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Real-time electricity pricing: TOU-MPC based energy management for commercial buildings

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Abstract

An adaptive real-time electricity pricing and optimal control system based on energy management of buildings is presented. This is made in the framework of a smart-grid according to energy demand and time-of-use (TOU) electricity tariff in conjunction with a model predictive control (MPC). The developed model is considered as a multiple single input single output MPC system that acts at a different rate of TOU- electricity tariffs (off-peak, standard and peak). A smart selective timer switching system links one to the other. The performance of the model design is expressed through the simulation results of the adaptive TOU-MPC for commercial buildings.

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*Keywords:*Commercial buildings, Energy management, Model predictive control, Real-time electricity pricing, Time-of-use tariff.

1. Introduction

The need for reducing the peak of energy consumption on the demand side is currently a concern of several countries [1]. However, the South African Energy Department states that the energy wastage of today is the shortage of tomorrow. They also argue that saving energy is in the ambit of any end user. In the U.S, The National Energy Technology Laboratory demonstrated that the flexibility of energy consumption in buildings is a function of smart grid infrastructure, operation strategies and building energy control [2]. Smart grid technology therefore offers the opportunity to the utility and the end-users to design a real-time optimum system [3]. On the demand side, this is essential firstly for the stability of power supply and secondly for reducing the cost of energy consumption [4].

A smart grid establishes the power quality requirement, without any disturbance of voltage, as its principal tool of stability analysis. Furthermore, optimization techniques are also considered as of one the

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fundamental computational tools for the design of a smart grid [3]. Relatively few works have been developed in context of optimizing the electricity consumption of specified load in commercial buildings [4-8]. This research therefore works on developing an adaptive design of minimizing the cost of electricity consumption according to the inner system design of a commercial building. This is based on shifting the MPCs system design in conjunction with TOU electricity tariff. This is also made by using a timer switching to adapt the MPC-model to the real-time electricity tariff.

The outline of this paper is as follows: the system modeling and design of shifting the MPCs system is proposed in section 2 and section 3 presents the MPC system. The simulation results are depicted in section 4 and section 5 draws the conclusion and recommendations.

2. System modelling and design

2.1. System description

Fig. 1 describes the model of the system. For this, the modeling for a demand management system is considered to be the benchmark for analyzing the inner system behavior. Many frameworks are used as a system model, and any given system can be analyzed according to the purposes envisaged [9]. It is assumed that this system will adapt to any rate of change due to TOU electricity tariffs. Therefore, the developed model given in Fig.1 can be considered as a multiple single input single output MPC system that acts at the different rate of TOU-tariffs (off-peak, standard and peak).

The smart meter of this system operates within the interaction of the optimal control system and the demand side. It also communicates the real-time energy demand of the adaptive MPC system with the demand side. The cost the electricity usage will depend on the energy consumption and the real-time electricity tariffs is defined as:

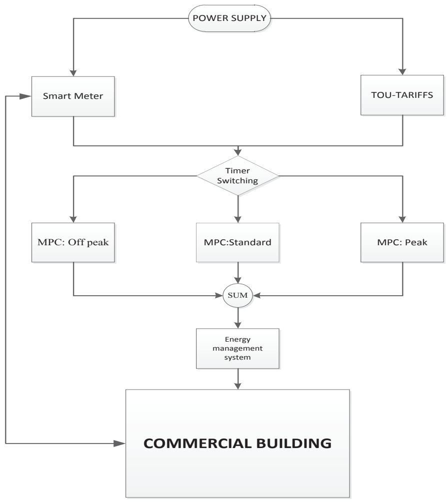

Fig.1. Adaptive TOU-MPC energy management system

$$C(t) = \int_0^t P_{TOU}\, E(t)dt \tag{1}$$

where C is the cost of electricity to pay [Rand], E the energy consumption [kWh] and P_{TOU} is TOU-Tariffs [kWh/Rand].

2.2. System design

It is supposed that the input of given system in Fig. 1 is the increment of the energy demand. The equation (1) therefore can be described by using the Euler back forward developed in [10]. This is expressed as a discrete single input and single output state space system as:

$$\begin{cases} c(k+1) = Ac(k) + Be(k) \\ y(k) = Cc(k) \end{cases} \tag{2}$$

where $A = 1$; $B = P_{TOU}$ and $C = 1$. The matrices A, B and C can be augmented to define eq. (2) as the function of input increment. The equation (3) defined the augmented system for the robustness of the MPC design [11] as follows:

$$\begin{cases} c(k+1) = A_p c(k) + B_p \Delta e(k) \\ y(k) = C_p c(k) \end{cases} \tag{3}$$

where $A_p = [A\ O;\ C^*A\ 1]$, $B_p = [B;\ C^*B]$, and $C = [O\ 1]$.

