Applied Energy 231 (2018) 456–467

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Coordination optimization of multiple thermostatically controlled load groups in distribution network with renewable energy

Congying Wei, Jian Xu*, Siyang Liao, Yuanzhang Sun, Yibo Jiang, Zhen Zhang

The School of Electrical Engineering, Wuhan University, Wuhan 430072, China

HIGHLIGHTS

- Multiple thermostatically controlled load groups are coordinated to deal with the power fluctuation.
- A proportion load aggregation and an optimal task decomposition are developed.
- A hierarchical and iterative algorithm is proposed to solve the two-stage optimization model.
- Both net exchange power fluctuation and load regulation costs are all reduced in standard system.

ARTICLE INFO

Keywords:
Thermostatically controlled load
Distribution network
Two-stage optimization
Load aggregation
Power fluctuation

ABSTRACT

As the increasing penetration of distributed renewable energy sources, the inherent fluctuation of their output power aggravates more control burden for the power system. Based on the direct load control, the regulation potential of distributed flexible loads can be developed to relieve this pressure. This paper proposes a real-time two-stage optimization model for multiple thermostatically controlled load groups to smooth the power fluctuation in distribution network. The upper-level evaluates the load regulation capacity and suppresses the net exchange power fluctuation; the lower-level further minimizes the regulation costs and makes the target demand curves for each load group, which can guide the subsequent load power tracking. Besides, within the load group, a proportion aggregation method is applied to reflect its external power regulation characteristics, while the decomposition program assigns the regulation task to each terminal user. For the complex problem established above, a hierarchical and iterative solving strategy is proposed to obtain the approximate optimal solution. The simulation results show that the proposed approach can effectively decrease the net exchange power fluctuation as well as regulation costs.

1. Introduction

With the depletion of fossil resources, distributed renewable energy sources (RES) have been rapidly developed, particularly photovoltaic generation (PV) [1]. However, the inherent power fluctuation of the distributed RESs spreads within the distribution network, and can be further delivered to the transmission network through the substation transformer. For power systems lacking power ramping capacity, the rapid change of the node power affects the power balance, aggravates the regional control deviation and increases operation costs [2]. In some severe cases, it can also lead to the voltage fluctuation [3], frequency deviation [4] and unintentional islanding [5], which can directly deteriorate the power quality and system stability. Due to the concern about the above potential impacts, EirGrid (Ireland), Sate Grid (China) and PREPA (the U.S.) require minute-level ramp rate limits for RES output, and HECO (the U.S.) further sets similar limits in multiple time scales [6]. Horizon Power (Australian) even has rejected applications for new RESs in Exmouth and Carnarvon, and restricted new installations in Broome and Leonora [7]. That is, the power fluctuation slows down the development of RESs. Therefore, corresponding power regulation measures are needed to track the output of distributed RESs, which can locally smooth the net exchange power of distribution network and reduce the regulation pressure [8,9].

Fortunately, with superior power regulation performance, distributed flexible loads (FL) can be employed as important power regulation resources [10]. Especially thermostatically controlled load (TCL) is one of the most common FLs, such as heating, ventilation and air-conditioning systems (HVAC) and water heaters. They account for a significant portion of residential and commercial electricity consumption [11,12], and demonstration projects have also been carried out in

* Corresponding author.
E-mail address: xujian@whu.edu.cn (J. Xu).

https://doi.org/10.1016/j.apenergy.2018.09.105
Received 11 June 2018; Received in revised form 7 August 2018; Accepted 9 September 2018

Nomenclature

Sets and indices

t, τ	index for time
i, j	index for network nodes
m	index for renewable energy sources
n	index for flexible load (thermostatically controlled load) groups
c	index for users (or thermostatically controlled devices)
l	index for segments
k	index for iterations
ND	set for network nodes
RN	set for renewable energy sources
FL	set for flexible load (thermostatically controlled load) groups
$\mathbf{C}_n$	set for users in group n
$\mathbf{P}_{n,t}$, $\mathbf{Q}_{n,t}$	active and reactive power regulation characteristics
$\mathbf{U}_{n,t}$	sequence of the threshold value $u^*_{n,c,t}$
$\mathbf{L}_{n,t}$	set for segments in $\mathbf{U}_{n,t}$
$\mathbf{L}_t$	combination of $\mathbf{L}_{n,t}$

