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Peak power demand reduction for combined manufacturing and HVAC system considering heat transfer characteristics

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ABSTRACT

The industrial sector is one of the main drivers in the continuously rising electricity demand in the United States. Electricity Demand Response is an effective demand side management tool for reducing power demand especially during peak periods. However, according to the Energy Information Administration (EIA), the actual peak load reduction by the industrial sector is much lower than its potential target. Within a typical industrial manufacturing plant, the two main energy consumers are the manufacturing system and the heating ventilation and air conditioning (HVAC) system. In this paper, we introduce a method to reduce the power demand during peak periods using an HVAC working load model that considers manufacturing heat sources. The effect of the manufacturing operation on the indoor temperature and the HVAC working load is quantified by considering the heat transfer characteristics of the machines in the manufacturing system. A mathematical model is formulated using mixed integer nonlinear programming (MINLP) and solved using General Algebraic Modeling (GAMS). An optimal schedule for the manufacturing operation and control scheme for the HVAC temperature set-points that can minimize the power demand during peak periods under the constraint of production target is identified. A numerical case study is used to illustrate the effectiveness of the proposed method.

1. Introduction

It has been reported that the "peak-to-average" ratio, the ratio that describes the difference between peak power demand and average power demand throughout the electricity grid, has been rising consistently in much of the country in the past decades (Kennedy, 2014). For example, Fig. 1 shows the increase of the "peak-to-average" ratio in New England over the past 20 years, where in 2012 the "peak-to-average" ratio is 78% higher than the average value of such ratios from 1993 to 2012.

A high "peak-to-average" ratio for the electricity grid implies a large range of fluctuation in the daily electricity demand. This can influence everything from electricity cost to energy availability. As explained by the Energy Information Administration (EIA), this higher ratio translates into decreasing average utilization levels for generators deployed in the grid. Electric systems need to maintain sufficient capacity to meet expected peak loads plus a reserve margin. Therefore, more capacity needs to be created to satisfy this increasing trend. It has been estimated that a $2 trillion investment is needed for the construction of new electricity generation capacity and distribution and transmission systems (Chupka et al., 2008).

To reduce this tremendous cost, electricity demand response has been proposed as an effective tool to balance the electricity demand between peak periods and regular periods. Electricity demand response is defined by the Federal Energy Regulatory Commission (FERC) as "the changes in electricity usage by end-use customers from their normal consumption patterns in response to the changes in the price of electricity over time or the incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" (FERC, 2010). It consists of several types of programs that encourage consumers to shift or reduce their power consumption during peak hours to achieve more economic and environmentally responsible usage patterns.

The benefits through the implementation of electricity demand response have been widely studied. It has been reported that a 5% reduction of peak power in the United States can lead to the elimination of the operation of 625 peaking power plants, which can be translated into an annual savings of $3 billion (Faruqui

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Notation list

BU_{ij}	the buffer contents in buffer i at the beginning of interval j
C_i	the capacity of buffer i
c_i	the convection fraction of machine i
C_p	the heat capacity (kW h/kg C) of the building
CQ	the heat transferred from the manufacturing operation during interval j
CQ_{Cj}	the instantaneous convective heat transferred from the manufacturing operation in interval j
CQ_{Rj}	the radiant heat transferred from the manufacturing operation up to the current interval j
CQ^*	the required HVAC load during interval j
EFF_i	the production efficiency of machine i
GQ_j	the heat generated due to manufacturing operation in interval j
H	the duration of the time interval
i	the index of the machines in the manufacturing system
j	the index of the slotted time intervals
k	the index of the radiant time series
M	total number of the time intervals in the planning horizon
N	the total number of the machines in the manufacturing system
OP	the set of intervals that belong to peak periods
P_i	the rated power of machine i
PR_i	the production rate of machine i (unit per interval)
Q_j	The heat that needs to be added or removed when taking into account all of heat sources influencing the indoor temperature except for the manufacturing operation during interval j
s_k	the radiant time series coefficients
TP	the production throughput of the manufacturing system throughout the planning horizon
TP^*	the production target of the planning horizon
T_j	the forecasted temperature of the building (when HVAC is neglected) considering all heat sources except for the manufacturing operation
$T_{\max}$	upper bound of acceptable indoor temperature
$T_{\min}$	lower bound of acceptable indoor temperature
V	the volume of the building (m^3)
w_j	the coefficient of performance (COP) of the HVAC
x_{ij}	binary decision variable to denote the ON/OFF decision for machine i in interval j
y_j	decision variable for the HVAC temperature setpoint in interval j
Z_j^1	binary variable reflecting the heating state of the HVAC system
Z_j^2	binary variable reflecting the cooling state of the HVAC system
α	conversion factor that converts a unit of temperature to the unit of heat in the building
ρ	the density of air (kg/m^3)
ΔT_j	the temperature difference between T_j and the temperature setpoint
η_i	the motor efficiency of machine i

