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A multi-objective market-driven framework for power matching in the smart grid

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ABSTRACT

Smart grids, to facilitate the electricity production, distribution, and consumption, employ information and communication technologies simultaneously. Electricity markets, through stabilizing the electricity prices, attempt to alleviate the challenges of power exchange. On one hand, buyers, by considering their full demand satisfaction, endeavor to purchase the electricity cost-effectively. On the other hand, sellers, by taking their limited electricity generation capacity into account, are interested in increasing their financial benefits. To address this challenge, this paper introduces a highly-functional semi-decentralized power matching framework based on multi-objective optimization techniques executing in a day-ahead electricity market. A two-stage price updating mechanism to continuously balance the electricity prices is also provided. At each time interval, buyers and sellers submit their individual electricity price offers to the market operator. The market operator tunes them and then, announces the electricity market price. A robust multi-objective power matching algorithm is developed to make the matching contracts considering buyers' and sellers' objectives along with grid stability constraints imposed by distribution system operators. It also considers the minimization of electricity distribution loss in the matching procedure. Simulation results indicate that the framework successfully reaches a reasonable balance of aforementioned conflicting objectives while conducing negotiating electricity price offers to an equilibrium. It is shown that the proposed algorithm behaves better compared to well-known multi-objective evolutionary algorithms in terms of both optimizing the social welfare and computational complexity (scalability). Finally, effects of the two-stage price updating mechanism on the stability of the proposed evolutionary algorithm is discussed. Performance comparisons show that the proposed framework outperforms the similar approaches available in the literature.

1. Introduction

The current structure of the electrical grid is inefficient in responding to the growing demand for electricity. The smart grid, by, for instance, demand response programs and distributed power matching, aims at revolutionizing the current electrical grid to reveal its concerns. Nevertheless, a solid introduction of the smart grid confronts numerous challenges in designing, controlling, and implementation. The smart grid employs bilateral electricity and information streams to establish a reliable energy management infrastructure (Farhangi, 2010). This is done by dividing it into: 1) smart infrastructure system for electric power transmission, 2) smart management system for controlling and managing grid services, and 3) smart protection system for protecting the smart grid (Fang et al., 2012). To integrate these systems while identifying main stakeholders and feasible communication paths in the smart grid, National Institute of Standards and Technology (NIST) has developed an inter-operable smart grid conceptual model (National Institute of Standards and Technology, 2014).

This paper concentrates on the interconnectivity of *customers* and *markets* domains in the smart grid. The first domain supports three customer types named industrial, commercial, and residential. For the sake of simplicity, this paper considers residential customers, in which they are characterized by *buyer* and *seller* agents. Each agent is an individual entity providing the markets domain with its preferences, requirements, and constraints. Hereinafter, customer and agent are interchangeably used as contextual synonyms. Markets domain, particularly electricity markets, intends to effectively manage the customers' information (Bichler et al., 2010).

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Nomenclature

Constants

$\mathbb{P}$	Pareto-front
$\delta_{s_{j,g}}$	Malleability rate of seller $s_{j,g}$
$\gamma_{b_{i,k}}$	Malleability rate of buyer $b_{i,k}$
$L_{b_{i,k}}$	Location of buyer $b_{i,k}$
$L_{s_{j,g}}$	Location of seller $s_{j,g}$
L_{ξ}	Location of the power plant ξ
p_l	Minimum offerable electricity price ($/kWh)
p_u	Maximum offerable electricity price ($/kWh)
$loss_{b_{i,k}\xi}$	Electricity distribution loss between buyer $b_{i,k}$ and the power plant ξ
$loss_{b_{i,k}s_{j,g}}$	Electricity distribution loss between buyer $b_{i,k}$ and seller $s_{j,g}$
$\mathrm{SEF}_{\mathbb{P}}$	Solution efficiency factor of solutions on Pareto-front $\mathbb{P}$
φ_a	Feasible power matching solution a
ξ	Power plant
$b_{i,k}$	Buyer i connected to feeder k
E	Euclidean distance parameter
f_k	Feeder k
K	Number of feeders
M_g	Number of sellers connected to feeder f_g
N_k	Number of buyers connected to feeder f_k
$p\xi$	Fixed electricity price offered by the power plant ξ ($/kWh)
p_c	Crossover probability
p_m	Mutation probability
Q	Population size of the evolutionary algorithm
$s_{j,g}$	Seller j connected to feeder g
T	Number of time intervals
W	Number of generations of the evolutionary algorithm
ELF_f	Electricity loss factor in the Customer–Customer trading method
ELF_{ξ}	Electricity loss factor in the Customer-to-PowerPlant trading method

