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Dynamic energy management in smart grid: A fast randomized first-order optimization algorithm

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A B S T R A C T

A crucial issue in the smart grid is how to manage the controllable load resources of end-users, in order to reduce the economic costs of system operation and facilitate to utilize renewable energies. This paper investigates a fast randomized first-order optimization method to explore the solution of dynamic energy management (DEM) for the smart grid integrated large-scale distributed energy resources. A complicated time-coupling and multi-variable optimal problem is presented to determine the load scheduling for the electricity customers. The main challenge of the proposed problem is to enable the efficient processing of the large data volumes and optimization of aggregated data involved in DEM. The first-order method as one of big data optimization algorithms is able to exhibit significant performance for computing globally optimal solutions based on randomization techniques. Using such solution approach, we can reformulate the original problem into an unconstrained augmented Lagrangian function. The optimal results can be obtained from computing the gradient based on the information of the first-order derivative. To speed up the calculations of obtaining the feasible solutions, the optimization variable matrix used to update the Lagrangian multiplier can be replaced with the corresponding low-rank representation in the iteration process. Both theoretical analysis and simulation results suggest that the proposed approach may effectively solve the optimal scheduling problem of DEM considering users' participation.

1. Introduction

The dynamic energy management (DEM) enables electricity customers to change their energy consumptions by means of price-driven demand response mechanisms, to facilitate the users to actively take participation into the process of power system operation. In the conventional power grids, DEM is a well-investigated topic but not the case for the smart grid [1]. A smart grid is the modern power grid integrated with a large amount of distributed renewable energy, controllable electricity appliances, energy storage devices from the energy supply and consumption sides. This will make the DEM become much more complicated, which brings the challenge to achieve the real-time decision-making process for the control center of the power system operation. The infrastructure shows the advanced technical characteristics of the smart grid can be beneficial to enhance the economic, reliability and sustainability of the power system, but it also will pose a significant problem that how to manage the electricity load and controllable distributed energy resources in the context of massive data information. In more detail, DEM in the power grid can be described as an optimal problem for the scheduling of all of the controllable appliances of the users [2]. However, the large volumes of aggregated data generated by millions of end-users in the optimization process become a simple optimal control problem into a time-coupling, multi-variable, high-dimensional optimization issue in the smart grid environment. Thus, in order to achieve more efficient analyzing performance of DEM in the load scheduling, the solution algorithm to tackle such complicated optimization problem, which is associated with massive load data, needs to be investigated and studied.

Some researchers have focused on the DEM problem in the context of the smart grid. In [3], an optimal DEM scheme based on Lyapunov optimization theory was presented to perform the load scheduling with consideration of unpredictable load demands and distributed energy resources. An approach based on the mixed-integer linear programming paradigm was developed to determine power consumption and management of renewable resources in [4]. The work in [5] showed a rule-based energy management strategy was able to improve the fuel economy of plug-in hybrid electric vehicles using dynamic programming. Different

