A Service-based Approach Toward Management of Grid-tied Microgrids

Babak Asghari, *Member, IEEE,* Ali Hooshmand, *Member, IEEE,* and Ratnesh Sharma, *Member, IEEE*

***Abstract*—This paper presents an energy management framework in which various services can be delivered by a microgrid to the utility. A service is defined in terms of an adjustment in power flow profile at the point of common coupling that should be enforced during the service period. A microgrid equipped with a diverse set of generations, storage units, and flexible demands can provide a range of services for reliable and economic operation of the grid. A multi-objective optimization approach is used to formulate the energy management problem based on service definition and operational cost of a microgrid. It is shown that a set of Pareto optimal solutions can be calculated for operation of a microgrid during each service period. Simulation results for two case studies related to peak shaving and minimum power fluctuation services are presented and discussed to verify the proposed approach.**

***Index Terms*—Microgrid, Service-based Management, Multi-objective Optimization, Weighted Sum Method.**

I. Introduction

GROWING number of distributed generation (DG) and energy storage installations by the end-users have introduced new challenges and opportunities for reliable and efficient operation of the grid. The electricity demand is increasing in the world but it is also getting equipped with automated control systems which add more flexibility to the electricity consumption. Moreover, advanced metering infrastructure (AMI) have provided the necessary tools to realize a smart grid in which two way communication between utilities and end-users as well as real-time measurement and monitoring of consumption/generation at each node on the grid is possible.

The evolution of smart grid has resulted in the emergence of intelligent structures called microgrids that can exchange power, information, and control signals with each other and the rest of the grid as requested. A grid-tied microgrid is an aggregated system consisting of local loads, energy resources, energy storage units, and a utility connection to import/export power from the grid if necessary [1]. One of the main objectives of operating a microgrid is to reduce final cost of electricity supplying the demand in the microgrid.

The authors are with the Energy Management Department, NEC Laboratories America, Inc., Cupertino, CA 95014, USA (e-mail: babak@nec-labs.com, ahooshmand@nec-labs.com, ratnesh@nec-labs.com).

Utilities have already started to take advantage of the smart grid by introducing demand response programs for demand management in the grid [2]. In price based programs (PBP) a microgrid adjusts its operation to minimize its cost based on dynamic tariffs set by the utility [3],[4]. In incentive based programs (IBP) participants usually receive payments as a credit based on their performance in the programs [5].

The combination of generation, storage, and flexible load which is present in a microgrid provides a powerful tool for adjusting the power flow between the grid and the microgrid at the point of common coupling (PCC). Fig. 1 shows typical power flow among components of a grid-tied microgrid and the grid at PCC. The power flow profile (P_G) at PCC can be adjusted over a period of time to achieve a certain objective function (service) requested by the utility. In this way a microgrid not only serves the internal purpose of reducing its operational cost, but also delivers a wide range of services to the grid operator to improve grid conditions.

This paper presents a general framework for optimizing operation of a microgrid when it delivers a service to the utility. A multi-objective optimization approach is utilized because in this scenario two different (and sometimes contradictory) objective functions related to microgrid operational cost (internal) and quality of delivered service to the grid (external) should be optimized at the same time. The multi-objective optimization solution is usually not unique and consists of a set of points (Pareto front) that all fit a predetermined definition for an optimum [6]. Two case studies for a microgrid with flexible loads and an energy storage unit delivering peak shaving and minimum power fluctuation services to the utility are studied. It is shown that the Pareto front solution in each case provides insight about how to operate the microgrid. The rest of this paper is organized as follows. Section II describes the operational cost formulation for a grid-tied microgrid with distributed generations, flexible loads, and storage units. Section III defines the service objective function. Multi-objective optimization and its application to microgrid operation is discussed in Section IV. Section V presents and discusses the results for two case studies followed by conclusion in Section VI.

