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A cost-efficient and reliable energy management of a micro-grid using intelligent demand-response program

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ABSTRACT

Providing a cost-efficient and reliable energy is one of the main issues in human societies of the 21st century. In response to this demand, new features of micro grid technology have provided huge potentials, specifically by the capability of having an interactive coordination between energy suppliers and consumers. Accordingly, this paper offers an improved model for achieving an optimal Demand Response programing. To solve the proposed multi-objective optimization problem, Artificial Bee Colony algorithm and quasi-static technique are utilized. The considered objectives in this paper are minimizing the overall cost of energy consumption and also improving the technical parameters of micro grid over a time horizon. This optimization is subject to several constraints such as satisfying the energy balance and the operating constraints of each energy supply sources. Manageable load or load as source is another enabling feature existing in smart energy networks, which is considered in this paper and its effect on cost reduction and reliability improvement is studied. Trying to examine the performance of the proposed Demand Response Programing in real conditions, the uncertainties are also analyzed by stochastic methods. The results show significant improvements which are obtained by applying just intelligent programming and management.

1. Introduction

Optimizing and attempting to achieve the best options have always been one the appealing concepts in the philosophy of control. One of the most serious challenges facing the human societies of the 21st century is energy issue. Among very different solutions and methods offered to deal with the concept of energy saving, smart grid networks and DR (Demand Response) provide both an opportunity and an enabling infrastructure for improving the efficiency and energy consumption [1–4]. US DOE (Department of Energy) defines DR as: changes in electric usage by end-use customer from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system stability is jeopardized [5]. According to this definition, it will be essential to propose a methodology like in Ref. [6] to evaluate and quantify the economic parameters (costs and benefits) attached to customer electricity consumption by analyzing the service provided by the different "pieces" of absorbed electricity. Using these parameters draw conclusions for optimal mix energy choices.

As one of the most enabling features in smart grid infrastructure, two-way information flow between energy markets and customers, makes it possible to use intelligent DR programs to fulfill both sides' interests by improving load profile characteristics and achieving customers' satisfaction. Specifically speaking, by using direct digital controls for building HVAC (heating, ventilation, and cooling systems), and dimmable ballasts [7], customer can play a more active and intelligent role to reach not only his interests but also by playing a cooperative game with energy providers, more general goals like environmental and technical issues are achievable. Along with the proliferation of large sums of renewable energy across the globe, a shift in the balance of energy resources has occurred. Indeed, this trend will considerably affect supply strategies, as renewable energy sources are available for a certain period of time in a day and normally the peak demand occurs in some other times.

In line with these notable challenges, several algorithms and models have been formulated in the literature. In Ref. [8], an optimization model is proposed which utilizes the MINLP (mixed

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Nomenclature

t Time period index, $t = 1, 2, \ldots, T$.
τ Period span (in hour).
$p(t)$ Power from the grid at t (kW).
$p_s(t)$ Solar generation at t (kW).
$p_b(t)$ Battery charge or discharge at t (kW).
$p_c(t)$ CHP generation at t (kW).
$q_c(t)$ Cooling quantity supplied by CHP unit at t (kW).
$V(t)$ Volume of natural gas used by CHP unit at t (m^3).
$e_{HVAC}(t)$ Electrical energy consumption of HVAC (kWh)
$e_{electrical}(t)$ Electrical energy consumption at t (kWh)
$C_p^d(t)$ Electrical energy supply price at t (RMB/kWh)
$C_p^u(t)$ Electrical energy price fed into power grid at t (RMB/kWh)
$C_t^p(C_p^d(t), C_p^u(t), p(t), \tau)$ Total cost of electrical energy at t (RMB)
$c_n(t)$ Natural gas price at t (RMB/m^3)
$C_t^n(c_n(t), V(t), \tau)$ Total cost of natural gas at t (RMB)
$e(t)$ Quantity of grid energy supply at t (kWh)
P_R Charging and discharging cost (RMB)
P_{m,d_m} Total Consumed power over t
N Number of slots for each interval
$e_s(t)$ Quantity of solar energy at t (kWh)
e_j^{charge} Quantity of battery energy charge at j (kWh)
$e_j^{decharge}$ Quantity of battery energy charge (positive) or discharge (negative) at t (kWh)
$e_c(t)$ Quantity of CHP energy delivery at t (kWh)
$x_c(t)$ Electrical load rate of CHP at t, (ratio between power supply and the capacity)
$\underline{x}_c(t)$ Minimal generation rate of CHP unit
$\overline{x}_c(t)$ Maximal generation of CHP unit
$\overline{e}_b(t)$ Capacity of battery (kWh)
$\overline{x}_b$ The lower bound of state of charge of battery
$\underline{x}_b$ The upper bound of state of charge of battery
$\overline{p}_c(t)$ Capacity of CHP (kW)
$\underline{p}_c(t)$ Minimal output power of CHP (kW)
π_i Profit in period i (RMB)
C_j^{net} Net price in period j (RMB)
COP Coefficient of performance
D_m Total number of loads
y_{m,d_m}^i Consumed energy by d_h in i^{th} interval
E_{m,d_m} Total energy consumption over t

