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Price-optimal Energy Flow Control of a Building Microgrid Connected to a Smart Grid

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***Abstract*—This paper discusses model predictive control for energy flows in a microgrid as a part of the overall hierarchical organization of energy management in a building. The control is performed in the presence of time-varying building and grid conditions: weather-dependent production, energy prices and consumption. Detailed analysis of microgrid energy and operation cost is presented with real weather data and energy prices, building dynamics and optimal building consumption. Cost-optimal interaction between the building-side energy management system and the grid in conditions of volatile energy price and possibility of building's active participation in the energy market is proposed.**

Model predictive controller for optimizing total economic cost of energy and microgrid operation is implemented and verified on a model of a building belonging to University of Zagreb, Faculty of Electrical Engineering and Computing, using actual test site data for 2014. Reduction of maximum power, minimization of energy consumption, storage degradation during operation, day-ahead energy profile following and intra-day deviations as energy market incentives are included in the cost function for ensuring building ancillary services as a prosumer in the smart grid.

***Index Terms*—Microgrid, Battery storage, Smart grid, Efficient energy management, Model predictive control, Ancillary services**

I. INTRODUCTION

Passive integration of renewable energy sources is expected to introduce higher uncertainty and increased operational costs of the electrical grid [1]. Since getting quick response to load changes from conventional power plants is becoming rather challenging as their share in total production decreases [2], the concept of power system operation shifts to empowering flexible load to follow these new generation uncertainties. A promising approach to solve this problem is load shifting using controllable loads, e.g. heating, ventilation and air conditioning (HVAC) systems [3], [4]. Electrical energy storages, e.g. batteries, are also used as an additional energy reserve for load balancing [5]. All of the approaches require a well-established interaction between the grid and the building energy management system (EMS).

Interaction of the building-side EMS and the grid is usually market-based, which means that the grid-building energy exchange is primarily driven by market prices [6]. Volatile energy prices can help the microgrid to maximize economic profit [7].

The EMS concept we consider in this paper relies on the existing equipment without introduction of additional hardware costs, but rather by improved control actions/algorithms with the goal of operational cost reduction. The proposed EMS concept consists of three modules put in a hierarchical organization: zones comfort module, central HVAC module and microgrid energy flows module, as shown in Fig. 1 [9]. Further on, each of the modules incorporates three different submodules: prediction and estimation, optimal control and interfaces to the equipment, as depicted in detail in Fig. 2 for the microgrid module. The microgrid module is utilized as the highest hierarchy level and is responsible for interaction with the electricity grid and for enabling the building to provide the ancillary services.

The focus of the paper is on model predictive control (MPC) concept for the microgrid module and achieving the cost-optimal building participation in the market through volatile wholesale market prices. The building offers its planned consumption profile and flexibility to the grid and receives day-ahead energy prices in return, calculated according to the current energy market conditions. We consider a simplified grid-microgrid interaction scenario here: the building adapts its previously declared day-ahead consumption profile based on the provided day-ahead prices and flexibility requests from the grid which are actually required deviations of the building from its declared day-ahead profile. The microgrid MPC optimizes the microgrid operation and creates outputs in the form of required energy exchange profiles for controllable elements on the microgrid level.

All of the EMS modules can operate independently. However, when put to coordinated operation, the savings are significantly increased as shown in [8] for the case of zones and microgrid MPC modules coordinated operation modules (additional savings of 15%). This is achieved only by further mathematical (software) adjustments, without additionally required hardware or installations. In this paper the focus is put solely on the microgrid MPC operation while the control problem formulation used within it makes the mentioned coordination possible. Battery degradation costs are also taken into consideration and different scenarios are compared in terms of the overall cost for the building.

