CONTENT

Anita Banjac[1], Nikola Hure[1], Marko Kovačević[1], Hrvoje Novak[1, 2], Mario Vašak[1], Nedjeljko Perić[2]

Modular Hierarchical Model Predictive Control for Coordinated and Holistic Energy Management of Buildings – Battery Storage Considerations

[1] University of Zagreb, Faculty of Electrical Engineering and Computing, Department of Control and Computer Engineering, Laboratory for Renewable Energy Systems, Unska 3, 10000 Zagreb, Croatia,
[2] Innovation Centre Nikola Tesla, Unska 3, 10000 Zagreb, Croatia

Abstract

In the paper, a modular building energy management strategy based on a three-level hierarchical model predictive control is applied to the daily operation scheduling of a full-scale building consisting of 248 offices. Such an approach provides a holistic energy management strategy and enables significant demand response ancillary services for buildings as prosumers, while retaining the independence of required expertise in very different building subsystems. The three-level coordination encompasses building zones, central medium conditioning and a microgrid subsystem. Compared to rule-based control, detailed realistic simulations for typical days in summer show that the indoor comfort is substantially improved with a considerable reduction of the overall building operation cost. The analysis also considers the margin of a battery storage system contribution to the operating costs reduction which underlines the potential of software-based coordination.

Keywords: *building energy management system, zone comfort control, thermal medium conditioning, microgrid energy management, hierarchical coordination, model predictive control, energy efficiency, price-optimal control*

1. Introduction

Due to the proven flexibility, a model predictive control (MPC) approach emerged as a promising solution for widespread problems of energy management within buildings. In addition to climate control, the MPC approach increases savings by 13% when applied to heat pump [1], with load shifting by up to 61% [2, 3, 4] and for peak electricity power reduction by 35-72% [5]. The introduction of microgrid in buildings enables additional savings by providing ancillary services to the utility grid or through coordinated microgrid and building climate control [6, 7].

Buildings are complex systems composed of many coupled subsystems responsible for maintaining safe and steady operation such as: building zones, central heating, ventilation and air conditioning (HVAC) system, microgrid with energy production units, storages and controllable or passive loads, etc. These subsystems differ in their dynamics, priorities, and their means of operation but also in their implementation aspects such as energy levels, protocols, maintenance services, etc. Typical applications of a building energy management system (BEMS) are only locally focused on a specific subsystem, while neglecting the interconnections and cooperation among all constituent subsystems. As a result, the building achieves uncoordinated and non-optimal behaviour. The aim of the modular building energy management strategy introduced in [6, 7] is to separate building subsystems in a hierarchical fashion rather than having one large control structure to handle all the subsystems at once. The considered BEMS consists of three levels following the building energy system vertical decomposition in its major parts: (A)

