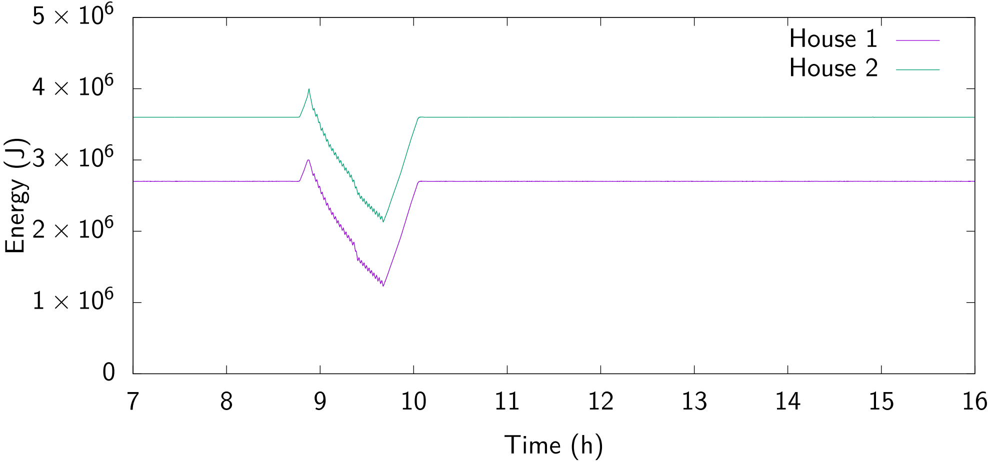
Power used by loads



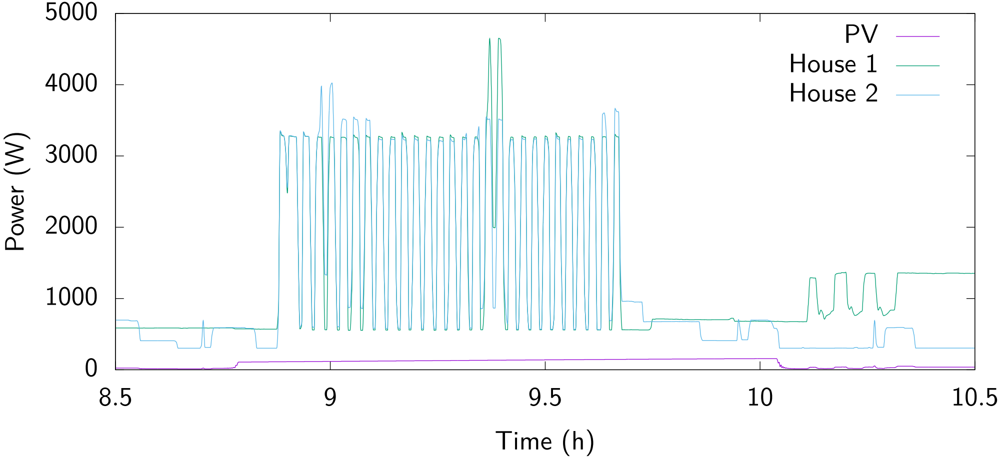
Power generation



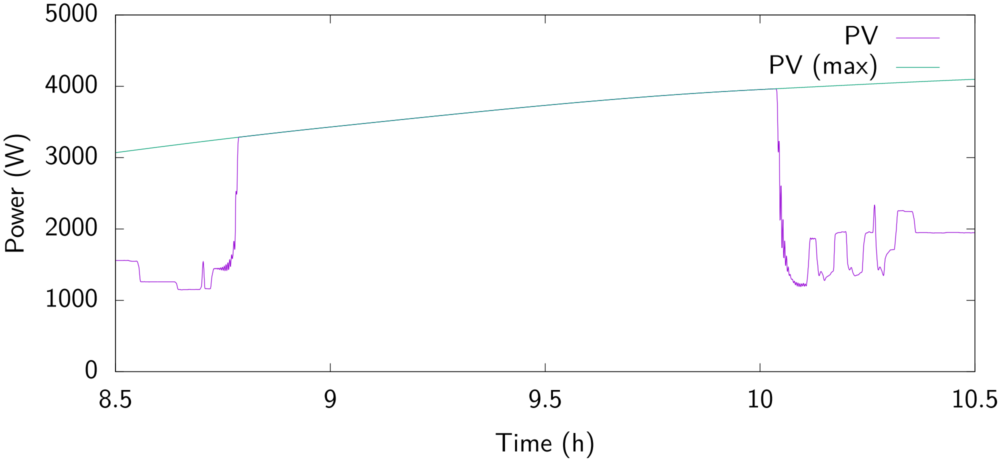
Energy in the storage



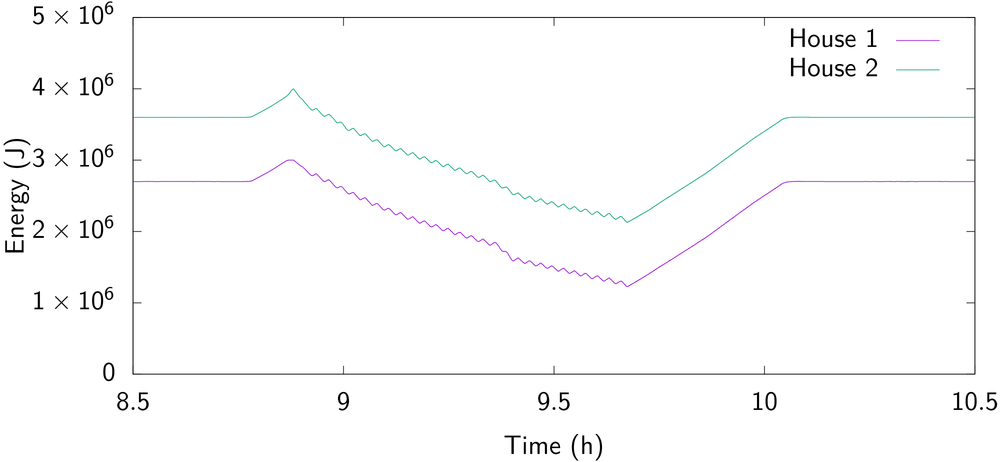
Power used by loads (zoomed)



Power generation (zoomed)



Energy in the storage (zoomed)



Control Design

Discretization

Numerical Study

Summary

Summary

Current Results

- Nested control architecture consisting of
  - Agents that coordinate information between the microgrid and the various control algorithms
  - Real-time controller
  - Predictive engine
  - On-line controller
- Hermite cubic splines used to discretize DAE and bound state, control parameters
- Obtained the optimal control of a microgrid driven by collected, real-world data
- Coordinated use of storage devices

Future Work

- Perform additional case studies with other scenarios
- Run scenarios with entire, combined control framework
- Refine and mature software stack

Contact

For additional questions or interest please contact `joe@optimojoe.com`