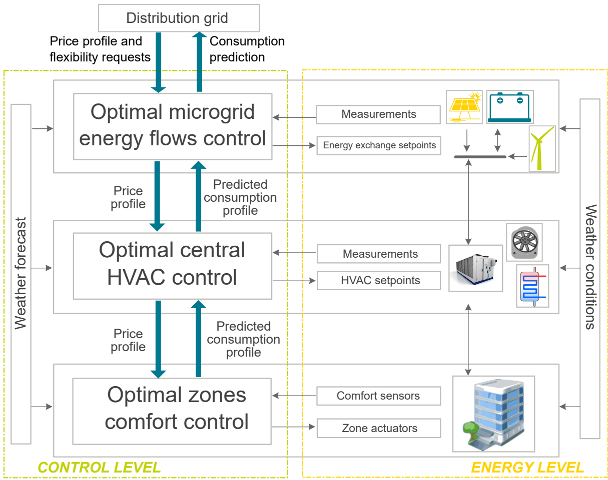

Fig. 1: Functional diagram of the proposed EMS hierarchy on the building side [9].

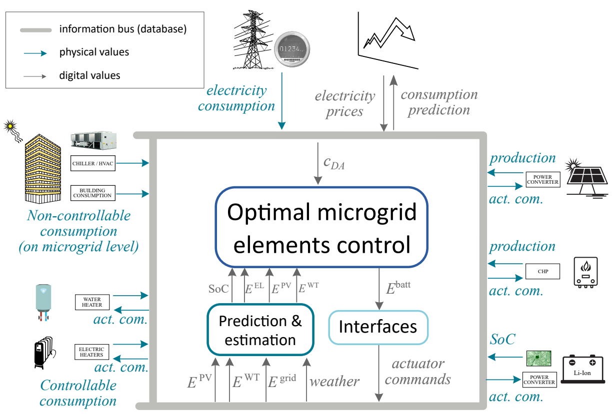

Fig. 2: Microgrid level organization of the EMS [9].

The paper is organized as follows. In Section II, mathematical models of energy storage unit and microgrid energy balance equations are presented. In Section III, means of interaction between building-side EMS and grid-side EMS are described, together with all partial energy and microgrid operation costs. Optimization problem formulation and total cost of energy consumed by the building and microgrid operation is presented in Section IV. Simulation environment is described in Section V and simulation results are presented in Section VI. Conclusions are given in Section VII.

II. Microgrid elements model

In this paper, a battery storage is used as a controllable microgrid element, while in general more controllable elements can be combined (e.g., hot water boilers, electric heaters, etc.). In the sequel such a microgrid is described including the corresponding storage model.

A. Energy storage model

When observing a microgrid storage component with a sampling time large enough to disregard the transients on its energy links, it can be modeled via its state-of-charge (SoC):

$$SoC_{k+1} = SoC_k + \frac{1}{C}\eta E_{batt,k}, \tag{1}$$

where C is energy storage capacity, η is efficiency of the storage unit, E_{batt} is applied charging or discharging energy and k indicates the sampling time instant. When charging, a part of the charging energy will be dissipated and thus $\eta < 1$. For discharging, the microgrid will receive less energy than sent by the storage and thus $\eta > 1$. In order to avoid high calculation complexity of a mixed-integer problem formulation, energies and efficiencies are split to charging and discharging components [10]:

$$SoC_{k+1} = SoC_k + \frac{1}{C}\Big(\eta_{ch} E_{ch,k} + \frac{1}{\eta_{dch}} E_{dch,k}\Big), \tag{2}$$

where $E_{batt,k} := E_{ch,k}$ for $E_{batt,k} \geq 0$ and $E_{batt,k} := E_{dch,k}$ for $E_{batt,k} \leq 0$.

For the MPC implementation, (2) is formulated as:

$$x_{k+1} = \mathbf{A}x_k + \mathbf{B}u_k, \tag{3}$$

where $x_k = SoC_k$, $u_k = [E_{ch,k} \;\; E_{dch,k}]^T$, $\mathbf{A}$ and $\mathbf{B}$ are model matrices.