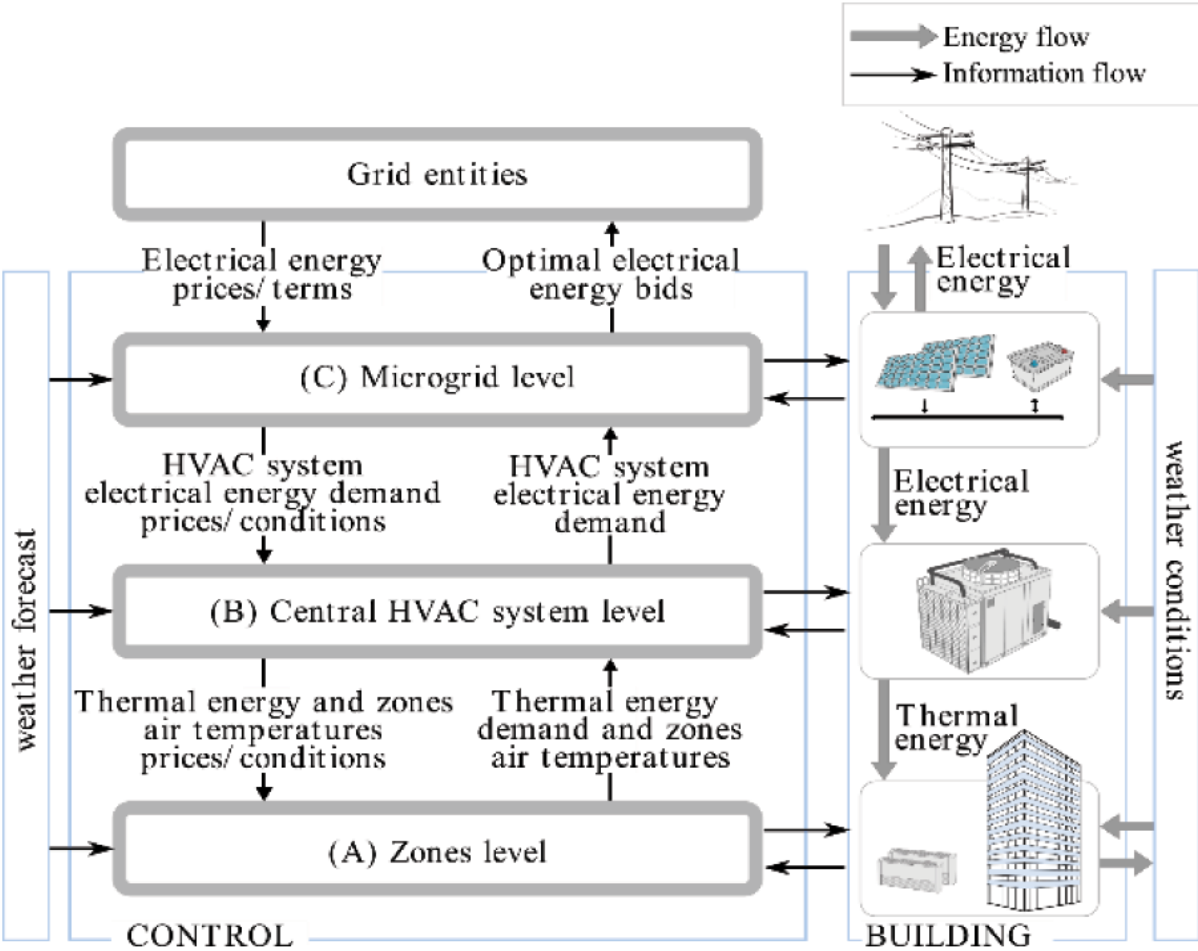

Figure 1. The modular decomposition and hierarchical coordination in a building [6, 7].

building zones level, (B) central heating/cooling medium conditioning system level (referred to as central HVAC level), and (C) building microgrid level (Fig. 1).

Zone level comfort control is envisioned as the lowest level in the proposed hierarchy. If other levels are missing, the improvement of energy-efficiency and comfort is achievable even through the application of only level (A) modules, if they consider weather forecast and comfort requirements to decide on the optimal profile of energy consumption for maintaining comfort conditions in each zone. If no other building level is present, energy prices from the utility grids are directly transferred to level (A) which then induces energy-cost-optimal behaviour instead of the energy-optimal behaviour for maintaining comfort. By also including level (B) next to level (A) the benefits can be multiplied since conventional solutions only introduce energy-connections with the central HVAC system, which consequently cannot consider the current and near-future energy requirements in the zones, and thus operates with a reduced efficiency. Especially important is the ability to intelligently shift the power demand based on the smart grid signals or predicted outdoor temperature that affects the efficiency of the central HVAC system. Finally, at level (C), the BEMS offers the possibility to manage energy storages, energy conversion systems and controllable loads at the building level. Hence, minimum energy costs can be achieved with respect to the planned energy consumption and production profile by making the building an active entity in smart grids or smart energy distribution systems at the district level. Consequently, level (C) enables further modular build-up of the concept beyond the building area and towards smart districts, grids, and cities.

The coordination in the imposed modular structure is based on the so-called "price-consumption" talk, where at each level the information about own optimal operation is communicated to the higher-level module and the cost sensitivity with respect to the lower-level operation is communicated to the lower-level module. Cost sensitivity calculation resides on multi-parametric programming and critical regions [8].

In this paper the approach developed and proposed in [6, 7] is applied to the daily operation scheduling of a full-scale skyscraper building. The benefits of the approach are demonstrated by comparing the operational costs of the building controlled by conventional control algorithms with the costs incurred by energy-optimal hierarchical building control and price-optimal coordinated building control. A special attention is put on comparing the benefits of optimal coordination achievable with and without the battery storage system.

2. Case-study analysis

The case-study building consists of 248 controllable zones equipped with two-pipe fan coil units (FCUs) for seasonal heating or cooling. The cooling energy for the building is supplied from the chiller station with the ability to control the supply temperature of the cooling medium at the central HVAC level. Besides the controllable building zones, the chiller also supplies thermal energy to the adjacent faculty building whose thermal energy consumption is considered non-controllable. The considered microgrid consists of a battery storage system with a fully controllable power converter and a solar power plant. The central HVAC level electrical energy consumption is a controllable load at the microgrid level. It consists of the consumption of the chiller and of the FCUs' fans. The non-controllable electrical energy load at the microgrid level includes the production of the solar power plant and the consumption of the office lighting, computers, building elevators as well as electrical air conditioning units in the server rooms.