978-1-4673-6605-2/15/$31.00

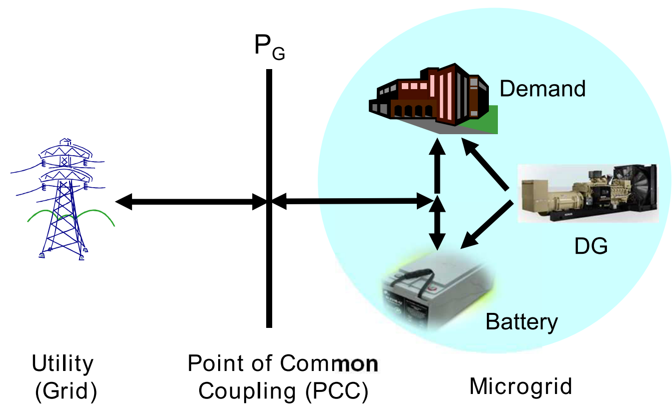

Fig. 1. A grid-tied microgrid.

II. Microgrid Operational Cost

The energy management system (EMS) of a microgrid is usually designed in a way to minimize operational cost of the microgrid with minimum impact on the user's comfort. This minimization problem for a grid-tied microgrid consisting of distributed generations, energy storage units and flexible loads over a time period of T can be written as:

$$\min \quad f := \sum_{t=0}^{T} C_G(t)P_G(t) + C_{DG}(t)P_{DG}(t) + C_{Batt}(t)\,|P_{Batt}(t)| + C_{DM}(t) \tag{1}$$

where f is the objective function (operational cost). C_G, P_G, C_{DG}, P_{DG}, C_{Batt}, P_{Batt}, and C_{DM} are gird tariff, grid power, DG generation cost, DG power, battery wear cost, battery power, and demand management cost respectively.

DG generation cost usually depends on DG fuel cost. Renewable generation cost is assumed to be free as there is no fuel cost involved in the electricity generation from these resources. An average battery wear cost based on rated battery parameters can be calculated as follows:

$$C_{Batt} = \frac{C_{Batt}^{capital}}{L_{rated} \times DoD_{rated} \times C_{rated} \times 2} \tag{2}$$

where $C_{Batt}^{capital}$, L_{rated}, DoD_{rated}, and C_{rated} are capital cost of the battery($), rated cycles, rated depth of discharge, and rated capacity respectively. The battery wear cost in (2) is divided by two and then multiplied by the absolute value of battery power in (1) so that equal charge and discharge powers have the same impact in terms of battery wear cost. A more detailed battery wear cost formulation based on actual charge and discharge of battery can also be used as described in [7].

Demand management cost of a microgrid, C_{DM}, in (1) is captured through a disutility function. This function models the dissatisfaction of the user based on the deviation of the actual electricity consumption from customer scheduled consumption, as follows:

$$C_{DM}(t) = \alpha\,|P_D(t) - P_D^*(t)| \tag{3}$$

where $P_D(t)$ and $P_D^*(t)$ are actual and scheduled (target) demand at time t respectively. α is the load sensitivity factor determined based on the impact of deviation in demand on the user dissatisfaction.

The cost minimization problem in (1) is subjected to following constraints:

(1) Supply-Demand balance which is an equality constraint and the primary task of management system. This constraint is formulated as follows:

$$P_G(t) + P_{DG}(t) + P_{Batt}(t) = P_D(t) \tag{4}$$

which means the summation of generated power by grid, battery, and renewable source should be equal to demand at each time.

(2) Battery state of charge (SoC) difference equation:

$$SoC(t+1) = SoC(t) - k\,P_{Batt}(t) \tag{5}$$

in which $SoC(t)$ is battery state of charge at time t and k is a coefficient which converts battery power into SoC changes.