integer nonlinear programming) technique for minimizing the electricity cost and reducing the peak demand. In this paper, however, storage systems are not considered in the modeling. In Ref. [9], the authors formulate a model which uses battery charge and discharge to minimize the overall cost of energy. However, a single-objective function is proposed in this paper and the battery utilization in enhancing other parameters such as peak load reduction is not considered. Ozturk and et al. propose an integrated solution to predict and re-engineer the electricity demand (e.g., peak load reduction and shift) in a locality at a given day/time [10]. The major drawback of using a predictor is its high sensitivity on system model accuracy and the issue that model mismatches will influence the performance. In Ref. [11], a demand side scheduling algorithm is proposed to arrange the household appliances for operation such that the monetary expense of a customer is minimized based on the time-varying pricing model. The proposed algorithm takes into account the uncertainties in household appliance as well as variable frequency drive and capacity-limited energy storage. Dynamic demand-responsive generation management based on energy price adjustments is one of the mechanisms for efficient and reliable energy generation that creates a balance in energy markets. [12] presents a control theoretic approach for management of energy balance with this mechanism.

In this paper, an intelligent DR program algorithm is presented which utilizes Artificial Bee Colony algorithm and quasi-static technics to minimize a multi-objective optimization model. The objectives included in this optimization model are minimizing the overall cost of energy consumption and reshaping the load profile by reducing the demand peak. The studied case, in this paper, is a low power building with the electrical and thermal load profiles from the related work [13]. The considered energy supply sources are power grid, solar PV (Photovoltaics), battery, and CHP (Combined Heat and Power) unit so the overall cost function can be formulated as a function of electricity cost declared by the utility and the natural gas price. Obviously, the key to minimize the cost is to fully utilize the solar energy, battery, and CHP unit as much as possible because of their initial investment costs. The second objective in this paper is demand peak reduction, which helps improving the overall micro grid reliability as well as reducing the energy generation costs [14]. It is shown that the combination of both the cost minimization and demand profile refinement with electrical source scheduling is an effective way in energy management. To evaluate the performance of this algorithm in real conditions, the uncertainties and their impacts are also captured and analyzed by the scenario tree method.

2. Model formulation

Defining the economic characteristics of distributed energy resources, different models have been formulated in the literature so far [9,15]. In this paper, however, an improved model is proposed. This model is a combination of previous works and newly added formulations for battery charge and discharge. In this programming, load is playing an active role as a source which facilitates achievement of the mentioned objectives. The seeking objectives can be summarized in two goals: firstly, minimizing the overall energy cost and secondly, reducing the rebound peak. The overall energy cost is a function of electricity price with TOU (time of use) ratings and natural gas calculated over a scheduling horizon.

To simplify the procedure, the two-objective function can be equivalently solved in two steps. Firstly, the scheduling problem is considered as determining the supply quantity of each energy resources over a scheduling horizon. In this step, load profile is considered fixed and the seeking goal is minimizing the total cost of electricity and natural gas. In the second step, an energy consumer h with $D_{h-total}$ devices and D_h "schedulable" devices is considered. A schedulable device means a device which has certain flexibility in its time of use, rather than with a fixed or determined schedule like some refrigerator. Thermal loads including thermostatically controlled appliances, however, are not considered schedulable as they are dependent on end-users' desire. As shown in Ref. [15], load management can affect very much on reducing rebound peak. Accordingly, 10% of the electric energy consumption is considered schedulable in this paper.

It will be shown in the following that by combining these two steps, the final goals, which are minimizing the energy cost and reducing the demand peak, are achievable.