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Development and validation of an intelligent load control algorithm

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ABSTRACT

The renewable generation technologies form a significant (>20%) fraction of grid capacity, however their generation capabilities remain variable in nature. Therefore, utilities will be forced to maintain a significant standby capacity to mitigate the imbalance between supply and demand. Because more than 75% of electricity consumption occurs in buildings, building loads can be used to mitigate some of the imbalance. This paper describes the development and validation of an intelligent load control (ILC) algorithm that can be used to manage loads in a building or group of buildings using both quantitative and qualitative criteria. ILC uses an analytic hierarchy process to prioritize the loads for curtailment. The ILC process was developed and tested in a simulation environment to control a group of rooftop units (RTUs) to manage a building's peak demand while still keeping zone temperatures within acceptable deviations. The ILC algorithm can be implemented at a low cost on a supervisory controller without the need for additional sensing. By anticipating future demand, the process can be extended to add advanced control features such as precooling and preheating to alleviate comfort when operation of the RTUs is curtailed to manage the peak demand.

1. Introduction

To mitigate the impacts of climate change, there is a significant impetus to make generation of electricity in the United States cleaner by installing rooftop solar photovoltaic (PV) and utility-scale wind generation systems. Although these renewable generation technologies are cleaner, their electric generation is variable in nature. These technologies form a significant (>20%) fraction of the grid capacity, so utilities will be forced to maintain a significant standby capacity to mitigate the imbalances between supply and demand. This traditional approach of balancing power is cost-effective when the utilities only had to maintain between 5% and 10% of the capacity. An alternate approach to mitigating this imbalance is to manage the load (demand side). Because more than 75% of electricity consumption occurs in buildings, building loads can be used to mitigate some of the imbalance.

The control of building end-use loads has been shown to provide significant demand relief in response to utility requests [11]. In addition, building loads have been used to limit the electric demand when a demand charge is a significant percentage of the total energy cost or when a building has to maintain a certain level of maximum demand in response to changes in the price of electricity over time. However, an accurate and reliable load control strategy is required to manage peak loads because even one excursion could cause a significant increase in utility bills.

The duty-cycling control strategy has been traditionally used to manage peak demand by controlling the ratio of the on-period to the total cycle time of rooftop units (RTUs) or air-handling units [9]. Two traditional duty-cycling strategies exist for operating building RTUs [14]: (1) a parallel duty-cycling approach, in which all RTUs are cycled ON or OFF at the same time; and (2) a staggered duty-cycling approach, in which the RTU ON and OFF cycles are staggered. For example, in case of the staggered duty-cycling only some (e.g., 1/3 or 2/3) of the RTUs operate at any given time. Although both duty-cycling methods provide relief from electric demand, neither dynamically prioritizes the RTUs to be curtailed to manage peak electricity consumption. It is generally difficult to identify the RTUs that can be curtailed without affecting zone comfort, and indiscriminate curtailment of RTUs can lead to comfort issues by negatively affecting the zone temperature and humidity conditions. Therefore, a load control strategy is needed that anticipates the future effects of thermal comfort and peak load relief based on current conditions and past historical data.

This paper describes the development and validation of one such intelligent load control (ILC) algorithm that can be used to manage load while also considering occupant comfort. The ILC can dynamically prioritize the available loads for curtailment using

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Nomenclature

A	Judgment matrix
A_{normal}	Normalized criteria judgment matrix
A_p	Principal eigenvector
a_{ij}	Entry of criteria judgment matrix
AHP	Analytic hierarchy process
B	Normalized alternative decision matrix
B	Entry of alternative decision matrix
C	Decision priority vector
C	Entry of decision priority vector
CR	Consistency ratio
Cooling	Cooling mode
$C.I.$	Consistency index
$C_{z,eff}$	Effective zone thermal capacitance
Heating	Heating mode
n_{rtu}	Number of times the RTU has been curtailed
P_{rated}	Rated RTU power consumption
P_{peak}	Target electric power consumption
$Power_{rtu}$	RTU power consumption
$Power_{bd}$	Whole building electric power consumption
Q_b	Rate of instantaneous heat gain to the building air
Q_c	Sensible cooling load
RI	Random index of consistency
$Room_{rtu}$	Room priority
$RTUs$	Rooftop units
$s(t)$	Binary signal
T	Fixed-length time period
T_{csp}	Cooling set point temperature
T_{hsp}	Heating set point temperature
T_{zone}	Zone temperature
ΔT_{zone_csp}	Temperature difference between zone and cooling set point
ΔT_{zone_hsp}	Temperature difference between zone and heating set point
ΔT_{zone_δ}	Zone temperature difference
T	Current time
$t\text{-}\delta$	Previous sampling time
Δt	Sampling period
V	Raw summation of alternative judgment matrix
v_i	Element of raw summation of alternative judgment matrix
W	Column summation of criteria judgment matrix
w_i	Element of column summation of criteria judgment matrix