(3) Upper and lower bounds for battery SoC which by considering the SoC difference equation (5) will be a dynamic inequality constraint:

$$SoC^{\min} \leq SoC(t) \leq SoC^{\max} \tag{6}$$

(4) Grid power, DG power, and demand are always greater than or equal to zero. Note that in this paper it is assumed that sell back of power to the utility is not allowed.

$$0 \leq P_D(t), P_G(t), P_{DG}(t) \tag{7}$$

The solution of minimization problem in (1) subject to (4)-(7) provides optimal setpoints for operation of generation, storage, and demand in a microgrid in order to minimize its operating cost over a period of T. Decision variables for this optimization problem are P_G, P_{DG}, P_{Batt}, and P_D. (1) can be reformulated into a convex LP problem by using auxiliary variables instead of absolute values [8].

III. Service Objective

A grid-tied microgrid is an aggregated entity which is electrically connected to the utility at the point of common coupling (PCC). Thus, a service from a microgrid to the utility is defined as a function of the grid power (P_G) that needs to be minimized over a period of time (T). The original definition of a service requested by the utility might not be in the form of a minimization problem as will be shown in case Study I. Therefore it is necessary to transfer the original service request into a minimization problem as follows:

$$\min\, g := \sum_{t=0}^{T} G(P_G) \tag{8}$$

where g is the objective function for the service delivery and G is the service function.

The requested service by the utility could vary multiple times in a day depending on the grid conditions. For some of these requests a microgrid might not be able to deliver the service to its full extent because of its operational constraint such as (4)-(7). The microgrid EMS is also concerned about microgrid operational cost as discussed in Section II. Therefore, in situations where the requested service is in mutual conflict with a microgrid operational cost, the microgrid EMS might decide to compromise the quality of delivered service in favor of reduction in microgrid cost.

IV. Multi-Objective Optimization

To provide a decision-making framework for a micorogrid EMS when confronted with different objectives, a multi-objective (bi-objective) optimization approach can be used. In this way the EMS can evaluate the consequences of a decision with respect to all the objective functions considered. When a new service request from the utility is received, the multi-objective problem is defined and solved by a microgrid EMS as follows:

$$\begin{aligned} &\min\,[f,\, g] \\ &subject\, to\;\; (4)-(7) \end{aligned} \tag{9}$$

In contrast to a single-objective optimization, there is no single global solution to a multi-objective optimization. Usually it is necessary to determine a set of optimal points called Pareto front. Each point in the Pareto front is a solution where there exist no other feasible solution that improves at least one objective function without compromising any other objective function [9]. The Pareto front for multi-objective optimization in (9) can be obtained using the weighted sum method [6] which reduces it to a scalar problem of the form:

$$\min\,(\frac{w_1}{sf_1}f + \frac{w_2}{sf_2}g) \tag{10}$$

where w_1 and w_2 are weighting factors and sf_1 and sf_2 are scale factors for function f and g respectively.

Proper scaling (normalization) of objective functions in weighted sum method is important to ensure the consistency of optimal solutions with decision maker preferences. Different methods to calculate the scaling factors in weighted sum method are discussed in [9]. To ensure a convex combination of objectives, weighting factors are chosen such that:

$$w_1 + w_2 = 1\ ,\ \ 0 \le w_1, w_2 \tag{11}$$

By varying the weighting factors in (10) and resolving the scalar optimization problem, different points of Pareto front can be calculated. Once the Pareto front is obtained, a decision maker can pick a desirable operation schedule to be followed during the service period.

V. Results and Discussion

In this section, two case studies for optimal operation of a microgrid delivering two different services to the utility at separate time intervals are presented. It is assumed that the sample microgrid only consists of flexible loads, an energy storage unit and a grid connection. However, the same approach can be applied to microgrids with distributed generations. All simulation studies are carried out in MATLAB using the Optimization Toolbox for a 3 hour service period with sampling time of 15 minutes. Microgrid parameters are given in Table I. The target demand during the service period is defined as:

$$P_D^*(t) = [0.1, 0.1, 0.3, 1.5, 0.2, 0.3, 0.5, 0.3, 2, 2, 2, 0.1]\, kW \tag{12}$$

