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# Building-to-grid predictive power flow control for demand response and demand flexibility programs

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## HIGHLIGHTS

- Proposes a predictive method to control power flow of ESS, PV, buildings and grid.
- Presents two configurations for grid integration of buildings with ESS and PV.
- Develops model predictive control for demand response for building-to-grid systems.
- Develops a predictive method to prevent grid duck-curve by reducing load ramp-rate.
- Presents deterministic/probabilistic analysis of the proposed predictive framework.

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## ABSTRACT

Demand Side Management (DSM) provides ancillary service to the electric grid by modifying customers electricity demand. Demand Response (DR) and Demand Flexibility (DF) programs from buildings are well-adopted ancillary services to reduce the peak demand in grids by altering the power consumption strategy. Heating, Ventilation and Air-Conditioning (HVAC) systems are one of the largest energy demands in commercial buildings. In addition, HVAC systems are flexible to provide DR service to the grid. In this study, two common configuration topologies of building integration with Energy Storage Systems (ESS) and renewables are considered. A real-time optimization framework based on Model Predictive Control (MPC) is designed to control the power flow from the grid, solar Photovoltaic (PV) panels, and ESS to a commercial building with HVAC systems. The MPC framework uses the inherent thermal mass storage of the building and the ESS as a means to provide DR. Deterministic and probabilistic analysis are studied to investigate the effectiveness of the proposed framework on Building-to-Grid (B2G) systems. Our deterministic results show that the proposed optimization and control framework for B2G systems can significantly reduce the maximum load ramp-rate of the electric grid to prevent duck-curve problems associated with increase in solar PV penetration into the grid. Based on probabilistic results, even under prediction uncertainties, electricity cost saving and ramp-rate reduction is achievable. The results show that this DR service does not affect the building indoor climate in a way noticeable to humans and its effect on the operational building costs is reduced. The B2G simulation testbed in this paper is based on the experimental data obtained from an office building, PV panels, and battery packs integrated with a three-phase unbalanced distribution test feeder. A Monte-Carlo simulation is carried out to account for uncertainties of the proposed method. Both deterministic and stochastic analyses show the effectiveness of the proposed predictive power flow control to decrease the building operation electricity costs and load ramp-rates.



## 1. Introduction

Connectivity and interoperability of Building-to-Grid (B2G) systems are essential factors for a greener future of energy landscape. Developing advanced control strategies for B2G systems guarantees safety, reliability and interoperability of buildings and electric grid as energy and power hubs in a modernized grid.

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**Nomenclature**

| | |
|---|---|
| $\alpha_I$ | PV panel temperature coefficient of short circuit current (A/K) |
| $\beta_V$ | PV panel temperature coefficient of open circuit voltage (V/K) |
| $C_B$ | ESS battery capacity (A h) |
| $Ctap$ | capacitor tap position (–) |
| $d$ | vector of system disturbances (–) |
| $\underline{\epsilon}_t$ | optimization lower slack variable (K) |
| $\overline{\epsilon}_t$ | optimization upper slack variable (K) |
| $\phi_{k+t\|t}$ | maximum feasible building load (W) |
| $G$ | solar irradiation ($\mathrm{W/m^2}$) |
| $I$ | current (A) |
| $I^{bl}$ | building current (A) |
| $I^{cl}$ | capacitor bank current (A) |
| $I^{zl}$ | constant impedance current (A) |
| $I_{re}$ | receiving end current (A) |
| $I_{se}$ | sending end current (A) |
| $I_{0,ref}$ | PV panel reference diode saturation current (A) |
| $I_0$ | diode saturation current (A) |
| $I_{Ar}$ | PV array current (A) |
| $I_{SC}$ | PV panel short circuit current (A) |
| $I_L$ | PV panel photo-current (A) |
| $I_{L,ref}$ | PV panel reference photo-current (A) |
| $I_{MP}$ | PV panel maximum power point current (A) |
| $k$ | Boltzmann constant (eV) |
| $\lambda_F$ | HVAC fan power coefficient ($\mathrm{W\,s^3\,kg^{-3}}$) |
| $\dot{m}^r$ | supply air mass flow rate (kg/s) |
| $N$ | prediction horizon (–) |
| $N_p$ | number of parallel cells in a PV panel (–) |
| $n_I$ | diode ideality factor (–) |
| $n_{I,ref}$ | reference diode ideality factor (–) |
| $N_s$ | number of series cells in a PV panel (–) |
| $\Omega$ | LMP of electricity ($/kWh) |
| $P_{bldg}$ | active power consumption of building (W) |
| $P^C$ | HVAC power consumption for cooling (W) |
| $P_{DR_t}$ | DR signal power (W) |
| $P^F$ | HVAC fan power consumption (W) |
| $P_{g2s}$ | power flow from grid to ESS battery packs (W) |
| $P_{g2b}$ | power flow from grid to building (W) |
| $P^H$ | HVAC power consumption for heating (W) |
| $P^O$ | building load for lighting, plug load and appliances (W) |
| $P_{PV}$ | power flow from PV array to ESS battery packs (W) |
| $P_{s2b}$ | power flow from ESS to building (W) |
| $q$ | electron charge (C) |
| $R_p$ | parallel (shunt) resistance ($\Omega$) |
| $R_{p,ref}$ | PV panel reference parallel resistance ($\Omega$) |
| $R_s$ | PV panel series resistance ($\Omega$) |
| $R_{s,ref}$ | PV panel reference series resistance ($\Omega$) |
| $\underline{\Psi}_{t+k\|t}$ | load ramp-down rate limit (W/s) |
| $\overline{\Psi}_{t+k\|t}$ | load ramp-up rate limit (W/s) |
| $SOC$ | state of charge (%) |
| $\underline{SOC}$ | SOC lower bound (%) |
| $\overline{SOC}$ | SOC upper bound (%) |
| $T^C$ | HVAC cooling mode supply air temperature (K) |
| $T_c$ | PV cell temperature (K) |
| $T^H$ | HVAC heating mode supply air temperature (K) |
| $Ttap$ | regulator tap position (–) |
| $U_t$ | vector of control inputs, airflow temperature (K) |
| $V$ | voltage (V) |
| $V_{itr}$ | voltage of sending end branch where regulator is connected (V) |
| $V_{OC}$ | PV panel open circuit voltage (V) |
| $V_{MP}$ | PV panel maximum power point voltage (V) |
| $V_B$ | ESS battery pack voltage (V) |
| $x$ | vector of system states (–) |