3. MPC design

By considering the augmented state space system developed in (3), the adaptive MPC can be computed in each rate of TOU electricity tariffs by using the MPC gain developed in [11]. The objective of this study is to find the minimum cost of electricity to pay. The performance index of the MPC design is computed as a quadratic problem that has to find the minimum input increment. The objective is to minimize the cost of energy supplied by the utility. This optimum cost is defined as a function of the given reference R by the consumer, which is attached by a turning parameter r_w. The performance index is therefore described as:

$$J(k) = \left(Y(k) - r_w R(k)\right)^T \left(Y(k) - r_w R(k)\right) \tag{4}$$

The optimum cost of electricity to pay can then be computed as:

$$Y(k) = FC(k) + \Phi \Delta E(k) \tag{5}$$

where $C(k) = \left[c^T(k), c^T(k+1|k), \ldots, c^T(k+N_P-1|k)\right]^T$,

$\Delta E(k) = \left[\Delta e^T(k), \Delta e^T(k+1|k), \ldots, \Delta e^T(k+N_P-1|k)\right]^T$, and

$$F(k) = \begin{bmatrix} C_p A_p \\ C_p A_p^{\,2} \\ \vdots \\ C_p A_p^{\,N_P} \end{bmatrix}, \quad \Phi(k) = \begin{bmatrix} C_p B_p & 0 & \cdots & 0 \\ C_p A_p B_p & C_p B_p & & 0 \\ \vdots & & \ddots & \vdots \\ C_p A_p^{\,N_P-1} B_p & C_p A_p^{\,N_P-2} B_p & \cdots & C_p A_p^{\,N_P-N_c} B_p \end{bmatrix}.$$

It is important to notice that the matrix $F(k)$ and $\Phi(k)$ are determined by the MPC gain described in [11]. Thereafter, by substituting (5) in (4), the performance index can be described as follows:

$$\min J(k) = \min(\frac{1}{2} dE(k)^T G(k) dE(k) + H(k) dE(k)) \tag{6}$$

where $G(k) = \Phi(k)^T \Phi(k)$, and $H(k) = (Fc(k) - r_w R(k))^T \Phi$.

3.1 System constraint

The quadratic relation described in (6) is fully constrained, and each signal constraint is stepped as follows:

1. The increment of control signal is constrained by the relation as follows

$$M_1 = \begin{bmatrix} -I & , I \end{bmatrix}^T ; \gamma_1 = \begin{bmatrix} (-\Delta E^{\min}) & , (\Delta E^{\max}) \end{bmatrix}^T \tag{7}$$

where I is an identity diagonal matrix, ΔE^{min} and ΔE^{max} are the minimum and maximum increments of control signal.

2. The manipulated variable constraint is defined by the knowledge of the system's minimum and maximum input. The control system of plant is imposed as follows:

$$\begin{aligned} M_2 &= \begin{bmatrix} -U_2 , U_2 \end{bmatrix}^T ; \\ \gamma_2 &= \begin{bmatrix} (-E^{\min} + U_1 e(k_i - 1)) & , (E^{\max} - U_1 e(k_i - 1)) \end{bmatrix}^T \end{aligned} \tag{8}$$

where U_1 and U_2 are respectively the identity vector and lower triangular vector in which all elements are one.

3. The output constraint is derived from (5), and this can be described as follows:

$$\begin{aligned} M_3 &= \begin{bmatrix} -\Phi & , \Phi \end{bmatrix}^T ; \\ \gamma_3 &= \begin{bmatrix} (-Y^{\min} + Fc(k_i)) & , (Y^{\max} - Fc(k_i)) \end{bmatrix}^T \end{aligned} \tag{9}$$

From (7) to (9) the fully imposed MPC constraint system will combine as described in (10) [9, 11]. This is an inequality system matrix where the dimension is defined by the number of imposed constraints and the dimension of system input. The MPC system constraint is defined as:

$$ME(k) \le \gamma \tag{10}$$

4. Simulations Results and Discussions

The results of the designed system are computed over a day. The control horizon and the output horizon are 24 hours imposed to satisfy the system constraints. The daily profile of the input of the system is given as follows: 0h00 to 2h00: 15kWh, from 02h00 to 08h00:20kWh, from 08h00 to 16h00: 80kWh, from 16h00 to 21h00: 60kWh, from 21h00 to 24h00: 20kWh. The TOU electricity tariff is considered to be at the values of 0.6150 for off-peak mode which is from 0h00 to 6h00 and from 21h00 to 24h00; 1.073 for standard node from 6h00 to 7h00 and from 10h00 to 18h00; 4.115 for peak mode time from 07h00 to 10h00 and from 18h00 to 21h00 [12]. One hour is used as a sampling period. The system constraints are computed by using the profile of energy listed above to compute the input and the increment constraint. The output constraint is computed by using the equation (1) with the input constraints.