Indices

a	Index of power matching solutions
i	Index of buyers
j	Index of sellers
k, g	Index of feeders
t	Index of time intervals

Sets

$\mathbb{B}$	Collection of sets of buyers
$\mathbb{Q}$	Parent population in the evolutionary algorithm
$\mathbb{S}$	Collection of sets of sellers
$D_{b_{i,k}}$	Load demand set of buyer $b_{i,k}$
f_g^S	Set of sellers connected to feeder f_g
f_k^B	Set of buyers connected to feeder f_k
$Q_{s_{j,g}}$	Surplus energy set of seller $s_{j,g}$
F	Set of all feeders

Variables

$\mathbb{C}_{\varphi_a}^t$	Matrix of contracts of solution φ_a at time interval t
$d_{b_{i,k}}^t$	Load demand of buyer $b_{i,k}$ at time interval t (kWh)
$q_{s_{j,g}}^t$	Surplus energy of seller $s_{j,g}$ at time interval t
$\overline{pb}^t$	Weighted average of electricity prices offered by all buyers at time interval t
$\overline{ps}^t$	Weighted average of electricity prices offered by all sellers at time interval t
$pb_{i,k}^t$	Electricity price offered by buyer $b_{i,k}$ at time interval t
pd^t	Electricity market price at time interval t
$ps_{j,g}^t$	Electricity price offered by seller $s_{j,g}$ at time interval t
$x_{b_{i,k}\xi}^t$	Total electric energy units transferred from the power plant ξ to buyer $b_{i,k}$ at time interval t
$x_{b_{i,k}s_{j,g}}^t$	Total electric energy units transferred from seller $s_{j,g}$ to buyer $b_{i,k}$ at time interval t
EDT_k^t	Electricity demand threshold imposed by feeder f_k at time interval t (kWh)
PAC_k^t	Peak aggregate consumption of customers at time interval t (kWh)

This is done by the market operator, who typically applies the *pricing scheme* and *demand and supply balancing strategies* to the electrical grid. Thus, having a reliable interface between these two domains is critical since it directly affects “matching production with consumption.” Recent developments in electricity markets require the employment of a reliable power matching framework. In this regard, the market operator, to clearly specify the power exchange contracts over time, is responsible for matching buyer agents with seller agents. Nevertheless, far too little attention has been paid to build an effective framework considering the conflicting objectives and constraints that the customers and Distribution System Operators (DSOs) include.

This paper puts efforts into proposing a novel semi-decentralized power matching framework to the smart grid. Fig. 1 pictures the conceptual view of this framework. According to the current structure of the grid, the electricity is distributed to customers in a hierarchical manner. Since controlling all customers by a single system is not practically scalable, we propose to semi-decentralize such controlling system into a number of sub-systems. We consider *feeders* as the last points of delivering the electricity to households. Each feeder serves a non-overlapping set of customers. This will help the framework host a large number of customers in the grid. The framework runs the matching procedure in each feeder. In each feeder, on one hand, buyer agents have to satisfy their demands over time. They intend to minimize their power purchase cost considering their full demand satisfaction at each interval. On the other hand, seller agents are interested in maximizing their selling benefit considering their limited surplus electrical power production. It is becoming increasingly difficult to ignore the impact of grid stability constraints on market-driven power matching frameworks. We use the concept of “electricity demand thresholds” to respect the grid’s capacity (Azar et al., 2015). The framework is physically distinguishable and completely compatible with the existing electrical grid. This also ties in well with future smart grids that are based on Distributed Energy Resources (DERs) and flexibly interconnected energy supply grids (Jacobsen et al., 2015).

Owing to the conflictive nature of discussed objectives, this paper frames the power matching problem as a multi-objective optimization framework. Multi-objective optimization is an area of multiple criteria decision-making structure, which has extensively been used in smart grids particularly in the electricity consumption scheduling (Lu et al., 2015) and demand side management (Ramachandran and Ramanathan, 2015). We activate such framework by proposing a multi-objective power matching algorithm to match the total demand with the total surplus production. This algorithm is a *revised* version of well-known Non-Dominated Sorting Genetic Algorithm-II (NSGA-II). It consecutively provides the market operator with admissible power matching solutions. Performing this algorithm helps balance the grid operations and equilibrate the electricity market better. To reach this point, the market operator has to conduct power exchange contracts with quite reasonable electricity prices. The algorithm, to enable customers to update their electricity price offers periodically, also employs a two-stage price updating mechanism. At each time interval, in the first stage, buyers/sellers provide the market operator with their updated