TABLE I
Microgrid Parameters

Battery Capacity (Ah)	60
Battery Voltage (V)	48
Battery Minimum SoC (%)	50
Battery Maximum SoC (%)	100
Battery Initial SoC (%)	50
Grid Tariff ($/kWh)	0.2

A. Case Study I: Peak Shaving

In this case study, the requested service by the utility from the microgrid is peak shaving(PS). To deliver this service, the microgrid is expected to keep its imported power from the grid below a predetermined threshold during the service period. Although this service can be added as an extra constraint in the microgrid cost optimization of (1)-(7), it is desirable to formulate it as an independent minimization problem to be compatible with the general multi-objective optimization approach discussed in Section IV. For this purpose, the peak shaving service can be converted to a minimization problem be defining function g_{ps} as follows:

$$\min\;\; g_{ps} := \sum_{t=0}^{T} \max\{P_{peak-shaving}, P_G(t)\} - P_{peak-shaving} \tag{13}$$

where $P_{peak-shaving}$ is a constant for peak shaving threshold.

It can be seen from (13) that g_{ps} is equal to zero only if peak shaving constraint is satisfied completely during the entire service period. Depending on the duration and amount of violation from the peak shaving threshold during the service period, g_{ps} can assume positive values. (13) can be transformed into a LP problem by using the dummy variable $P_{\max}$ as follows:

$$\min\ g_{ps} := \sum_{t=0}^{T} P_{\max}(t) - P_{peak-shaving} \tag{14}$$

subject to:

$$P_{peak-shaving} \leq P_{\max}(t)\ ,\ \ P_G(t) \leq P_{\max}(t) \tag{15}$$

The Pareto front for peak-shaving service can then be obtained by solving the bi-objective optimization problem using (1) and (14) as the objective functions and (4)-(7), (15) as the constraints. To generate a well-distributed solution along the entire Pareto front region, an adaptive weighted sum method [10] is utilized in this case study.

Fig. 2 shows the Pareto front for two scenarios with the load sensitivity factor (α) equal to 10, peak shaving threshold equal to 1kW, and battery wear cost equal to 1$/kWh (scenario 1) and 0.1$/kWh (scenario 2) respectively. As can be seen in this figure, in both scenarios the service function (g_{ps}) varies between 0 (complete peak shaving) and 3.5 (no peak shaving) at extremes of Pareto front. However, over the entire Pareto front, microgrid operation cost is higher in scenario 1 compared to scenario 2 except when no peak shaving is applied in the microgrid ($g_{ps} = 3.5$). This is because in scenario 2 both load sensitivity factor and battery wear cost are high which makes any peak shaving through load shedding and/or battery discharge more expensive in terms of microgrid operation cost.

The microgrid EMS or system operator can use the Pareto front plots in Fig. 2 to chose the optimal operation schedule during the service period. For example the EMS might decide to provide full peak shaving service in scenario 2 because its impact on microgrid operation cost is less than 38%. However, in Scenario 1 partial or no peak shaving might be preferred because a full peak shaving will increase the microgrid operating cost by 370% compared to when no peak shaving is performed.

To compare the optimal microgrid schedule for scenarios 1 and 2, the grid power (P_G) and demand (P_D) profiles during the service period for solution points 1 and 2 from the Pareto fronts are plotted in Fig. 3. It can be seen that in both scenarios, the optimal demand schedule (P_D) follows the target demand ($P_D^*(t)$). This is because the load sensitivity factor (α) set by the user is equal to 10 which makes any load shedding expensive and thus non-optimal. Also, as expected from the Pareto fronto plot, the optimal grid power in scenario 1 (P_{G1}) is completely

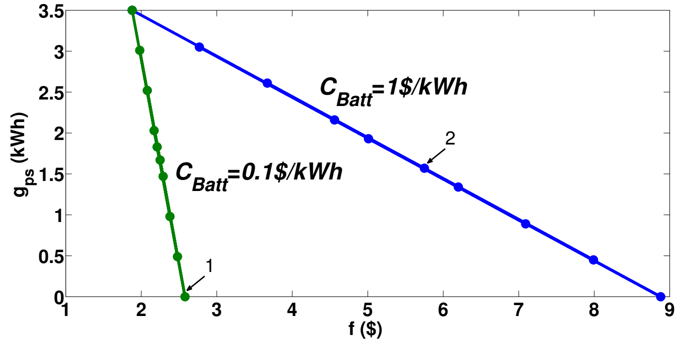

Fig. 2. Pareto fronts for scenarios 1 and 2 (Case Study I: PS service).

