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Research Paper

Challenges of implementing economic model predictive control strategy for buildings interacting with smart energy systems

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HIGHLIGHTS

- EMPC for buildings integrated into smart energy systems were summarized in detail.
- The challenges on how to implement EMPC in practice were investigated.
- Implementing a stationary Kalman filter to overcome the uncertainty.
- Adding soft constraints to ensure feasible solutions for optimization problems.
- EMPC outperformed the traditional PID schemes for energy saving and load shifting.

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ABSTRACT

When there is a high penetration of renewables in the energy system, it requires proactive control of large numbers of distributed demand response resources to maintain the system's reliability and improve its operational economics. This paper presents the Economic Model Predictive Control (EMPC) strategy for energy management in smart buildings, which can act as active users interacting with smart energy systems. The challenges encountered during the implementation of EMPC for active demand side management are investigated in detail in this paper. A pilot testing study shows energy savings and load shifting can be achieved by applying EMPC with weather forecast and dynamic power price signals.

1. Introduction

In Denmark as well as in many other countries, fluctuating renewable energy sources (RESs) account for an increasing share of power generation. As a leading wind power country, Denmark has achieved a record of 42% penetration of wind power in 2015, and the nation is well on its way to hitting its 2020 energy goals-50% of traditional electricity supply must come from wind power [1]. According to Danish government's energy policy, oil burners and coal must be phased out of power plants in Denmark no later than 2030. By 2050, the entire supply of energy and transportation sectors will be provided by RESs [2]. In order to ensure that the transition to a greener economy is a good investment, RESs must be intelligently integrated into the energy system.

A smart energy system is a cost-effective, sustainable and secure energy system in which renewable energy production, infrastructures and consumption are integrated and coordinated through energy services, active users and enabling technologies [3]. This integration requires more flexibility in the entire energy system, and it will challenge the existing energy (electricity, heat, transportation and gas) infrastructure and its control systems with more complicated dynamics and uncertain problems. One of the important flexibilities is distributed energy resources (DERs) located at the demand side, and these DERs need better control and management to get their values maximized.

Buildings are the largest energy consuming sector in the world, and account for over one-third of total final energy consumption and an equally important source of CO_2 emissions [4]. In the Nordic countries, buildings account for up to 40% of society's energy demand, and the energy is mainly used for heating, lighting, and electrical appliances. The thermal mass of buildings is "for free"

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and can provide a very large possibility for flexibility. Therefore, buildings play a key role in the green transition, and smart buildings can extend beyond the buildings themselves when they act as flexible components in a diverse energy system [5]. The projects presented in [6–8] are examples of buildings that hold the potential needed for energy efficiency and flexibility to be integrated in the smart energy system of tomorrow.

Model Predictive Control (MPC) is a control algorithm that optimizes a sequence of manipulated variable adjustments over a prediction horizon by utilizing a process model to optimize forecasts of process behaviour based on a linear or quadratic objective, which is subjected to equality or inequality constraints [9]. In MPC, the optimization is performed repeatedly on-line. This is the meaning of receding horizon, and the intrinsic difference between MPC and the traditional optimal control. The receding horizon optimization can effectively incorporate the uncertainties incurred by model-plant mismatch, time-varying behaviour and disturbances [10]. MPC is now recognized as a powerful approach with well-established theoretical foundations and proven capability to handle a large number of industrial control problems [11].

Recently, MPC has drawn the attention of the energy system community, because it is based on future behaviour of the system and predictions, which is appealing for systems significantly dependent on forecasting of energy demand and RES generation; moreover, it provides a feedback mechanism, which makes the system more robust against uncertainty [12–14]. The MPC strategies, that employ an economic-related objective function for real-time control, have lately proved a numerically efficient approach to managing the portfolio of energy usage with provable stability properties [15,16]. It is designated as an economic MPC (EMPC), which always copes with dynamically changing energy prices. Unlike the traditional MPC, EMPC optimizes the process operations in a time-varying manner, rather than maintain the process variables around a few desired steady states or tracking the reference. The process may thus totally operate in the transient state with EMPC [17]. EMPC for building temperature control has been investigated in several papers [18–22] that mainly with the purpose of increasing the energy efficiency in the buildings. Most of the results of the aforementioned literatures are based on the simulation study; however, the application of EMPC requires extensive knowledge in the areas of data processing, modelling, hardware and communication, state estimation, controller architecture design and optimization, which are highlighted and discussed in detail in this paper.

