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Harmony search optimization of renewable energy charging with energy storage system

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ABSTRACT

We propose an efficient harmony search algorithm for charge scheduling of an energy storage system (ESS) with renewable power generators under time-of-use pricing and demand charge policy. We show the superiority of the proposed method by simulating experiments with load and generation profiles of typical residential customers. ESS scheduled by the proposed harmony search algorithm showed improved result over the system optimized using genetic algorithm.

Introduction

When we use the electric grid, the electricity entering the grid (referred to as *generation*) must be equal to the electricity exiting the grid (referred to as *load*). However, as technologies like utility-scale wind power, rooftop solar PV, and electric vehicles continue in popularity, the electric grid equation (i.e., generation equals load in real-time) gets complicated. Fortunately, energy storage systems (ESSs) available today can be incorporated in different utility applications to act as a buffer between generation and load to ensure the seamless delivery of the electricity powering our lives. Commercial and industrial end users can also improve their power quality and reliability, and reduce their electricity expenses by installing an energy storage system. For the end user, an integrated storage solution can reduce peak demand and level load profiles, improve overall power quality, and act source of back-up power.

In the near future, energy storage will be ready and be more important for the residential customer with dynamic pricing. Economists have long argued to remove the fixed retail prices in favor of prices that change during the day. Such dynamic pricing reflects the prices of the wholesale market and has been predicted to lead to lower demand peaks and lower the average level and volatility of the wholesale price [2].

Dynamic pricing has been enabled by recent smart-grid technologies such as smart meters. A representative example of dynamic pricing that is being increasingly adopted is time-of-use pricing (TOU pricing), whereby electricity prices are set for a specific time period on an advance or forward basis, typically not changing more often than twice a year. Such schemes typically provide two or three price levels (e.g., 'off-peak', 'mid-peak', and 'on-peak') where the level is determined by the time of day. Prices paid for energy consumed during these periods are predetermined and known to consumers in advance, allowing them to vary their usage in response to such prices and manage their energy costs by shifting usage to a lower cost period or reducing their consumption overall. By storing energy during low off-peak price periods and using that stored energy during times of high TOU pricing, consumers and businesses could continue to operate at the optimum levels even at peak times and avoid paying high TOU rates. TOU pricing is used by providers to drive down demand at peak periods through price pressure rather than through more invasive means like involuntary curtailment or dynamic or passive demand response mechanisms [20,22].

In addition to TOU-based charge, electricity bill may include *demand charge*. In this case, users are also required to pay for the energy capacity available to them (whether or not they are using that capacity) at all times. This is called a demand charge. It is defined as a charge that is determined using the maximum demand (or *peak demand*) occurring during a certain billing period [24]. The demand charge is billed as a fixed rate calculated on a per kW basis. This charge is based on the premise that commercial cus-

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tomers and other large users, who require even brief peaks of power from the grid, should pay a share of the infrastructure and maintenance costs, associated with the capacity to provide the power when needed [14].

Demand charges are common in industrial rate structures, but not in residential rates because residential electricity loads were usually the same from one customer to another. However, nowadays all residential load patterns are not the same due to new technologies such as LED lights, smart thermostats, plug-in electric vehicles, rooftop solar, demand-flexible water heaters, and battery energy storage. Billing a demand charges may be a good way to motivate customers to reduce strain on the system [9]. In literature, there have been researches on the effects of a time-of-use demand charge for residential customers using energy use data from Duke Power Company [24,25]. The Duke rate contained both TOU rate and demand charge that applies to consumption during the peak pricing period. Also, in practice, more than a dozen utility companies in the United States have implemented or are currently considering residential demand charges. For example, two utilities, Salt River Project and Westar Energy, recently added demand charges to the bills of residential customers with PV, and Black Hills Power in South Dakota and Wyoming offers a demand charge option for all residential customers with and without PV [9]. Recent analysis of residential rate designs showed that designing residential rates with demand charges might make significant progress toward a more efficient rate design [18].

While energy charges are based only on the amount of consumed energy and the corresponding TOU price, demand charges are based on the highest level of electricity supplied during the billing period. In the case, total energy consumption and demand are not necessarily related. We consider both energy charge based on TOU pricing and demand charge [24].

There have been a number of studies to optimize the energy storage system with regard to charge and discharge scheduling in order to maximize the benefits related to the electricity price differences under time-of-use of real time pricing [7,8,12,26]. There were researches especially focusing on residential ESS [8,26,28] and there was also an interesting paper which studied ESS control from utility operator's point of view [10].