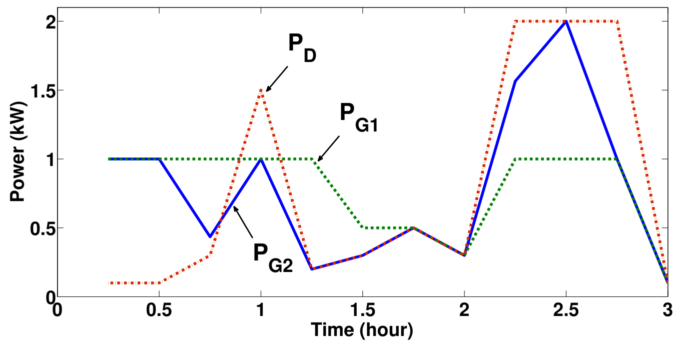

Fig. 3. Optimal grid and demand power profiles for points 1 and 2 in Fig. 2 (Case Study I: PS service).

regulated below or equal to the peak-shaving threshold of 1kW. However, in scenario 2 only partial peak shaving during the service period is scheduled to avoid excessive operation cost. The battery state of charge (SoC) for scenarios 1 and 2 are depicted in Fig. 4. It can be seen that battery SoC variation (charge and discharge events) scheduled for scenario 2 is less than scenario 1 in order to reduce battery wear cost and therefore reduce the overall microgrid operation cost.

B. Case Study II: Minimum Power Fluctuation

In the second case study, minimum power fluctuation (MPF) service is studied. To deliver this service to the utility, a microgrid needs to minimize the grid power (P_G) fluctuation at the PCC during the service period. By providing this service a microgrid can contribute to grid stability and reduce the necessary amount of reserve on the network. The minimization problem associated with this service can be described in terms of the grid power variance during the service period by defining function g_{mpf} as follows:

$$\min\ g_{mpf} := \frac{1}{T}\sum_{t=0}^{T}(P_G(t) - \mu_{P_G})^2 \tag{16}$$

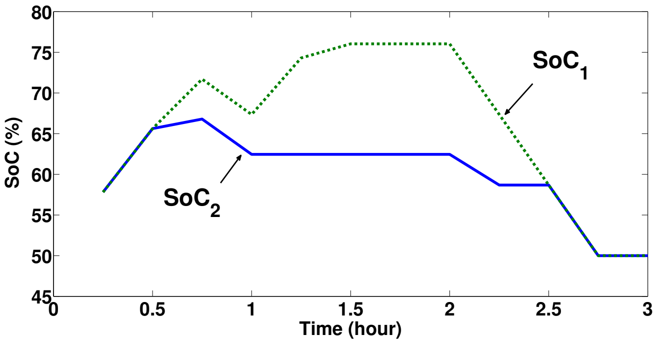

Fig. 4. Optimal SoC profiles for points 1 and 2 in Fig. 2 (Case Study I: PS service).

where μ_{P_G} is the average grid power during the service period:

$$\mu_{P_G} = \frac{1}{T}\sum_{t=0}^{T} P_G(t) \tag{17}$$

After some algebraic manipulation, the objective function g_{mpf} can be written in a standard quadratic programming (QP) format as follows:

$$g_{mpf} = \frac{1}{T}\bar{P}_G^T(I - \frac{1}{T}\Lambda)\bar{P}_G \tag{18}$$

where $\bar{P}_G$ is the grid power vector during the service period. I is the Identity matrix and Λ is a matrix of ones.