In particular for batteries, η_{ch} and η_{dch} include battery and power converter efficiency and can be considered constant. Constraints for the optimization problem are given with maximum charge/discharge energy within one sampling period::

$$u_{min} \leq u_k \leq u_{max}, \tag{4}$$

and SoC is constrained between capacity limits (e.g. 10% and 90%) as:

$$x_{min} \leq x_k \leq x_{max}. \tag{5}$$

B. Microgrid energy balance

The microgrid energy balance condition (energy conservation law on the microgrid link) implies that sum of all input and output energies is zero, i.e. the difference between the consumed and produced energies in the building represents the energy exchange with the grid. This is described as the condition satisfied at each discrete time step k:

$$E_{grid,k} = E_{load,k} + \mathbf{1}_d^T d_k + \mathbf{1}_u^T u_k, \tag{6}$$

where E_{grid} is a vector of energies exchanged with utility grid over a certain prediction horizon $k = 0, 1, ..., N$-1 where N is the MPC prediction horizon, E_{load} is a vector of energies supplied to loads (building consumption), d_k is a vector of energy productions of different generation units (e.g., wind turbines, photovoltaic arrays), u_k is a vector of energy exchange with storage units and controllable loads (e.g. HVAC system), $\mathbf{1}_d$ and $\mathbf{1}_u$ are appropriately sized vectors of ones introduced to mathematically represent the summation of all production contributors and controllable loads.

III. Interaction of the building EMS with the grid

Electrical energy market and distribution grid are independent systems entities and each of them can provide the building with certain conditions put on the exchange of energy between the building and the grid. The hierarchical control system on the building side takes into account the announced market conditions and decides how to control the building climate and internal building energy flows through all the levels (zones, central heating/cooling medium preparation, microgrid) in an optimal way such that minimum or no discomfort is established at the minimum overall price for the building.

A common time base of operation (i.e. sampling time) is defined as the time interval where the conditions on grid-building energy exchange do not change.

The building-side EMS optimizes the comfort and the overall economic cost of the energy exchange with the utility grids. Comfort is transformed into energy and finally into cost through suitable weighing factors and model-based transformation [11].

The economic parameters for defining the cost for energy exchange with the grid that are to be taken into account in the building-side EMS are given in the sequel. These parts are all integrated in the microgrid level MPC.

A. Cost of maximum power

Maximum monthly power value is charged with a fixed cost. This cost is only charged for power taken from the distribution network and not for sold power. Mathematically, this is represented as:

$$J_{MP} = c_{Pmax}\varepsilon_1, \quad s.t. \begin{cases} \varepsilon_1 \geq 0 \\ \varepsilon_1 \geq E_{grid,k} - E_{grid,MM} \quad \forall k \\ E_{grid,MM} = \text{max so far in the month } \; E_{grid,k} \end{cases}, \tag{7}$$

where ε_1 is a slack variable, $E_{grid,MM}$ is the maximum of total energy consumption required by the building within one sampling instant (worst case) obtained from the previous consumption for the current month. This variable is reset to zero at the beginning of every month. Relation (7) is graphically illustrated in Fig. 3.

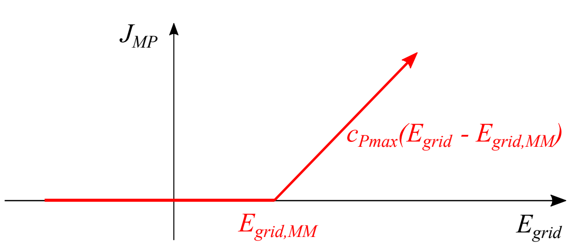

Fig. 3: Maximum power cost function sketch.

B. Cost of energy, day-ahead

The building EMS receives day-ahead (DA) prices of energy from the grid operator. Here they are taken from historical data (EPEX [12]), with a sample time of 1 hour, resulting in 24 prices per day. In real-world application, the day-ahead prices need to be known 12 hours prior to start of the observed day and are a result of the market clearing process. Different sample rates (e.g. 15 min, 30 min, 2 hours) are also possible. The DA prices will be used by building-side EMS as known values for the optimization process, i.e. for cost minimization which results in optimal demand profiles for given prices.