In the view of methodologies for solving the problem, various optimization methods such as dynamic programming [8,10,13,17,26], linear programming [15,30], nonlinear programming [7], Kalman filter [28], particle swarm optimization approach [12], genetic algorithm [29], and hybrid optimization technique of stochastic and deterministic algorithms [5] are considered for solving the problem.

In this study, we try to design a new harmony search algorithm to find optimized ESS scheduling under TOU pricing with demand charge in the case that renewable energy generation facilities like wind and solar are available. There has been a research focusing on ESS scheduling under the same electricity pricing policy for residential customers with PV generation system [29]. In [29], the problem was formally defined for that case, and an effective approach using a genetic algorithm was introduced. In this paper, we propose an improved method for the same problem by designing an efficient harmony search algorithm. It is the first trial to use harmony search for ESS charge scheduling problem. We attack formally defined problem in [29] and propose an effective approach using the harmony search. We also show the superiority of the proposed method by performing experiments with load and generation profiles of typical residential customers.

The remainder of the paper is organized as follows. In Section 'ESS scheduling problem under TOU pricing with demand charge', we explain the ESS scheduling problem under TOU pricing with demand charge. And then in Section 'Harmony search algorithm for the ESS charge scheduling problem', the harmony search algorithm we design for the problem is presented. In Section 'Simulation results' we show the effectiveness of the proposed harmony search through simulation results, and finally we give our conclusion in Section 'Conclusion'.

ESS scheduling problem under TOU pricing with demand charge

Let l_i and g_i be the amounts of load and generation during time interval i, respectively, and x_i be the battery residual value when the interval i ends. Time intervals can be set arbitrarily according to the design of the problem. In this study, one hour was used for the time interval and it is assumed that $x_0 = 0$, which means that the battery is initially empty. Then, charge amount during time interval i is $x_i - x_{i-1}$ and E_i^{net}, the net energy supplied from the grid, is calculated as follows:

$$E_i^{net} = x_i - x_{i-1} + l_i - g_i.$$

The energy charge(cost) at time interval i becomes $E_i^{net} p_i$, where p_i is the price at time interval i. The amount of net energy can be negative. For example, if the load during a time interval is 1.2kWh, the generation during the time interval is 1.5kWh, and ESS charge amount is zero, then the amount of generation exceeds the amount of load. The net energy has the negative value of -0.3kWh. In this case, electricity is sent back to the grid. There may be several pricing policies for this feed-in electricity. If the compensation of feed-in electricity is small, residential customers can be expected to consume most of the energy that they generate themselves. This promotes self-consumption of electricity and has environmental benefits. Conversely, a large compensation can promote stability of supply at on-peak times. The compensation of the feed-in electricity is not considered in this study, even if the amount of net energy is negative. This reflects the forecast that the price of the feed-in electricity will be almost zero in the near future to promote the self-consumption of PV energy. Actually, PV feed-in-tariffs is decreasing in some European countries [3]. In this case, if E_i^{net} is negative or equal to zero, the energy charge during time interval i is just zero because the residential customer does not need to buy electricity and does not receive any compensation from the electricity utility. Otherwise, if E_i^{net} is positive, the energy charge during time interval i is $E_i^{net} p_i$. So, C_i^{net}, the energy charge during time interval i, can be calculated as follows:

$$C_i^{net} = \begin{cases} E_i^{net} p_i, & \text{if } E_i^{net} > 0 \\ 0, & \text{if } E_i^{net} \leqslant 0 \end{cases}$$

The total energy charge is $\sum_{i=1}^{T} C_i^{net}$, where T is the number of time intervals. We considered 24 hourly data for this study, so T is set to be 24 for the analysis and experiments in this study.

The total electricity charge is calculated as the sum of energy charge at each time interval and demand charge. Demand charge is calculated by multiplying a fixed rate and the amount of peak demand during a certain period. Let p^* be the fixed rate, then the demand charge is $\max_{1 \leqslant i \leqslant T} E_i^{net} p^*$. In summary, if we do not consider the efficiency factor of a battery, the problem is formulated in the following.

Minimize

$$\sum_{i=1}^{T} C_i^{net} + \max_{1 \leqslant i \leqslant T} E_i^{net} p^*, \tag{1}$$

subject to

$$0 \leqslant x_i \leqslant C, \quad i = 1, 2, \ldots, T, \tag{2}$$

$$-P_d \leqslant x_i - x_{i-1} \leqslant P_c, \quad i = 1, 2, \ldots, T, \tag{3}$$