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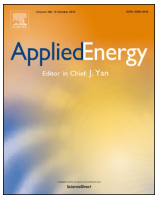

Flexible operation of active distribution network using integrated smart buildings with heating, ventilation and air-conditioning systems

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HIGHLIGHTS

- A prediction model of building energy consumption with different zones and different orientations is developed.
- Different optimal control methods of the Heating, Ventilation and Air-Conditioning system in a building are developed.
- A combined optimization method for active distribution network with smart buildings integrated is proposed.
- The piecewise linearization and second-order cone relaxation method is used to solve the combined optimization problem.

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Activedistribution network
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ABSTRACT

Aiming to utilize the flexibility of smart buildings for flexible operation of active distribution network, a combined modeling and optimal scheduling method for the active distribution network with integrated smart buildings is proposed in this paper. Based on the heat storage characteristics of a building, the energy consumption prediction model of the building considering different heating zones with different orientations is developed using the Resistor-Capacitor thermal network model. Then, different optimal control methods of the heating, ventilation and air-conditioning system in the building are developed. The energy consumption management of the heating, ventilation and air-conditioning system is achieved by adjusting the room temperature within the suitable temperature comfort range. In order to further consider the impact of the integration of smart buildings on the economic and security operation of the active distribution network, the optimal scheduling method of the active distribution network with integrated smart buildings is developed considering the load factor of the aggregation of the smart buildings. Finally, the optimal scheduling results of the aggregation of the smart buildings under different heating, ventilation and air-conditioning control methods in the winter heating scenario are analyzed. In addition, based on the branch flow model, the optimal power flow model of active distribution network with on-load tap changer is constructed by piecewise linearization and second-order cone relaxation to achieve flexible and optimal operation of the active distribution network. Thus, the impacts of the optimal schedules of the aggregation of smart buildings on the economic and security operation of the active distribution network are further evaluated. Numerical studies demonstrate that the proposed optimal scheduling method can make full use of the demand response potential of the smart buildings and further contribute to the operating costs reduction of the smart buildings. Meanwhile, the optimization of the active distribution network with the load factor of the aggregation of buildings can reduce the power loss and increase the minimum voltage magnitude of the active distribution network utilizing the flexibility of the smart buildings.

1. Introduction

Increasing attention is being paid to technologies in energy efficiency improvement due to the rapid growth of global energy usage and environmental deterioration [1,2]. According to the Buildings Energy Data Book, buildings' share of the worldwide energy usage is almost 40% [3], with approximately half of it being used in their Heating, Ventilation and Air-Conditioning (HVAC) systems [4]. With the continuous improvement of the urbanization level around the world and the adjustment of industrial structure, such proportion is growing continually.

Due to the thermal inertia of buildings, the indoor temperature can

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Nomenclature

Abbreviations

ADN	Active Distribution Network
BEMS	Building Energy Management System
B2G	Building-to-grid
DSO	Distribution System Operation
HVAC	Heating, Ventilation and Air-Conditioning
OLTC	On-Load Tap Changer
RC	Resistor-Capacitor
SOC	Second-Order Cone

