Energy Resiliency for a Large House through Intelligent Control using Model Predictive Control

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***Abstract*—**

I. Introduction

A. Setup:

A single house with rooftop solar photovoltaic modules (PV), battery storage (Tesla Powerwall) and loads which consist of: AC and other loads grouped into eight prioritized circuits.

B. Control Goals:

1) Maintain thermal comfort within the house by running the AC with the help of battery storage and PV.
2) Serve the total load demand (not including AC demand) for the house such that maximum load is served and at least critical load is always served.
3) Maintain the Tesla Powerwall SOC such that the system never runs out of energy till grid power is restored.

C. Flexibility for Intelligent Controller:

1) Flexibility in house total demand.
2) Flexibility due to thermal inertia of the house.

II. System Description and Models

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III. Control Algorithms

A. Model Predictive Control (MPC)

The control decisions are computed at discrete time steps $k = 1, 2 \ldots N$ with ΔT_s as the sampling period, and N is the total number of time steps in the planning/prediction horizon. The decision variables for the optimization problem elemental to the MPC controller are as follows: the states of the process $x(k) = [E_{bat}(k), T_h(k)]^T$; the control commands $u(k) = [\Gamma^i(k), u^i_{ac}(k), E^i_l(k)]^T$, where $\Gamma(k)$, $u_{ac}(k)$ and $E_l(k)$ are the fraction of the normal battery charging energy, energy consumed by loads other than the AC and the AC on-off control command respectively; the internal variables $v(k) = [g(k), \zeta_h(k), \zeta_l(k), f_{on}(k), f_{off}(k), \theta_{bat}(k)]^T$, where $g(k)$ is the energy produced by the PV panels between k and $k+1$ time steps, $\zeta_h(k)$ and $\zeta_l(k)$ are the slack variable for house temperature and minimum critical load (E^i_{cri}) respectively to ensure feasibility, $f_{on}(k)$ and $f_{off}(k)$ are the AC turn-on and turn-off indicators as described in Eq.(1) and Eq.(2), and $\theta_{bat}(k)$ is the battery storage discharge indicator. The exogenous inputs whose predictions are assumed to be known for the N time steps $w(k) = [E_{pv}(k), \bar{E}_l(k)]^T$, where E_{pv} and $\bar{E}_l(k)$ are the available energy from the PV panels and the forecast of the total load demand of the house except AC demand respectively. Hence, the complete decision vector for the optimization problem is given as $[X, U, V]^T$, where $X := [x(k+1), \ldots, x(k+N)]^T$, $U := [u(k), \ldots, u(k+N-1)]^T$ and $V := [v(k), \ldots, v(k+N-1)]^T$. Moreover; u_{ac}, f_{on}, f_{off} and θ_{bat} are binary variables i.e. $\in 0, 1$.

$$f_{on}(k) = \begin{cases} 1\,, & u_{ac}(k) = 1 \,\&\, u_{ac}(k-1) = 0 \\ 0\,, & \text{otherwise} \end{cases} \tag{1}$$

$$f_{off}(k) = \begin{cases} 1\,, & u_{ac}(k) = 0 \,\&\, u_{ac}(k-1) = 1 \\ 0\,, & \text{otherwise} \end{cases} \tag{2}$$

A constrained optimization problem is solved, to generate control commands for N time steps, which tries to keep the refrigerator temperature in the prescribed temperature range, maximize the battery state of charge, minimize the health degradation of the battery, and maximize the operation of the secondary loads. This objective is achieved subject to constraints on the refrigerator and battery model dynamics, energy balance equation, battery state of charge constraints, and the constraints on charging and discharging rate of the battery. The optimization problem at any time index j is given mathematically as follows:

$$\begin{aligned}\min_{X,U,V} \sum_{k=j}^{j+N-1} \Big[&\lambda_1(N-k)\zeta_h(k) + \lambda_2(N-k)\zeta_l(k) - \\ &\lambda_3(N-k)E_l(k) - \lambda_4 E_{bat}(k) + \\ &\lambda_5\theta_{bat}(k)\Big],\end{aligned} \tag{3}$$

subject to the following constraints:

$$T_h(k+1) = AT_h(k) + Bu_{ac}(k)Q_{ac} + DT_{am}(k), \tag{4}$$

$$E_{bat}(k+1) = E_{bat}(k) - \Gamma(k)\eta_{bat}^{c,dc,con}\bar{E}_{bat}^{c}, \tag{5}$$

$$u_{ac}(k)E_{ac} - \Gamma(k)\bar{E}_{bat}^{c} + E_l(k) = g(k), \tag{6}$$

$$u_{ac}(k) = \sum_{m=j}^{k} f_{on}(m) - \sum_{m=j}^{k} f_{off}(m), \tag{7}$$

$$f_{on}(k)\bar{P}_{ac} \leq \theta_{bat}(k)\bar{P}_{bat} + \frac{g(k)}{\Delta T_s}, \tag{8}$$

$$\underline{T}_h \leq T_h(k) \leq \bar{T}_h + \zeta_h(k), \tag{9}$$

$$\underline{E}_{bat} \leq E_{bat}(k) \leq \bar{E}_{bat}, \tag{10}$$

$$\underline{\Gamma} \leq \Gamma(k) \leq \bar{\Gamma}, \tag{11}$$

$$E_{cri}(k) - \zeta_l(k) \leq E_l(k) \leq \bar{E}_l(k), \tag{12}$$

$$0 \leq g(k) \leq \bar{E}_{pv}(k), \tag{13}$$

$$f_{on}(k) + f_{off}(k) \leq 1, \tag{14}$$

$$\zeta_h(k) \geq 0, \tag{15}$$

$$\theta_{bat}(k) \geq \Gamma(k), \tag{16}$$

$$E_{cri}(k) \geq \zeta_l(k) \geq 0, \tag{17}$$

Points of concern/improvement:

1) The cost function Eq.(3) consists of quadratic terms in ζ_h^i, ζ_l^i, E_l^i and E_{bat}^i for providing fairness in terms of house temperature deviations, critical load shedding, secondary load servicing and battery usage.
2) The cost function Eq.(3) consists of linear terms in ζ_h^i, ζ_l^i and E_l^i along with E_{bat}^i, we need to minimize the slacks and maximize secondary load servicing along with maximizing battery state of charge which is not possible through just quadratic cost.
3) The cost function Eq.(3) has $(N-k)$ time index dependent constant weights for linear terms in ζ_h^i, ζ_l^i and E_l^i but not for the quadratic terms in the same variables as fairness is required throughout the planning horizon while desired objectives are favored more early in the planning horizon. An anomaly to this is the variable E_{bat}^i, since battery state of charge is desired to be high throughout the planning horizon as it helps keeping the system alive.
4) We introduce another decision variable θ_{bat}^i to indicate the discharging batteries so that the AC startup power constraint can be formulated properly as in Eq.(8) leading to omission of the earlier slack on energy ζ_e^i.

1) Real-Time Control:

B. Baseline Controller

1) Real-Time Control:

IV. Simulation Study Setup

The period selected for simulation is the time hurricane Irma passed over Gainesville, FL, USA, starting from its landfall on Sept. 11, 2017, to Sept. 17, 2017. Weather data is obtained from National Solar Radiation Database (nsrdb.nrel.gov). The simulations are run for 7 days starting at 00:00 hours (midnight) at day 1 (September 11, 2017) with a planning horizon of 24 hours and a time step of 10 minutes ($\Delta T_s = 10$ mins, $N = 144$) with battery initial state at $\bar{E}_{bat}$ (i.e., $E_{bat}(0) = \bar{E}_{bat}$) and the refrigerator initial temperature at $2°C$ (i.e., $T_{fr}(0) = 2°C$). The internal house temperature, $T_{house}(k)$, for the planning horizon is computed using the linear model given by [?], which models a typical, detached, two-story house in the USA.

A. PV Battery System Sizing

B. Computation

The plant is simulated in MATLAB. The optimization problem is solved using GUROBI [?], a mixed integer linear programming solver, on a Desktop Linux computer with 8GB RAM and a 3.60 GHz $\times$ 8 CPU.

C. Simulation Parameters

The parameters for the plant components; PV panels: ; Battery: and Loads: AC -. The system voltage is $V_d = 24\ V$ and the inverter efficiency is $\eta_{inv} = 0.9$.

The parameters for the house thermal model are .

The parameters for the optimization problem are .

V. Results and Discussion

VI. Conclusion