It is observed that the minimum cost of electricity to pay satisfied the system constraints and adapted the behavior of each computation design. This computation of switching the MPC design is mostly affected by reference turning parameters r_w that play an important role in terms of satisfying the objectified function. Fig. 2 shows the computation of different modes, and it is observed that each system design is robust and optimum according to the objectified function to follow. Fig. 3, depicts that the optimum cost of electricity to pay is at a minimum and below the average of electricity costs (reference) without an adaptive MPC design. The value of the cost of energy that this system can gain at the optimum points is about 60.5 percent of the normal cost to pay. This is a computational adaptive system of the results shown in Fig. 2. It is important to notice that the choice of turning parameter r_w depends on the optimum cost of electricity to pay at each mode for an optimum computation analysis. The values of r_w for an optimum computation are 1 for off-peak, 1 and 10 for standard and 1.0526 and 1.126 for the peak.

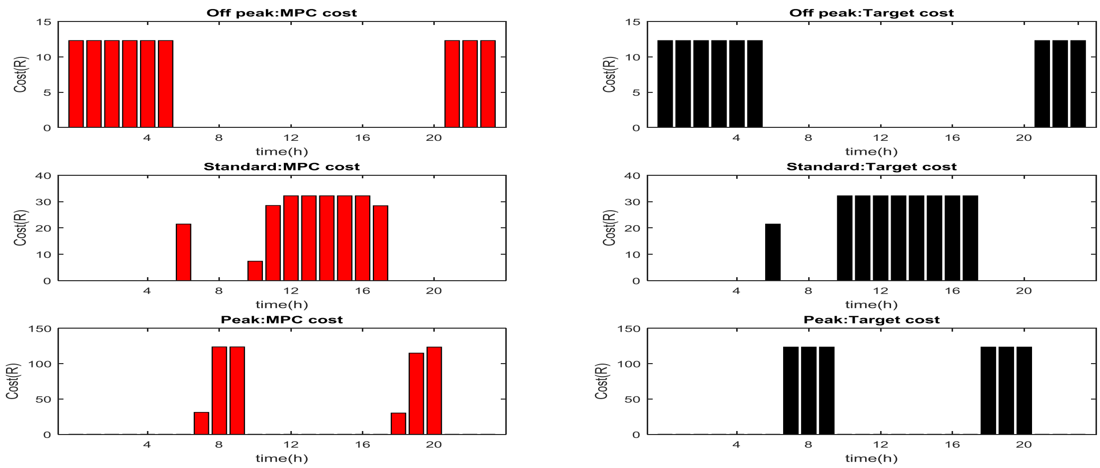

Fig. 2. Opimum cost of electricty to pay and target costing during the modelling of the electricity tariff.

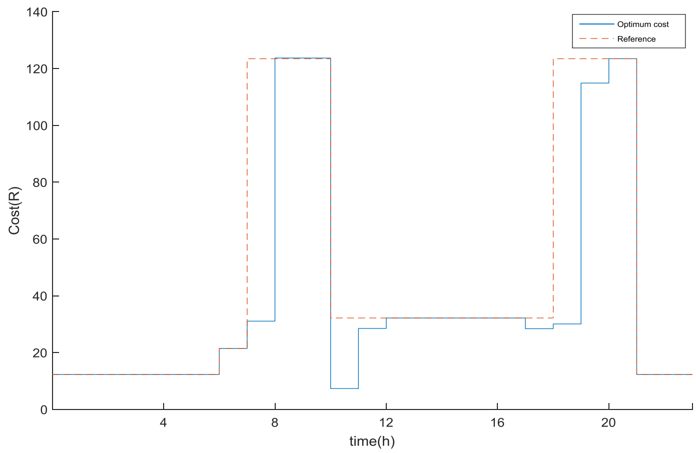

Fig. 3 Daily TOU-MPC cost of electricity vs target of electricity cost.

5. Conclusion

An optimal adaptive model of minimizing the cost of electricity for commercial building is proposed. This is made in conjunction with a smart grid to include real-time electricity pricing and an energy management system in the framework of a model predictive control. It has been found that the model is robust enough to handle a system full of constraints, and the reference turning parameter has a huge effect on the optimal cost electricity to pay. It has also been observed that the model can be controlled easily by the end-users and can give them the opportunity to decide on the amount of money they want to pay for the electricity. Therefore, a future work can be seen which would integrate renewable energy resources with this to ensure a total and optimum power supply.

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Biography

Prof. Ramesh Bansal has 25 years of experience and currently he is Professor and group-head (Power) in EEC Department at University of Pretoria. He has published over 250 papers. He is Editor-IET-RPG & ECPS. He is Fellow and CEngg IET-UK, Fellow Engineers Australia and Institution of Engineers (India) and Senior Member-IEEE.