*Abbreviation*

| | |
|---|---|
| *B2G* | Building to Grid |
| *BEMS* | Building Energy Management System |
| *COP* | Coefficient of Performance |
| *DF* | Demand Flexibility |
| *DR* | Demand Response |
| *DLC* | Direct Load Control |
| *DSM* | Demand Side Management |
| *ESS* | Energy Storage Systems |
| *FERC* | Federal Energy Regulatory Commission |
| *GHG* | Greenhouse Gas |
| *GSHP* | Ground Source Heat-Pump |
| *GTI* | Global Tilted Irradiation |
| *HVAC* | Heating, Ventilation and Air-Conditioning |
| *ISO* | Independent System Operators |
| *LF* | Load Factor |
| *LMP* | Locational Marginal Pricing |
| *LTC* | Load Tap Changer |
| *MISO* | Midcontinent Independent System Operator |
| *MO* | Market Operator |
| *MPC* | Model Predictive Control |
| *MPP* | Maximum Power Point |
| *NOCT* | Nominal Operating Cell Temperature |
| *PV* | Photovoltaic |
| *PJM* | Pennsylvania-New Jersey-Maryland |
| *RES* | Renewable Energy Sources |
| *SOC* | State of Charge |
| *SRC* | Standard Reference Conditions |

Due to intermittent distributed renewable power generation and its increasing penetration into the power grid, electricity generation is changing from predictable and dispatchable to unpredictable and non-dispatchable sources [1]. By increasing small-scale distributed Renewable Energy Sources (RES), and the increase of non-dispatchable power generation ratio, the mismatch between power demand and generation occurs more frequently. Likewise, in the advent of extreme weather conditions, the demand-generation balance is jeopardized. This mismatch and load intermittent lead to volatility of the electricity price in the market. As an example, customers in part of Pennsylvania-New Jersey-Maryland (PJM), faced an 86-fold spike in electricity price in the extreme weather conditions due to polar vortex in January 2014 [1,2]. The demand-supply mismatch necessitates deployment of Demand Side Management (DSM) for adjusting power generation and load which is crucial in modern grids.

DSM has several benefits for demand and supply sides including (i) increased operation efficiency in electric power (generation, transmission and distribution), (ii) reduced the electricity price and volatile of electricity price, and (iii) integration of high penetration renewables [3]. Demand Response (DR) programs are ancillary services in which end-users (in our case commercial buildings) adjust the power consumption in response to a certain signal from the grid. The DR signal may contain information regarding electricity price, incentives, or system reliability emergencies [4]. In the traditional look to the power systems, demand side is not flexible