By defining MPF service function as in (18) a QP solver can be utilized to calculate the Pareto front for bi-objective optimization of (1) and (18) with (4)-(7) as the constraints. Fig. 5 shows Pareto fronts for two scenarios with the load sensitivity factor (α) equal to 1 and battery wear cost equal to 1\$/kWh (scenario 1) and 0.1\$/kWh (scenario 2) respectively. Similar to Case Study I, an ideal service (zero power fluctuation at PCC) can be delivered by the microgrid to the utility in both scenarios. However the adverse impact of ideal service delivery on microgrid operation cost in scenario 1 is 55% which is considerably less than scenario 2 (320%). Pareto front of Fig. 5 can be used by the microgrid EMS or system operator to decide upon the optimal operation schedule during the MPF service period.

Fig. 6 shows grid power profiles (P_G) during the MPF service period for different points on the Pareto front of scenario 1. As can be seen, grid power fluctuation decreases as more weight is given to the service objective compared to the microgrid operation cost objective. In other words, less fluctuation in grid power occurs when the value of w_2 in multi-objective optimization of (10) is increased. To study a sample microgrid operation schedule during the MPF service period, power profiles of grid (P_G), demand (P_D), and battery (P_{Batt}) for point 1 in Pareto front of Fig. 5 are depicted in Fig. 7. It can

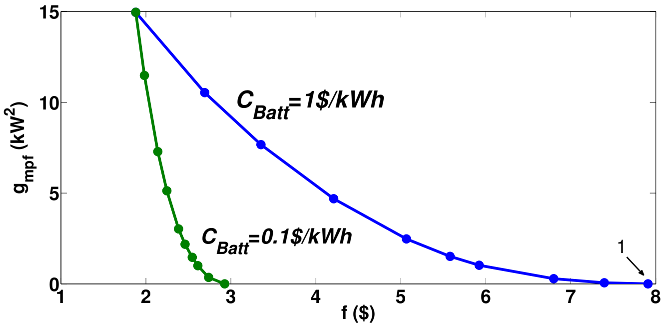

Fig. 5. Pareto fronts for scenarios 1 and 2 (Case Study II: MPF service).

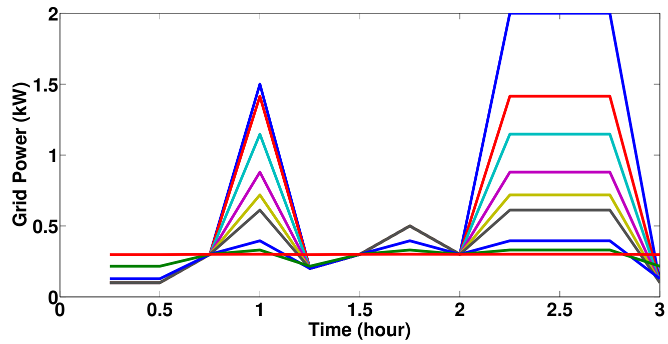

Fig. 6. Grid power profiles across Pareto front of scenarios 1 (Case Study II: MPF service).

be seen that grid power profile (P_G) is constant at 300W (zero fluctuation) during the entire service period. This is expected from the value of function g_{mpf} at point 1 which is equal to zero. To achieve a flat grid power profile, microgrid electricity consumption ((P_D)) is severely reduced compared to the target demand ($P_D^*(t)$). Battery charge/discharge profile (P_{Batt}) is also adjusted in a way to compensate any load deviation below or above the 300W reference point. It is to be noted that battery and demand profiles of Fig. 7 minimizes the microgrid operation cost when ideal MPF service is delivered to the utility.