2.1. Simulation scenario

The considered control strategies are validated for a typical sunny workday in July [7]. The non-controllable consumptions at the central HVAC system level and the microgrid level are estimated based on the historical building data [7]. Equivalent heat disturbances in all zones are assumed to be zero. The volatile energy market electricity prices, shown in Fig. 2, are taken from the European Power Exchange company portal [9] and scaled to match the two-tariff prices comprising grid fees and the cost of energy supplied in Croatia.

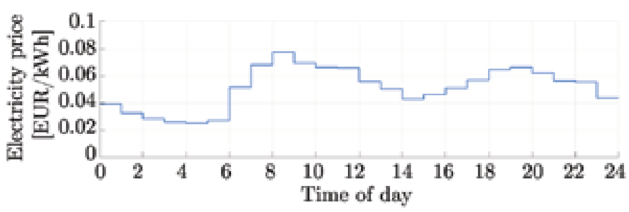

Figure 2. Day-ahead electricity price profile for grid-building energy exchange.

It is assumed that the building is occupied from 7:00 until 20:00. During the occupancy periods the zone temperature should be within an interval of 24±1.5°C. Outside that interval the allowed deviation from the temperature reference is matched with the building protect limits defined as 24±8°C.

The following control strategies are considered:

Baseline control: The baseline algorithms correspond to the usual way of commercial BEMS operation: simple discrete hysteresis control of zone temperature, supply medium temperature kept at constant predefined value, and simple transactive battery storage controller used to flatten the energy exchange profile.

Energy-optimal control: In energy-optimal control, the BEMS operates in an uncoordinated manner where each building optimization level operates independently (local-wise optimal) with only energy demands exchanged between the levels. During this exchange no feedback is provided from the superior levels regarding the consumption profiles and the corresponding energy prices and no tuning of the initial energy demands is performed.

Price-optimal control: In coordinated control, all control levels considered are joined together by the iterative parametric hierarchical coordination presented in [6, 7].

The performance of all considered control strategies is verified in a scenario with the enforced repeated behaviour from day to day, i.e. the initial state of the building (at the beginning of the day, at midnight), which is subject to optimization, is equal to the final state of the building (at the next midnight). In this way the system does not exploit any initial condition in the building to achieve savings, but leaves the building in the same condition as it was at the beginning of the day – i.e. no energy accumulated in the initial state is exploited.

All MPC controllers operate with a sampling time of 15 min. The zone level MPC equally weights the comfort and energy consumption/cost – the comfort-savings trade-off parameter [7] is set to 1. The detailed list of the considered simulation scenario parameters can be found in [7]. To review the energy flexibility and the potential of the battery energy storage, the battery degradation cost approximated to be as high as 0.226 EUR/kWh [7] is set to zero in the simulation scenario considered since for the estimated price the battery use would be completely prohibited in the case of price-optimal control. The responses of the thermal and electrical power profiles are averaged over 15-minute time intervals in all results.

2.2. Results

To fully investigate the contributions and savings possibilities of hierarchical coordination between energy flows and consumption levels, the corresponding building operation costs and achieved thermal comfort are investigated for cases with and without the battery storage system. In the case without battery storage flexibility is only achieved by modifying the central

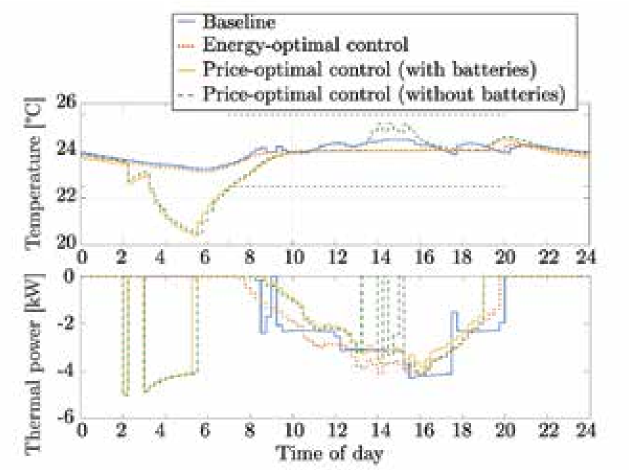

Figure 3. The temperature and mean thermal power provided from the FCUs to the zone air within the analysed day.

