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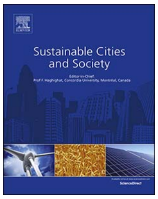

A δ-constraint multi-objective optimization framework for operation planning of smart grids

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ABSTRACT

With the increasing penetration of renewable energies into the smart grid, satisfying load and avoiding energy shortage have become a challenging issue for energy providers, owing to the intermittent nature of renewable energies. The need to reduce energy shortage and pollutant gas emissions has led to a large-scale development of energy management programs such as demand side management (DSM) to control the peak energy demand on a smart grid. The implementation of DSM programs makes the operation planning of smart grids more difficult with an additional objective of customer stakeholder. The operation plan should satisfy all the conflicting objectives of stakeholders (i.e., minimization of the total cost, minimization of the GHG emissions, and maximization of customer satisfaction). In this paper, we present a novel multi-objective optimization framework for energy management in the smart grid to significantly reduce the peak load demand and reshape the load profile. The proposed framework is comprised of four main components: (1) a forecasting model that predicts the 24-h-ahead energy load, (2) a load shifting DSM program that reduces the energy load during peak demand, (3) a piecewise linear approximation method that linearizes the non-linear objective functions and constraints, and (4) a δ-constraint multi-objective optimization method that efficiently finds the Pareto frontier solutions. The capabilities of the proposed framework demonstrated on a synthetic smart grid case study with 50 buildings. The results reveal that the proposed framework has successfully met the desired load curve while obtaining a significantly larger Pareto frontier solution set (with more non-dominated solutions) in less computational time.

1. Introduction

Smart grid represents a vision of future power systems with integration of advanced communication technologies, control mechanisms, and renewable energy sources (Logenthiran, Srinivasan, & Shun, 2012; Mišák, Stuchlý, Platoš, & Krömer, 2015). While smart grid promises a user-oriented, high security, and economic efficiency service; the total capacity of installed generation in the system must be larger than the maximum load demand to ensure the security of supply in the face of uncertainty (i.e. generation breakdowns and interruptions to primary fuel sources) and variations in demand (Agrawal, 2006; Logenthiran et al., 2012). A reliable electricity supply in a grid with a large share of volatile generators can be guaranteed with adequate balancing power reserves being available as backup; however, this results in high investments for electricity storage technologies such as flywheels, pumped storage water plants, and compressed air (Gao & Sun, 2016; Gottwalt, Ketter, Block, Collins, & Weinhardt, 2011; Mazhari et al., 2011). Alternatively, the gap between supply and demand can also be reduced by incorporating demand side management (DSM) programs to prevent black or brownouts during load variation and uncertain energy generation. DSM programs harmonize the activities of energy providers and consumers to manage the energy loads during peak load demand and avoid additional installation of generation units. With the emergence of new load types (such as plug-in hybrid electric vehicles (PHEVs), that may potentially double the average residential load), DSM programs can potentially become an even more substantial tool in the future smart grids. Furthermore, DSM programs can reduce the market-clearing price and help avoid energy shortages during a peak load demand (Batić, Tomašević, Beccuti, Demiray, & Vraneš, 2016; Logenthiran et al., 2012). Fig. 1 illustrates the major DSM programs including: (1) Peak clipping: reducing peak load demand using a time-based incentive for interrupted customers; (2) Load shifting: shifting loads from on-peak to off-peak time periods; (3) Valley filling: encouraging customers to build off-peak loads (filling the valley); (4) Flexible load shaping: controlling customer loads during critical periods in exchange for various incentives; (5) Strategic conservation: reducing the load shape through application of demand reduction methods directly at customer premises; and (6) Strategic load building (load growth): increasing the energy sales and market to fulfill

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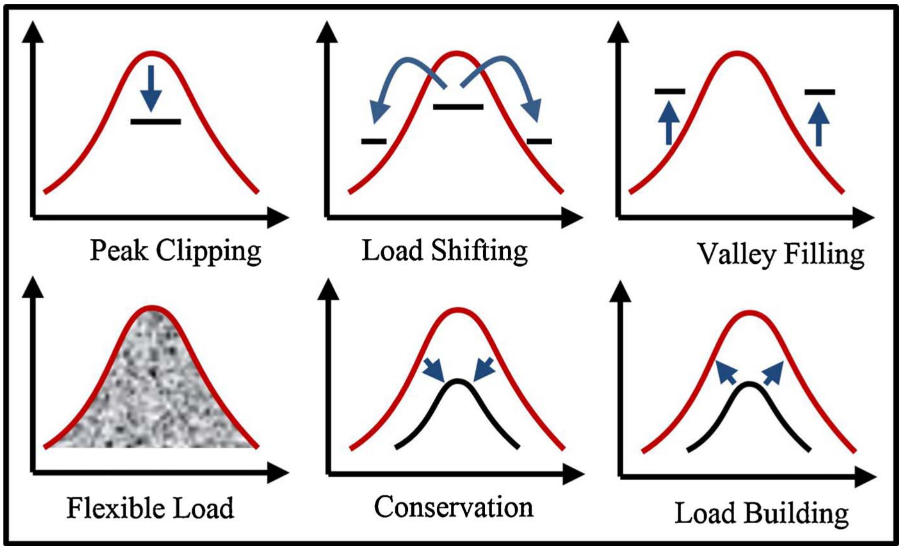

Fig. 1. Major demand side management programs.

the desired load curve (Gelazanskas & Gamage, 2014; Logenthiran et al., 2012).