et al., 2007). In addition, the incurred energy saving in kW h due to the reduction of peak power demand in kW has also been reported. It is estimated that a 1 kW reduction of power demand during peak periods can lead to a 65 kW h reduction of electricity consumption (Siddiqui, 2008).

The studies of electricity demand response are conducted from two different perspectives, i.e., electricity supplier and electricity consumers. From the perspective of electricity supplier, the research is mainly focused on the program design and policy investigation (Yang et al., 2013; Greening, 2010), electricity market restructuring (McGovern and Hicks, 2004; Lindblom and Andersson, 1998), electricity price identification (Doostizadeh and Ghasemi, 2012; Faria et al., 2011), etc. From the electricity consumer side, many studies have been conducted on electricity demand response in commercial and residential sectors (Bel et al., 2009; Alcázar-Ortega et al., 2011; Yin et al., 2010; Lujano-Rojas et al., 2012). However, the research in the industrial sector is considered less developed compared to the progress in commercial and residential sectors (Li et al., 2012), which leads to the fact that the state-of-the-art of peak load reduction in the industrial sector is much lower than the corresponding potential value as shown in Fig. 2 (EIA, 2014).

Recently, with the deepening understanding that the industrial sector is one of the main drivers in the continuously rising electricity peak demand in the United States (Wang and Li, 2014; EIA, 2011a, 2011b), the research on electricity demand response in the industrial manufacturing sector has gradually attracted attention from both industry and academia. In a typical manufacturing facility, the top two energy consumers are the manufacturing system and the heating, ventilation, and air-conditioning (HVAC) system. In such facilities, the energy consumption related to manufacturing processes and equipment is the largest contributor; and the

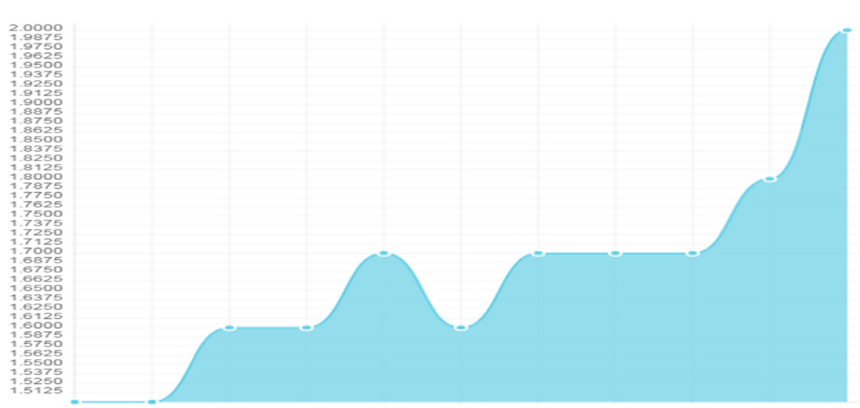

Fig. 1. New England peak-to-average demand ratio.
Source: http://www.yourenergyblog.com/peak-to-average-electricity-demand-ratio-climbing-across-the-u-s/.