HVAC system consumption according to the thermal comfort demands of the building zones. The introduction of the non-wearable battery energy storage system into the building additionally increases the building flexibility and enables additional extensions of the savings margin.

Typical temperature profiles and mean thermal power provided from the FCUs to the zone air for one exemplary building zone is presented in Fig. 3

The permissible zone temperature interval during occupancy periods is shown with black dashed lines. The deviation of the zone temperature from the reference for the price-optimal control and the case without batteries in intervals around 14:00 is a clear result of coordination where the microgrid and central HVAC level force the zones to lower the thermal energy demand in intervals in which the peak power demand occurs. For the price-optimal control and the case with batteries, the peak is already flattened in the initial microgrid iteration where in all subsequent iterations the zone level thermal energy consumption is shifted towards the intervals with more beneficial electrical energy prices and HVAC system efficiency.

In the considered case of seasonal cooling, the comfort with the baseline controller is significantly disrupted in zones in which the available thermal power is insufficient to cover the peak demand. The comfort levels calculated separately for zones oriented towards north and towards south, for cases with and without batteries, are shown in Fig. 4 and compared to the resulting thermal energy consumption of the zones considered.

The comfort level indicator is measured as the average deviation from the temperature reference. The large overheating of the south-oriented zones when using the baseline control strategy is a clear result of lacking predictive feature. In both MPC based strategies the temperature in all building zones is kept within the permissible temperature range, reducing thus the overheating by up to 56% and improving the overall comfort in all building zones by at least 57%.

The energy exchange of the battery storage system and its state of energy levels during the day are depicted in Fig. 5.

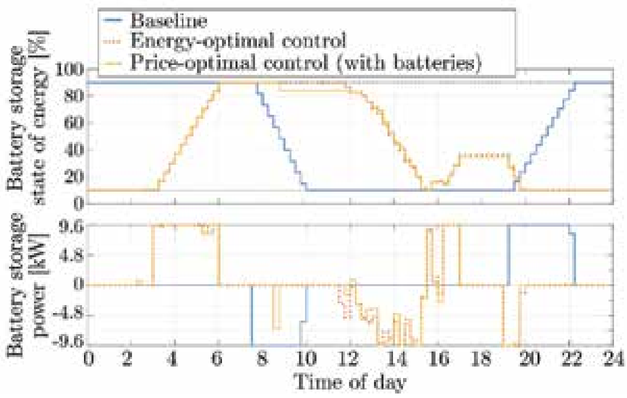

Figure 5. Battery storage state of energy and power exchange profiles.

In the MPC strategies, the batteries are charged during the lowest electricity prices in the early morning and exploited during the period 11:00-16:00 for peak power reduction. Additional savings are obtained by utilizing

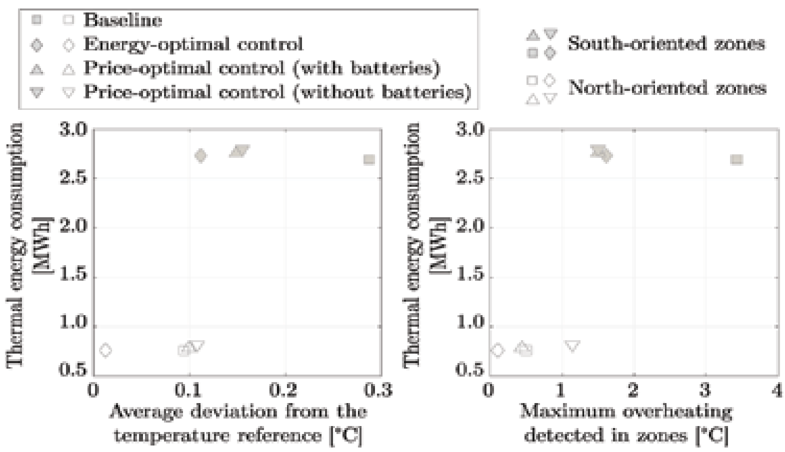

Figure 4. Comfort level indicators for different controller strategies.

the electricity price difference during the period from 16:00-20:00, when the overall building consumption is lower and a peak power reduction is not needed. Figure 5 shows that the storage system operational limits as well as operation repeatability are respected. The daily energy exchange with the distribution grid is depicted in Fig. 6.