Among different incentive-based programs (IBPs), load shifting and interruptible load management (ILM) have been studied extensively in the literature of DSM (Arteconi, Hewitt, & Polonara, 2013; Huang, Chin, & Huang, 2004; Logenthiran et al., 2012; Vandael, Claessens, Hommelberg, Holvoet, & Deconinck, 2013). Huang et al. (2004) proposed a fuzzy dynamic programming approach to utilize ILM; however, their approach is meant for small-sized problems and requires a high amount of computational time that is not applicable real-time smart grids. Mohsenian-Rad, Wong, Jatskevich, and Schober (2010) proposed an optimal incentive-based energy consumption scheduling algorithm in smart grids to minimize the cost using the peak-to-average strategy. While the proposed game theoretic approach for time of use (TOU) strategy minimizes the energy generation cost efficiently, that study does not consider the different stakeholders of energy market such as customers and environmental agencies. Thillainathan et al. (2012) proposed an evolutionary algorithm for a day-ahead load shifting program in smart grids that results in near-optimal schedules (not optimal) for only limited number of constraints. Saad, Han, Poor, and Basar (2012) investigated the application of game-theoretic methods for DSM programs in smart grids. They consider the cooperative and non-cooperative Nash equilibrium for the energy interruption pricing; however, no attention has been paid to load shifting programs and emission functions. Shi, Damgacioglu, and Celik (2015) proposed a dynamic data-driven approach for operation planning of microgrids. Their approach optimizes the operation planning of microgrids regarding the costs and emissions while lacking the customer satisfaction and details of the operation planning and demand response programs. Finally, Siano (2014) provided a survey of demand response programs in smart grids. The survey summarizes the potential benefits of DSM, enabling technologies, control devices, monitoring systems and communication systems for demand response based on the practical applications and research projects in the literature. Our literature review reveals that a framework that the integration of load shifting programs in smart grids with different stakeholders' objective (i.e. utility company, environmental agencies, and customers) has not been considered yet. A list of selected work in the literature of DSM is shown in Table 1.

In this paper, we present a novel multi-objective optimization framework for operation planning in smart grids via load shifting program. We consider three main objective functions considering different stakeholders including utilities, environmental agencies, and customers: minimization of cost and GHG emissions, and maximization of customer satisfaction.

Fig. 2 represents the overview of the proposed multi-objective optimization operation planning framework for smart grids to satisfy the objectives using four main components: (1) a forecasting model that predicts the 24-h-ahead energy load, (2) a load shifting DSM program

Table 1
Selected load shifting and ILM studies in the literature of DSM.

Method	Main Idea	Drawbacks
● Model Reference Adaptive Control (MRAC) strategy using fuzzy dynamic programming (Huang et al., 2004)	● Minimization of interruption cost using optimization model; ● Fuzzy dynamic programming for interrupted loads	● Applies to small ILM problems and requires high computation time
● Genetic algorithm (GA) for scheduling time-shiftable loads in smart grids (Logenthiran et al., 2012)	● Finding near-optimal scheduling of time-shiftable loads on a device level	● Only considers the minimization of cost as an objective function; ● Optimal solution is not guaranteed
● Incentive-based optimization model for DSM of PHEVs (Vandael et al., 2013)	● Optimization of PHEV fleet to minimize costs for energy supplier	● Proposed dynamic programming for PHEVs is not applicable to large-scale problems; ● Limited to scheduling of PHEVs
● Simulation model to use water heat pump and thermal energy storage (TES) for load shifting (Arteconi et al., 2013)	● Heat-pump heating systems demonstrate ability to have active role in DSM programs	● Limited to thermal storage and satisfies energy storage planning
● Optimal incentive-based load scheduling in smart grids (Mohsenian-Rad et al., 2010)	● Minimization of the cost of TOU using the peak-to-average strategy	● Only considers the cost objective and does not consider other stakeholders
● A dynamic data-driven approach for operation planning of microgrids (Shi et al., 2015)	● Minimization of the total cost and emission	● DSM programs and customer satisfactions are not modeled
● Game theoretic approaches for communications in smart grids (Saad et al., 2012)	● Finding the Nash equilibrium points for customers and utility companies	● No information regarding the practicality of the model and no information about emission