Day-ahead building energy consumption is the energy required for internal building processes and for balancing between production, consumption and storages. Mathematically, it is put to a form of minimizing the cost of energy bought from the utility grid:

$$J_{DA} = c_{DA}^T E_{grid}, \tag{8}$$

where E_{grid} can also have negative sign, referring to the process of selling the excess energy back to the grid. If the market price $c_{DA,k}$ is constant for every time step k, minimizing (8) yields control variables for energy-optimal building operation.

C. Intra-day pricing for maintaining the declared day-ahead profile

At the intra-day market, the building-side EMS needs to pay for energy which is missing/surplus from the profile announced day-ahead. For the evaluation purpose, price values for energy exchanged not according to the planned day-ahead exchange profile are taken as day-ahead energy prices multiplied by a factor of 1.2 (20% higher). Mathematical representation of intra-day following price is:

$$J_{IDf} = 1.2c_{DA}||E_{grid} - E_{grid}^*||_1, \tag{9}$$

where E_{grid}^* is reference day-ahead energy exchange that is planned and previously announced to the grid. Since the price in (9) is higher than in (8), the optimization will always give priority to intra-day following than to deviation from the declared profile unless it is infeasible or there is some other, even higher, incentive to perform deviation.

D. Intra-day pricing to incentivize deviation from the declared day-ahead profile

The grid can explicitly require a deviation of the building from the declared profile E_{grid}^* if it proves economical for the grid, e.g. either to balance some disbalances on intra-day market introduced by other actors or to safeguard power limitations of some elements or lines in the distribution grid. Beforehand some contract in the lines of providing flexibility should exist between the grid and the building. In this paper we will presume that such a contract exists and that the grid can ask the building for a deviation in a certain amount confined between the assessed maximum and minimum amount throughout the day.

The microgrid will be rewarded with $5c_{DA}$ for every kWh of activated flexibility. Inability to follow the requested deviation profile will be penalized with $100c_{DA}$:

$$\begin{aligned} J_{IDd} = &-5c_{DA}^T||\Delta E_{grid}^*||_1 \\ &+ 100c_{DA}^T||E_{grid} - E_{grid}^* + \Delta E_{grid}^*||_1, \end{aligned} \tag{10}$$

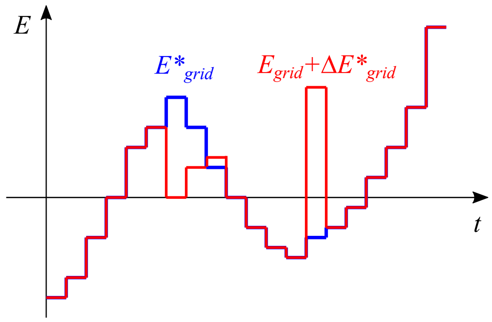

Fig. 4: Exemplary intra-day deviation from initial day-ahead building energy consumption profile.

where ΔE^*_{grid} is the requested deviation from planned day-ahead consumption.

E. Costs of battery degradation

Batteries have a limited life cycle and their performance is degraded with every charge/discharge cycle. Costs of battery degradation due to charging/discharging is modeled as:

$$J_{BD} = c_{BD,ch}E_{ch} + c_{BD,dch}E_{dch}, \tag{11}$$

or, in the vector form,

$$J_{BD} = \begin{bmatrix} c_{BD,ch} & c_{BD,dch} \end{bmatrix} \begin{bmatrix} E_{ch} & E_{dch} \end{bmatrix}^T \tag{12}$$

Prices $c_{BD,ch}$ and $c_{BD,dch}$ depend on battery properties and operating conditions. Values of $c_{BD,ch} = -c_{BD,dch} = 0.1704$ €/kWh are calculated from manufacturer's specifications of the used battery cells [13].