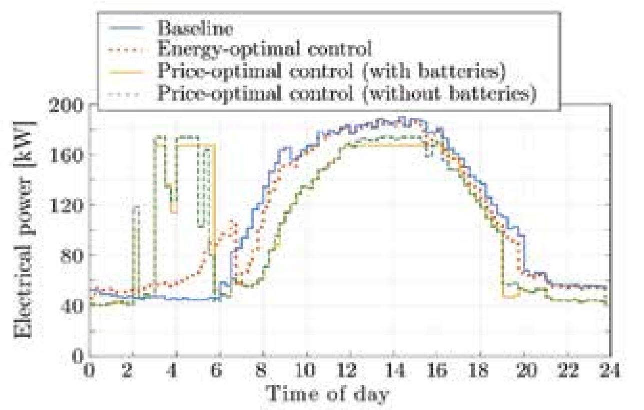

Figure 6. The overall day-ahead building energy consumption profile.

Lower electricity prices during the early morning hours from 03:00 to 06:00 are aimed to increase the overall building consumption such that the energy consumption during peak prices from 07:00 to 10:00 is decreased and the overall operation costs reduced. Additionally, the building operation costs are further reduced since the peak power consumption is decreased from 189.67 kW in the baseline scenario to 173.62 kW in the price-optimal scenario without batteries and additionally to 167.32 kW in the price-optimal scenario with batteries.

The comparison of the overall building operation costs stemming from baseline operation with the costs results obtained via energy-optimal control and price-optimal control is shown in Fig. 7.

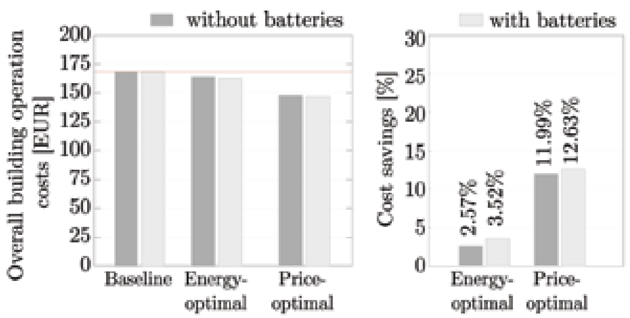

Figure 7. Comparison of overall building operation costs.

3. Conclusion

In this paper, the multi-level hierarchical model predictive control is applied to the daily operation scheduling of a full-scale skyscraper building. Coordination of the control levels of comfort in zones, heating/cooling medium preparation and building microgrid is achieved for attaining minimum building operation costs while maintaining comfort. The operation costs reductions achieved can be directly attributed to the established coordination mechanism. The results have shown that the software-based coordination between BEMS levels offers the possibility to transform the building energy consumption profile and to reduce the building peak power consumption without large financial investments in the installation of energy storage systems. The hierarchical control presented can be further extended for the provision of demand response services for energy grid entities as well as for the cooperation between buildings within energy communities.

References

[1.] F. Tahersima, J. Stoustrup, H. Rasmussen, and S. A. Meybodi. Economic COP optimization of a heat pump with hierarchical model predictive control. In 2012 51st IEEE Conference on Decision and Control, pages 7583-7588, Dec 2012.

[2.] D. Setlhaolo, S. Sichilalu, and J. Zhang. Residential load management in an energy hub with heat pump water heater. Applied Energy, 208:551-560, 2017.

[3.] F. Oldewurtel, D. Sturzenegger, G. Andersson, M. Morari, and R. S. Smith. Towards a standardized building assessment for demand response. In 2013 52nd IEEE Conference on Decision and Control, pages 7083-7088, 2013.

[4.] K. Klein, S. Herkel, H. M. Henning, and C. Felsmann. Load shifting using the heating and cooling system of an office building: Quantitative potential evaluation for different flexibility and storage options. Applied Energy, 203:917-937, 2017.

[5.] T. T. Gorecki, L. Fabietti, F. A. Qureshi, and C. N. Jones. Experimental demonstration of buildings providing frequency regulation services in the Swiss market. Energy and Buildings, 144:229-240, 2017.

[6.] M. Vašak, A. Banjac, N. Hure, H. Novak, D. Marušić, and V. Lešić. Modular hierarchical model predictive control for coordinated and holistic energy management of buildings, in IEEE Transactions on Energy Conversion (Early Access), 2021.

[7.] V. Lešić, A. Martinčević, and M. Vašak. Modular energy cost optimization for buildings with integrated microgrid. Applied Energy, 197:14-28, 2017.

[8.] F. Borrelli, A. Bemporad, and M. Morari. Geometric algorithm for multiparametric linear programming. Journal of Optimization Theory and Applications, 118(3):515-540, 2003.

[9.] EPEX SPOT. European Power Exchange Electricity Index. Available: http://www.epexspot.com.