Parameters

$T^{out}_{n,c,t}$	outdoor ambient temperature
$T^{db}_{n,c}$	temperature dead band
$T^{in,\min}_{n,c}$	minimum allowable indoor temperature
$T^{in,\max}_{n,c}$	maximum allowable indoor temperature
$u^{\min}_{n,t}$, $u^{\max}_{n,t}$	minimum and maximum limits of $u_{n,t}$
$P^{rate}_{n,c}$, $Q^{rate}_{n,c}$	rate active and reactive power of the thermostatically controlled device
$P^{FL,basic}_{n,t}$	active power demand baseline of load group n
$P^{Load}_{i,t}$, $Q^{Load}_{i,t}$	active and reactive power demands of the uncontrollable load
$P^{RN}_{m,t}$, $Q^{RN}_{m,t}$	active and reactive power outputs of the renewable energy source m
$V^{\min}_i$, $V^{\max}_i$	minimum and maximum limits of the voltage
$G_{i,j}$, $B_{i,j}$	conductance and susceptance of the line i,j
E^{Net}_i	network incidence matrix about the substation transformer
$E^{RN}_{i,m}$	network incidence matrix about the renewable energy source m
$E^{FL}_{i,n}$	network incidence matrix about load group n
$K^P_{n,l,t}$, $K^Q_{n,l,t}$	linear interpolation slope in segment l
$C^P_{n,l,t}$, $C^Q_{n,l,t}$	linear interpolation intercept in segment l
α	threshold of the relative power fluctuation

Variables

$T^{in}_{n,c,t}$	indoor temperature
$T^{set}_{n,c,t}$	indoor temperature set point
$\Delta T_{n,c,t}$	temperature set point change
$u_{n,t}$	proportion control signal in load group n
$u^*_{n,c,t}$	on/off boundary
$SU_{n,t}$	accumulative proportion control signal
P^{Net}_t, Q^{Net}_t	active and reactive net exchange power
$\Delta P^{Net,up}_t$	upward power fluctuation of the net power
$\Delta P^{Net,dn}_t$	downward power fluctuation of the net power
$P^{FL}_{n,t}$, $Q^{FL}_{n,t}$	total active and reactive power of load group n
$\Delta P^{FL,up}_t$	upward power regulation
$\Delta P^{FL,dn}_t$	downward power regulation
$e_{i,t}$, $f_{i,t}$	real and imaginary part of node voltage

Binary variables

$Z_{n,c,t}$	on/off state of the thermostatically controlled device
$I_{n,l,t}$	auxiliary variable in linear interpolation

some smart buildings [13]. Therefore, TCLs are selected to be the major flexible loads to offer demand response (DR).

1.1. Modelling and aggregation of TCLs

Because of the large quantity, small capacity and dispersed location, it is impossible and unnecessary to directly dispatch distributed TCLs one by one. Only a lot of users coordinate with each other and enable the total load demand to reach a certain level, their power regulation potential can be fully exploited [14]. Hence, some literatures have studied the aggregation of TCLs.

For example, based on the accurate TCL models built on Energy Plus, Ref. [15] presents an estimation framework to test their demand response capacity under different temperatures. Ref. [16] establishes smart home models with HVACs, and the demand curves are adopted to aggregate them. Nevertheless, collecting accurate parameters and modelling each TCL are difficult in practice. Therefore, after estimating the statistical distribution of parameters, Ref. [17] selects the tracer devices based on the best approximation, while k-means clustering algorithm is used in Ref. [18]. Their main idea is to replace the actual heterogeneous parameters with some virtual typical parameters. However, they are belong to the non-equivalent approximation, and the excessive difference of parameters can exacerbate the aggregation errors when the number of representatives is limited.

Ref. [19] proposes the state-queueing (SQ) model based on the temperature priority list. And on this basis, Ref. [20] further considers some random factors and Ref. [21] develops an energy-constrained state priority list. Ref. [22] proposes a correction method for the SQ model to improve its accuracy. The SQ method only exchanges the temperature information, so it is not affected by the model parameters. However, the temperature information also involves the user's privacy, and the different users have different preferences for thermal comfort, which means their temperature set points and acceptable regulation ranges are different. Hence, directly employing the temperature signal as the control signal is not practical.

1.2. Scheduling and control of TCLs

After discussing the power regulation characteristics of aggregated TCLs, how to dispatch them is another urgent problem. Related studies are carried out in this regard.

Ref. [23] develops a transactive control paradigm to participate in real-time retail markets. Ref. [24] adopts an adapted gossip algorithm for the continuous control of TCLs in microgrids. Ref. [25] presents an extended Lyapunov optimization to reduce the fluctuations of non-renewable power demand. As for the types of DR, Ref. [26] uses the price-based DR and develops a kernel density estimation method to evaluate the reserve capacity of TCLs; while Ref. [27] focuses on the incentive-based DR and presents a linear-time algorithm for load reduction. Ref. [28] points out that the constrained rebound effect significantly impacts the achievable modulation amplitude. Besides, a two-level scheduling method is proposed in Ref. [29], which minimizes the imbalance costs through upper-level optimization and lower-level power tracking. Ref. [30] proposes a dynamic water level adjustment model to deal with the fluctuations caused by RESs.

The literatures above offer some control methods for aggregated TCLs, and Refs. [25,30] further focus on suppressing the power fluctuation. However, they ignore the AC power flow constraints, which