IV. Optimization problem formulation

Microgrid optimization submodule and its corresponding MPC algorithm for energy flows management provides a decision when to buy from or sell energy to the utility grid and in which amount, i.e., when and how much to actuate the controllable microgrid elements. The overall optimization problem is a constrained finite-time optimal control problem expressed as a linear program. The complete optimization problem of the microgrid MPC submodule incorporates parts from sections II and III:

$$\begin{aligned} &J = J_{MP} + J_{DA} + J_{IDf} + J_{IDd} + J_{BD} \\ &s.t. \begin{cases} x_{k+1} = \mathbf{A}x_k + \mathbf{B}u_k \\ u_{min} \leq u_k \leq u_{max} \;\; \forall k \\ x_{min} \leq x_k \leq x_{max} \;\; \forall k \\ \varepsilon_1 \geq 0 \\ \varepsilon_1 \geq E_{grid,k} - E_{grid,MM} \;\; \forall k \\ E_{grid,MM} = \text{max so far in the month } \; E_{grid,k} \end{cases} . \end{aligned} \tag{13}$$

V. Simulation environment

The described MPC algorithm is validated by using a model of one floor of University of Zagreb - Faculty of Electrical Engineering and Computing (UNIZG-FER) building, with the following microgrid properties:

- The building consists of 253 zones as non-controllable loads, 22.5 kWp photovoltaics and a battery storage of 32 kWh capacity and 81% round-cycle efficiency.
- Constraint for energy exchanged with the grid:

$$-90 \text{ kW} \leq \frac{E_{grid}}{T_s} \leq 90 \text{ kW} \tag{14}$$

- Battery system constraints: $x_{min} = 0.1$, $x_{max} = 0.9$, $E_{dch,max} = -9.6$ kWh, $E_{ch,max} = 9.6$ kWh

Simulation of zone level building operation during a 1-year period was performed beforehand in order to obtain consumption energy profiles needed for heating/cooling, as described in [11]. The profiles were recorded for use as microgrid loads. Room temperature setpoint is set to 22°C, and energy consumption and comfort were equally penalized, as described in [8]. Weather data and electricity prices (EPEX) are the actual data for year 2014. Sampling time is chosen as $T_s = 1$ h and prediction horizon set to $N = 24$ h. Simulation environment used for testing the MPC algorithm also includes deliberately added disturbances:

- Day-ahead profile is obtained by simulating the system for a 1-year period using fixed energy prices, yielding an energy-optimal solution. Simulations are further performed for the complete cost function (13) while white noise [0,1] kW is added to consumption energy profile of heating/cooling power (respecting heating or cooling season) to add uncertainty to DA profile following. The added noise is visible on the prediction horizon.
- Intra-day deviation request is taken as 100 deviations placed randomly throughout the year, with random amplitude in interval [-5, 5] kW. Required deviation is anticipated by MPC as soon as the time instant in which it is required appears on the prediction horizon.

VI. Simulation results

The following figures show results for the cooling season with various weather conditions (sunny, cloudy and mixed) for a chosen week in July 2014. The weather data, photovoltaic production, electricity price profile and reference building energy consumption are shown in Fig. 5.

The building follows the intra-day deviation requests (Fig. 6) with the highest cost priority (financial reward) as described in (10) and therefore occasionally deviates from the promised DA profile.

More detailed insight to realized E_{grid} and the corresponding E^*_{grid} is given in Fig. 8, focused on July 13, 2014. The difference between the DA profile and actual grid energy exchange in period 00:00-01:00 is a result of the required intra-day deviation. A deviation in period 06:00-07:00 is a result of the building inability to follow the promised day-ahead profile due to microgrid operating constraints and introduced uncertainties.