VI. Conclusion

In a smart grid era with advanced communication infrastructure in place and abundance of microgrids connected to the bulk distribution system, it is necessary to redefine the nature of interaction between utilities and microgrids. Utilities can request a wide range of services from microgrids at different time intervals to achieve more efficient and stable operation of the grid. Similarly, microgrids can deliver various services to the utility by adjusting operation of their diverse resources such as distributed generations, energy storage units, and flexible loads. In this paper a multi-objective optimization framework for service-based management of grid-tied microgrids is proposed.

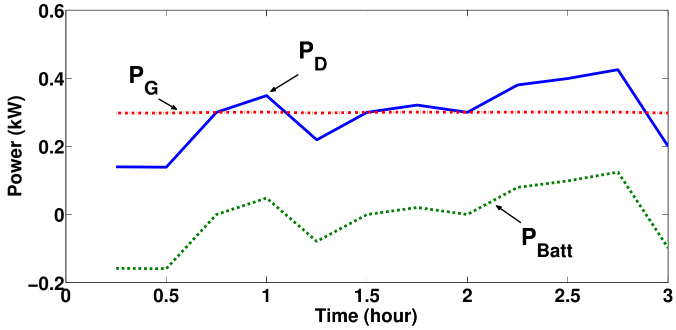

Fig. 7. Optimal grid, demand and battery power profiles for point 1 in Fig. 5 (Case Study II: MPF service).

In this framework the first objective is to minimize operating cost of a microgrid as the main driving factor for its utilization. For this minimization problem a comprehensive cost model including generation, storage, and demand management costs is discussed in the paper. In the second objective power flow profile at the point of common coupling is adjusted over a period of time to deliver a service to the utility. It is shown that weighted sum method can be used to obtain a set of optimal solutions (Pareto front) based on the service definition and parameters of the microgrid. To show the effectiveness of proposed approach, simulation results for two case studies related to peak shaving and minimum power fluctuation services delivered by a sample microgrid to the utility are presented and discussed. Pareto front solutions obtained from the proposed framework can be used by energy management systems or microgrid operators to define optimal operation schedule for different components of a microgrid during each service period.

REFERENCES

[1] R. Lasseter, and P. Paigi, "Microgrid: A conceptual solution", *IEEE Power Electronics Specialists Conference (PESC)*, pp. 4285-4290, 2004.

[2] M. H. Albadi, and E. F. El-Saadany, "Demand Response in Electricity Markets: An Overview", *IEEE Power Engineering Society General Meeting*, pp. 1-5, 2007.

[3] Zh. Pan, H. Sun, and Q. Guo, "TOU-Based Optimal Energy Management for Smart Home", *IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe) Conference*, pp. 1-5, 2013.

[4] A. J. Conejo, J. M. Morales, and L. Baringo, "Real-Time Demand Response Model", *IEEE Trans. on Smart Grid*, vol. 1, no. 3, pp. 236-242, Dec. 2010.

[5] P. Khajavi, H. Abniki, and A. B. Arani, "The Role of Incentive Based Demand Response Programs in Smart Grids", *10th International Conference on Environment and Electrical Engineering (EEEIC)*, pp. 1-4, 2011.

[6] R. T. marler, and J. S. Arora, "Survey of Multi-Objective Optimization Methods for Engineering", *Structural and Multidisciplinary Optimization*, vol. 26, no. 6, pp. 369-395, 2004.

[7] A. Hooshmand, B. Asghari, and R. Sharma, "A Novel Cost-Aware Multi-Objective Energy Management Method for Microgrids", *IEEE PES Innovative Smart Grid Technologies (ISGT) Conference*, 2013.

[8] J. Bisschop, "AIMMS-optimization modeling", *Lulu. com*, 2006.

[9] H. Mausser, "Normalization and Other Topics in Multi-Objective Optimization", *Proc. of the Fields-MITACS Industrial Problems Workshop*, pp. 89-101, 2006.

[10] I. Y. Kim, and O. L. De Weck, "Adaptive Weighted-Sum Method for Bi-Objective Optimization: Pareto Front Generation", *Structural and Multidisciplinary Optimization*, vol. 29, no. 2, pp. 149-158, 2005.