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Nomenclature

Symbols

$g_{DG,i}(t)$	output of distributed generation resource of user i in time period t
$d_{IDR,i}(t)$	energy provided for satisfying interruptible load demand of user i in time period t
$d_{DR,i}(t)$	energy provided for satisfying load demand of demand response resources of user i in time period t
$d_{G,i}(t)$	energy sold to power grids in time period t
$c_{DG,i}(t)$	energy saved in time period t
$g^{max}_{DG,i}$	maximum output of the distributed generation resource of user i
$L_{IDR,i}(t)$	interruptible load demand of user i in time period t
$L^{max}_{IDR,i}$	maximum interruptible load demand of user i
$g_{IDR,i}(t)$	energy drawn from the power grid to meet user i's interruptible load demand in time period t
$r_{IDR,i}(t)$	energy provided from energy storage device of user i to satisfy interruptible load demand in time period t
$L_{DR,i}(t)$	load demand of user i's demand response programs in time period t
$L^{max}_{DR,i}$	maximum load demand of user i's demand response programs
U_{DR}	aggregate demand of user i's all elastic load resources
T_D	set of times that the demand response appliances can work
$g_{DR,i}(t)$	energy drawn from the power grid to meet user i's elastic demand in time period t
$r_{DR,i}(t)$	energy provided from energy storage device of user i to satisfy elastic load demand in time period t
$E_i(t)$	energy level of user i's energy storage device in time period t
E^{max}_i	maximum capacity of user i's energy storage device
$C_i(t)$	energy charging the energy storage device in time period t
$R_i(t)$	energy discharged from energy storage device in time period t
C^{max}_i	maximum charging capacity of user i's energy storage device
R^{max}_i	maximum discharging capacity of user i's energy storage device
$c_{G,i}(t)$	energy drawn from the power grid for user i's energy storage device in time period t
$r_{G,i}(t)$	energy sold to the grid from user i's energy storage device in time period t
$I_{C_i(t)>0}$	state of charging the energy storage device
$I_{R_i(t)>0}$	state of discharging the energy storage device
$P(t)$	energy supplied from the load-serving entity in time period t
E^T_i	energy level of user i's energy storage device in time period T
λ	Lagrangian multiplier associated with equality constraints
μ	Lagrangian multiplier associated with inequality constraints
σ	scalar parameter
v	iteration count
α_v	iteration step-size
r	rank of matrix
N	number of end-users

Abbreviations

DEM	dynamic energy management
RTP	real-time pricing
SVD	singular value decomposition
RAM	random access memory
CPU	central processing unit
GA	genetic algorithm

from centralized optimization approaches, [6] established a decentralized model with minimal information exchange and communications between users to determine optimal energy trading amounts. Another modeling technique was proposed in [7–10], where the study of DEM with residential energy system was conducted. The authors addressed the model with individual end-user behavior constraints, whereby the optimal load scheduling could be obtained. Additionally, DEM can be effectively implemented in the manner of demand response programs or transactive energy [11]. The setting of the power prices will have a profound impact on encouraging consumers' participation in energy savings and cooperation. A load scheduling problem with price uncertainty and temporally-coupled constraints in the smart grid was presented in [12], where the real-time pricing (RTP) model was proposed to incentivize energy resources scheduling. The incentive mechanism is also used to perform household energy management. Ref. [13] designed a policy scheme to regulate household energy consumption behavior in a dynamic active energy demand management system. According to [14], the proposed real-time optimal demand response management for residential appliances was designed via stochastic optimization and robust optimization approached considering deferrable/non-deferrable and interruptible/non-interruptible load models. On optimization in residential energy management, [15] presented a mixed integer multi-time scale stochastic optimization to formulate the load scheduling considering different types of load classes.

It is highlighted that DEM can be described as an optimal control problem for the scheduling of all of the controllable appliances in the smart grid. Considering the complexity of modeling and solving such problem, some previous research associated with its modeling techniques and solution algorithms has been somewhat carried out. The study of [16] deals with load control in a multiple-residence setup, from which the optimal amount of electricity production and consumption schedule can be obtained using a distributed subgradient method. In addition, the authors of [17] proposed a joint scheduling scheme for the electric supply and demand of home energy management system in term of the sequential procedure of prediction. Instead of using an optimization formulation, [18] employed a simulation testing method for conducting the pre-cooling strategies of thermal appliance scheduling. Under the environment of the smart grid, mass energy appliances in the electricity demand side will participate into DEM and interact with the smart grid. The main challenge is how to analyze the emerging control problem for such DEM integrated with aggregated big data from energy customers.

In this paper, we proposed an optimization method from the area of big data analytics for the DEM considering different demand response programs. Our method makes decisions on the load scheduling of both elastic load and inelastic load, as well as the operations of distributed renewable energy resources and energy storage devices. We aim to obtain an optimal energy management scheduling associated with the usage of all the energy