The total yearly cost of the simulated building operation is computed for the following cases:

1) Without a microgrid and renewable energy production.
2) Using a microgrid and renewables production, but without offering ancillary services and using transactive control law as described in [8]. The transactive algorithm will fully charge the battery if current energy price is below average, and fully discharge the battery if current energy price is above average.
3) Using the proposed MPC controller for the microgrid, with the following costs included: J_{MP} and J_{DA}.
4) Using the proposed MPC controller for the microgrid, with the following costs included: J_{MP}, J_{DA} and J_{IDf}.
5) Using the proposed MPC controller for the microgrid, with the costs included: J_{MP}, J_{DA}, J_{IDf} and J_{BD}.
6) Using the proposed MPC controller for the microgrid, with all costs given in Section III included except J_{BD}.
7) Using the proposed MPC controller for the microgrid, with all costs given in Section III included.

It is assumed that contracting of DA consumption planning and following makes sense only if the microgrid control algorithm takes the intra-day following cost into account. Therefore, penalties for non-following the declared DA profile will not be charged for cases 1 to 3.

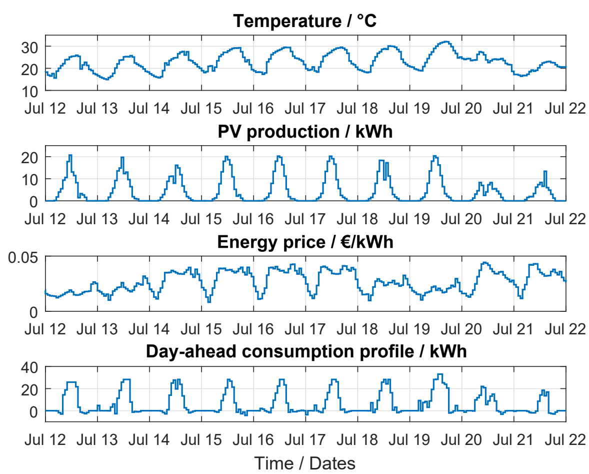

Fig. 5: Simulation scenario profiles for a sequence of summer days.

The comparison of building operating costs is given in Table 1. Compared to operating costs without a microgrid (case 1), operating costs of a microgrid using transactive control (case 2) are significantly higher. This is caused by the battery degradation cost which is 4131 € for our simulation case. Similar results are obtained if the MPC controller disregards battery degradation costs (case 3).

Operating costs for the case of offering ancillary services, but disregarding battery degradation cost (cases 4 and 6) significantly depend on the accuracy of DA consumption prediction: batteries are used only if deviation from the declared DA profile exists.

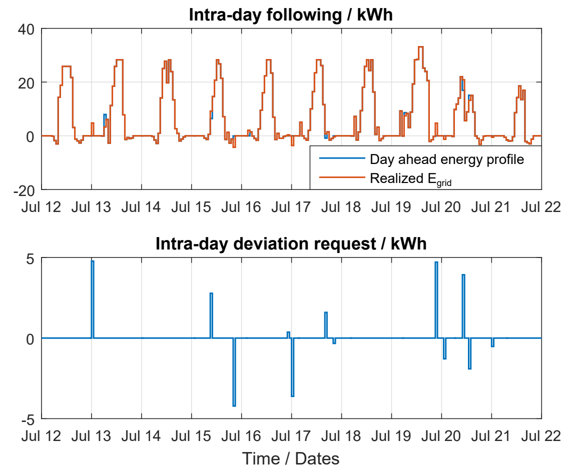

Fig. 6: Intra-day profile following and deviation, example for a sequence of summer days.

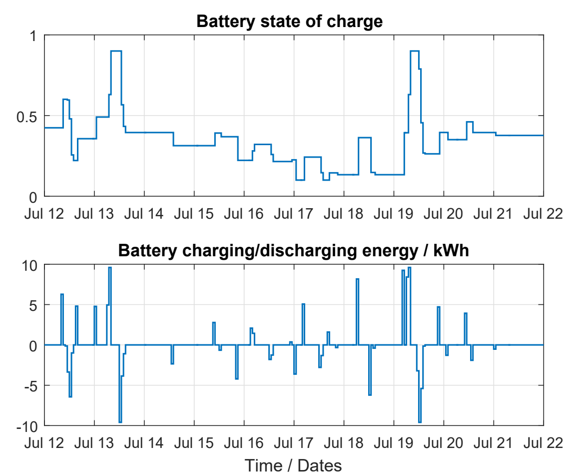

Fig. 7: Battery state of charge and energy exchanged with the battery, example for a sequence of summer days.