Parameters

$\alpha_{i,j}$	absorption coefficient of the wall between room *i* & *j*
$A_{i,j}^{w}$	the area of wall between room *i*th & room *j*th (m^2)
$A_{i,j}^{win}$	the total area of window between room *i*th & room *j*th (m^2)
c_p	specific heat capacity of indoor air [J/(kg °C)]
COP	coefficient of performance.
$C_{i,j}^{w}$	heat capacity of wall between room *i* & *j* (J/K)
C_i^r	heat capacity of the *i*th room (J/K)
$\underline{\varepsilon}_t$	lower slack variables vector.
$\bar{\varepsilon}_t$	upper slack variables vector.
$\dot{m}_i^r$	air mass flow rate into or out to the room *i* (kg/s)
$N_{i,j}^{w}$	the set of all neighboring nodes to the wall between room *i* & *j*
N_i^r	the set of all nodes surrounding room *i*
$\pi_{i,j}$	window identifier
P_t^h	power consumption of the heating system (W)
P_t^f	power consumption of the air supply system (W)
$P_t^H VAC$	the power consumption of the HVAC system (W)
$\dot{Q}_i^{\text{int}}$	internal heat generation in *i*th room (W)
Q_i^{rad}	radiative heat flux density on the window (W/m^2)
$Q_{i,j}^{rad}$	radiative heat flux density on the wall (W/m^2)
$r_{i,j}$	sunlit wall identifier.
$R_{i,j}^{w}$	thermal resistance between the centerline of wall and the side of the wall (K/W)
$R_{i,j}^{win}$	thermal resistance of window between room *i* & *j* (K/W)
T_i^r	temperature of *i*th room (°C)
T_i^s	supply air temperature of the ith room (°C)
T_j	temperature of *j*th node (°C)
$T_{i,j}^{w}$	temperature of the wall (°C)
$\overline{T}$	upper limits of indoor temperature set-points of the building (°C)
$\underline{T}$	lower limits of indoor temperature set-points of the building (°C)
u_t	vector of control inputs
$\underline{u}$	minimum value for control input
$\bar{u}$	maximum value for control input
$\delta\underline{u}$	lower limit on rate of change of control input
$\delta\bar{u}$	upper limit on rate of change of control input
V_m	the voltages of node *m* (p.u.)
v_m	the square of the voltage amplitude of the node *m* (p.u.)
I_{mn}	the current of the line *mn* (p.u.)
l_{mn}	the square of the current amplitude of the line *mn* (p.u.)
S_{mn}	the apparent power of the node *m* side (p.u.)
k_O	standard ratio of OLTC
k_{mn}	the ratio of OLTC in branch *mn*
Δk_{mn}	adjusting step length of OLTC in the branch *mn*
K_{mn}	the position of OLTC.
K_{mn}^{min}	the lower limit of the position of OLTC in branch *mn*
K_{mn}^{max}	the upper limit of the position of OLTC in branch *mn*
P^{Loss}	the total loss of distribution network (kW)
LF	load factor
P_{avg}	the average load of the system (kW)
P_{∞}	the peak load of the system (kW)
$w_{mn,i,j}$	continuous variable
$d_{mn,j}$	0–1 variable
Ω^T	the real time electricity price ($/MWh)
η_{fan}	the fan coefficients in the air supply equipment
η_{motor}	the motor coefficients in the air supply equipment
ΔP_{tot}	the pressure drop in the air supply equipment (Pa)
$PB\ t$	the power consumption of buildings (kW)
I^{HVAC}	the total energy consumption of HVAC system (kJ)
I^e	the total energy consumption of buildings (kJ)
V_m^{min}	minimum value for the voltages of node *m* (p.u.)
V_m^{max}	maximum value for the voltages of node *m* (p.u.)
P_{mn}	the active power of the node *m* side (kW)
Q_{mn}	the reactive power of the node *m* side (kW)
$P_{in,n}$	the injected active power of node *n* (kW)
$Q_{in,n}$	the injected reactive power of node *n* (kW)
N_{loop}	the number of ring nets
N_{br}	the total number of operable switches in the distribution network
$N_{e\text{-}bus}$	the number of distribution network nodes
P_{min}^{Loss}	minimum value for total loss of distribution network (kW)
P_{max}^{Loss}	maximum value for total loss of distribution network (kW)
κ	penalty factor ($/°C)
z_{mn}	the impedance of the line *mn* (Ω)

be controlled in a suitable zone [5]. In this case, the heating/cooling load can be adjusted according to the electricity price under the premise of ensuring the indoor temperature in the users' comfort zone. Hence in principle, the buildings as loads have the potential to become an important source for flexible operations of the system [6], and it is expected that flexible demand can play an integral role in efficient decarbonizing the modern power system.

By tapping the demand response potential of the building load, the operating costs of the building can be reduced as well. In addition, a large number of buildings connected to the distribution network can easily lead to the increasing of the difference between peak and valley load of electric power system, the voltage quality degradation of distribution network and so on [7]. Utilizing the combination of flexible load of buildings and the operation of distribution network to schedule the energy utilizations of the network and the buildings in an optimal way can achieve the goals of further improving the economy and reliability of distribution network operation, reducing user's electricity consumption and realizing energy saving and emission reduction of the grid [8].

The multiple benefits and opportunities of combined optimization of active distribution network (ADN) and smart buildings have been emphasized by the U.S. Department of Energy [9,10]: (1) Buildings can consume and preserve large amount of energy; (2) the resources of grid can be more efficiently utilized, as peak demand is curbed; (3) the grid can become more stable with fewer frequency excursions; (4) the need for large-scale power generation and transmission investments is deferred; (5) through the building-to-grid (B2G) integration platform, distributed energy resources (such as photovoltaic units and electric vehicles) at the buildings' premises can be integrated with the power grid more efficiently, turning into significant assets.

Studies have been carried out to investigate the optimization of ADN and smart buildings. In [11], the energy optimization strategy based on demand response is analyzed deeply from the perspective of demand response framework, characteristics, algorithm flow chart and