The remaining of this paper is organized as follows: in Section 2, the detailed EMPC strategy for smart buildings active interaction with the smart energy system is described, followed by a summary of the challenges encountered when we implement EMPC in practice. Section 3 presents how to implement EMPC in a residential building for a pilot testing. The testing results and analysis of running the EMPC controller on a test platform are discussed in Section 4. Finally, Section 5 concludes the paper and discusses the future research.

2. EMPC for active smart buildings

2.1. EMPC strategy

The EMPC is a variant of the classical MPC. It performs a dynamic economic optimization of the process with the objective of minimizing the costs [23]. In traditional tracking control, the objective is to minimize the error between a reference trajectory and the measured output. EMPC enables to define temperature bands or comfort zones realized by output constraints. The same as classical MPC, at each step, a look-ahead finite-horizon optimal control problem in EMPC is solved, but only the first step of control sequences is implemented. In addition, the hard constraints can be changed to the soft constraints to ensure feasibility in the linear optimization by adding a term to the cost function that penalizes constraint violation to obtain better controller performance. It was also proved that any stabilizable system can be asymptotically stabilized with soft constraints and state feedback [24]. The EMPC problem with soft constraints (grey coloured) can be expressed as linear program in the following form:

$$\min_{\{u_k, V_{k+1}\}_{k=0}^{N-1}} \phi = \sum_{k=0}^{N-1} c_k' u_k + \sum_{k=1}^{N} \rho V_k \tag{1a}$$

$$\text{subject to:} \quad x_{k+1} = Ax_k + Bu_k + E\omega_k \quad k = 0, 1, \ldots, (N-1) \tag{1b}$$

$$y_k = Cx_k + v_k \quad k = 1, 2, \ldots, N \tag{1c}$$

$$u_{\min} \leqslant u_k \leqslant u_{\max} \quad k = 0, 1, \ldots, (N-1) \tag{1d}$$

$$\Delta u_{\min} \leqslant \Delta u_k \leqslant \Delta u_{\max} \quad k = 0, 1, \ldots, (N-1) \tag{1e}$$

$$z_k^{\min} \leqslant y_k \leqslant z_k^{\max} \quad k = 1, 2, \ldots, N \tag{1f}$$

$$s_k^{\min} \leqslant y_k - v_k \leqslant s_k^{\max} \quad k = 1, 2, \ldots, N \tag{1g}$$

$$v_k \geqslant 0 \quad k = 1, 2, \ldots, N \tag{1h}$$

where $\boldsymbol{x_k}$ is the state vector; $\boldsymbol{u_k}$ is the manipulated input vector; $\boldsymbol{w_k}$ is the process noise; $\boldsymbol{y_k}$ is the measurement vector; $\boldsymbol{\rho}$ is the cost of breaking the constraints and $\boldsymbol{v_k}$ is the vector of slack variables.

2.2. Challenges of EMPC implementation for active smart buildings

According to the authors' experience on the implementation of EMPC, it presents considerable challenges in data analysis, modelling, hardware and communication, optimization technique and state estimation, etc. The investigations on these challenges are summarized in the following sub-sections.

2.2.1. Data availability and analytics

EMPC requires not only an appropriate model, but also a wealth of input data during operation. Active buildings installed with smart meters and advanced building systems generate significant real-time or near-real-time data on energy usage and occupancy. The expansion of data including forecast data (weather, load, and energy price) presents great opportunities to improve building energy management practices, but the data collected is valuable only if it is analysed consistently and communicated effectively to both building decision-makers and distribution system operators (DSOs). For example, currently, the available time interval of the day-ahead Elspot electricity price signals from Nordpool market [25] is hourly-based; while the available weather forecast data are in 10–15 min interval.

For the building data management, it is important to focus on the data worth collecting, the analysis worth sharing, and analytical tools for the coordination control on DERs. This is a time-consume and important preparation for the modelling and EMPC controller design.

2.2.2. Modelling

When large measurement data sets are available, a purely statistical approach for creation of a building model is preferred. EMPC inherently requires an appropriate model of the controlled plant, which is then used for the computation of the optimal control inputs. The relevant dynamic behaviour of the buildings for the active demand side management (ADSM) control tasks can be

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