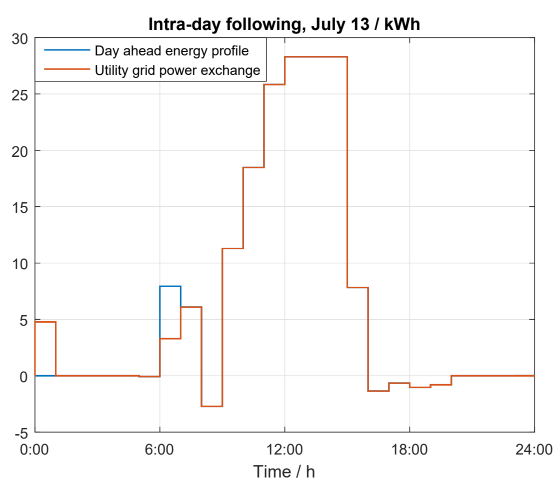

Fig. 8: Detail of the grid exchange profile. At 00:00 an intra-day deviation was requested. At 06:00 the building cannot follow the declared profile.

TABLE I: Comparison of yearly operating costs for the UNIZG-FER building broken down into cost parts.

Case	J_{MP}	J_{DA}	J_{IDf}	J_{IDd} **revenue**	J_{IDd} **penalties**	J_{BD}	**Total cost**
1	3780 €	3100 €	-	-	-	-	6780 €
2	2985 €	2861 €	-	-	-	4131 €	9977 €
3	2619 €	3093 €	-	-	-	4406 €	10118 €
4	2758 €	2750 €	0 €	-	-	486 €	5994 €
5	2878 €	2756 €	58 €	-	-	0 €	5692 €
6	2758 €	2841 €	54 €	205 €	618 €	737 €	6803 €
7	2752 €	2829 €	52 €	205 €	621 €	523 €	6572 €

If the control algorithm incorporates battery degradation cost into total cost function (cases 5 and 7), it will charge or discharge the battery only if it is economically justified. In our test scenarios including the battery degradation cost, batteries will generally be used only for offering ancillary services, and not for maintaining the DA profile.

The maximum amplitude and occurrence frequency of the intra-day deviation requests are set rather conservatively in our simulation environment (maximally 5 kW of reserve power, which is roughly one half of the storage power converter rating, in any random time instant which is known 24 hours in advance), yet penalization for not delivering the requested energy is higher than the revenue from the activation of ancillary services. This is caused by the grid requesting an arbitrary deviation which may not be feasible. The losses acquired in that part show that there is a need for a more systematic approach in flexibility contracting and in day-ahead profile planning once the flexibility is contracted.

VII. Conclusion

This paper describes a design procedure of a model predictive control (MPC) algorithm for a building microgrid. The controller is designed to operate in a hierarchically organized building energy management system (EMS). The MPC optimizes total energy and microgrid operation costs in presence of time-varying building consumption, renewables production and energy prices. Outputs of the MPC are reference energy profiles for controllable elements in the microgrid (e.g., batteries, domestic hot water boilers) with a chosen sampling time.

Validity of the proposed control algorithm was verified using actual data and building model of an university building. Costs of building operation were computed for several test cases: without a microgrid, using a microgrid with transactive control and using a MPC-controlled microgrid with and without offering of ancillary services and with and without taking battery degradation cost into account.

The presented results show that installation of microgrid without adequate control can lead to increase of total building operation costs. The proposed algorithm reduces the battery degradation cost by approximately 8 times compared to the transactive control algorithm, which yields savings of 34%.

If the intra-day deviation offers in terms of timing and flexibility in power as well as the day-ahead energy exchange profile are not carefully selected, it is possible that the building will not achieve economic profit from offering ancillary services.

Acknowledgment

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