Subscripts

I	Raw element of matrix
J	Column element of matrix
n	Raw number of matrix
m	Column number of matrix
T	Last reading
$t\text{-}\delta$	Previous reading

Greek

δ	Sampling period
λ	Eigenvalue
λ_{max}	Maximum eigenvalue
$\vec{v}$	Eigenvector

both quantitative (deviation of zone conditions from set point) and qualitative rules (type of zone) in a building or multiple buildings (a campus). ILC uses the analytic hierarchy process (AHP) to prioritize loads for curtailment.

The AHP is a structured technique for organizing and analyzing complex decisions based on mathematics and psychology [13]. The process can generate a numerical score to establish the prioritization of each alternative being considered based on associated decision criteria. The AHP is applicable when it is difficult to formulate goal or quantitative criteria for evaluation. The AHP also allows for the use of qualitative as well as quantitative criteria to solve complex decision-making problem [3]. It decomposes the problems into a hierarchy of elements influencing a system by incorporating three levels: the objectives, criteria, and alternatives of a decision. The process has the ability prioritize a set of criteria used to rank the alternatives of a decision and distinguish, in general, the more important factors from the less important factors. Pair-wise comparison judgments are made with respect to the attributes of one level of hierarchy given the attribute of the next higher level of hierarchy from the main criteria to the sub-criteria [4]. AHP can also solicit consistent subjective expert judgment by using a consistency test. Triantaphyllou and Stuart [15] applied the AHP method for solving complex multi-criteria decision-making problems in a matrix structure.

The AHP method has been used for demand response control in the power sector. Ding et al. [5] proposed a dynamic load-shedding scheme of electric power systems based on the AHP decision-making process. According to Aalami et al. [1], the AHP can be used to deal with multiple market operational problems such as price spikes, insufficient spinning reserve margin, and system security and reliability. Goh and Kok [6] discussed the AHP applied to similar dynamic load-shedding operational problems for the electrical power system. They prioritized dynamic loads according to their importance by using criteria determined from previous experiences and case studies.

Only a few studies have been related to use of the AHP in building applications. Yao et al. [16] applied the AHP to integrate the advantages of four forecasting models of cooling loads and improved accuracies. In that case, the AHP was employed to determine the optimal weights of each model. The proposed approach was shown to significantly improve cooling load forecasting by using pair-wise judgments between models with periodically updated weights. The research conducted by Wong and Li [17] proposed a multi-criteria decision-making model using AHP to evaluate the selection of intelligent building (IB) systems. They identified key selection criteria for IB systems based on a survey of IB practitioners. The AHP was applied to prioritize and assign important weights to the perceived criteria in the survey. The results suggest that the IB system was determined by a disparate set of selection criteria that had different weightings. *Work efficiency* is perceived to be the most important core selection criterion for various IB systems; *user comfort*, *safety*, and *cost effectiveness* are also considered significant. Brian et al. [2] introduced an expert-based demand curtailment allocation approach using the AHP, which allowed an electric utility to prioritize the load curtailment for each of its distribution substations using loading levels, capacity, customer types, and load categories. The AHP was used to model a decision-making process according to opinions from experts and objective parameters. Simulation case studies were performed to show the demand curtailment allocations among different distribution substations.

This paper describes a load control strategy based on a dynamic prioritization of a list of curtailable loads (e.g., RTUs) that is updated frequently. The ILC based on the AHP is evaluated and validated using a simulation model of a small commercial building that employs four RTUs. Simulation studies are performed to demonstrate how the ILC can be implemented to manage peak energy consumption. Simulation results show that ILC is capable of reducing peak demand without significantly reducing occupant comfort. Overall, the ILC allows coordination of the RTU operations and