ENERGY AND RESERVE SCHEDULING OF MICROGRID USING MULTI-OBJECTIVE OPTIMIZATION

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ABSTRACT

Demand response has become a key feature of the future smart grid. On the other hand, Renewable energy sources, in particular wind and solar power, are becoming significant power generation technologies around the world. However, the intermittency and inherent stochastic nature of renewable resources becomes the major obstacle for reaching a large benefit of them. In this paper, therefore, an operational planning model of a Micro Grid (MG) which considers multiple demand response (DR) programs is proposed. Operation cost and emission are two objectives function in this model that are minimized by epsilon constrain multi-objective optimization. The proposed model has been tested on a typical microgid network over a 24-hour horizon.

INTRODUCTION

In Micorgrid (MG) operational planning the following issues should be considered: Maintaining balance between the generation and consumption through the MG, facilitating the demand side participation in operational planning, helping the DG owners and loads to participate in multiple electrical energy programs that cause to earn more benefit, reserve scheduling for covering renewable generation forecast error.

In [1], a smart energy management system (SEMS) was presented to optimize the operation of the MG. This paper also considered photovoltaic (PV) output in different weather conditions as well as hourly energy price of main grid. However, this model did not allocate reserve for renewable uncertainty and did not consider load participation in demand response program. In In [2], both emission and economic objectives were considered in MG operational scheduling. It used Mesh adaptive direct search algorithm to minimize the cost function of the system but did not consider demand side participation in energy market and ignored the wind and solar forecast error. Control schemes for proper load sharing between parallel converters connected in a microgrid and supplied by DGs has been proposed in [3]. Each of the DGs has a local load connected to it and common loads are also connected to the MG which are supplied by the main grid. The proper load sharing and power quality was improved in this work.

The real-time pricing scheme for residential load management was proposed in [4] and [5]. These papers presented an automatic and optimal scheme for the operation of each appliance in household in presence of a real-time pricing tariff. Demand response roles as an additional option for reserve capacity has been discussed in [6], that the results showed DR can reduce wind balancing costs.

The main focus of this paper is simultaneous scheduling of energy and reserve in a microgrid with cost and emission minimization. Also the loads are able to participate in energy and reserve scheduling to earn some benefits. The reserve will be scheduled to cover the wind and solar generation error forecast.

MODEL DESCRIPTION

The energy and reserve scheduling of MG is run for 24-hour to calculate the hourly energy and reserve requirement form upstream grid for the next 24 hours. Also this scheduling will determine the generation output of DGs as well as demand participation. Moreover, the reserve requirement will be calculated in this stage.

In the proposed model, Microgrid Operator (MGO) intends to decrease the total operation cost of MG, and considers all technical constraints. The objective cost function of this model (F^{cost}) is sum of overall hourly operation cost of MG which is given by (1):

$$F^{cost} = \sum_{t=1}^{T}\sum_{i=1}^{I}[C(i,t) + SU(i,t)] + \sum_{t=1}^{T}[CG(t) - RG(t)] + \sum_{t=1}^{T}\sum_{l=1}^{L} IDE(l,t).IO_E(l,t) + \sum_{t=1}^{T}\sum_{h=1}^{H} HDE(h,t).HO_E(t) + RC \quad (1)$$

where $C(i,t)$ is the bid form ith DG at tth period that covers all fuel and maintenance costs as well as capital cost. $SU(i,t)$ is start-up cost of DG, $CG(t)$ and $RG(t)$ are the purchased energy cost and sold energy revenue to/from main grid, respectively. $IDE(l,t)$ and $IO_E(l,t)$ are the energy reduction amount in kWh and price offer in $\$/kWh$ by lth industrial or commercial loads, respectively. The residential (home) energy reduction by h th home is indicated with $HDE(h,t)$, the incentive payment for reduction is shown by $HO_E(t)$, and the reserve commitment cost is indicated by RC.

The bid function of each DG should contain the fuel cost and maintenance cost (a_i) as well as the investment cost (b_i). The cost function of DG is given by (2):

$$C(i,t) = a_i.PG(i,t) + b_i \quad (2)$$

where $PG(i,t)$ is the active power output of ith DG at tth period of scheduling.

The MG in interconnected mode can exchange power with main grid. The cost and revenue of purchasing and buying power from upstream network is calculated as follows:

$$CG(t) = Ta_{PP}(t) \times Pg_{pp}(t) \quad (3)$$

$$RG(t) = Ta_{SP}(t) \times Pg_{SP}(t) \quad (4)$$

where $Ta_{PP}(t)$ and $Pg_{pp}(t)$ are the purchased electricity tariff and imported power from main grid at tth period, respectively. On the other hand, $Ta_{SP}(t)$ and $Pg_{SP}(t)$ are the sold electricity tariff and exported power from main grid at tth period, respectively. The electricity tariffs which are used for power exchange cost calculations are equal to hourly grid electricity price.

The reserve cost in the objective function is calculated by (5):

$$RC = \sum_{t=1}^{T}\sum_{l=1}^{L} IDR(l,t).IO_R(l,t) + \sum_{t=1}^{T}\sum_{h=1}^{H} HDR(h,t).HO_R(t) + \sum_{t=1}^{T}\sum_{h=1}^{H} R_{DG}(i,t).PR_{DG}(t) \quad (5)$$

where $IDR(l,t)$ and $IO_R(l,t)$ are the reserve amount and offer from lth load, respectively. Also $HDR(h,t)$ and $HO_R(t)$ are the residential load amount and price offer for participation in reserve market, respectively. The other source of offering reserves is DGs with $R_{DG}(i,t)$ and $PR_{DG}(t)$ that indicate reserve amount and bid.

The start up cost of DG units is calculated as follows:

$$SU(i,t) \geq Scost(i).(u(i,t) - u(i,t-1)) \quad (6)$$

$$SU(i,t) \geq 0 \quad (7)$$

where $Scost(i)$ is the start up cost of ith DG, and $u(i,t)$ is a binary variable that shows the on-off state of DGs.

The emission function (EF) of distributed generation is given as follows [7]:

$$\mathrm{F}^{\mathrm{emission}} = \sum_{t=1}^{T}\sum_{\mathrm{i}=1}^{\mathrm{I}} [\alpha_\mathrm{i} + \beta_\mathrm{i}\mathrm{PG(i,t)} + \gamma_\mathrm{i}\mathrm{PG(i,t)}^2]\, \xi_\mathrm{i} e^{\lambda_\mathrm{i}\mathrm{PG(i,t)}} \quad (8)$$

Where α_i, β_i, γ_i, ξ_i, λ_i are the coefficients of the air pollutants emission functions for distributed generation i.

The constraints of the proposed model are:

- power balance equation

$$\left(\sum_{i=1}^{I} PG(i,t)\right) + Pg_{pp} - Pg_{sp} + \eta.P_B^+(t) - P_B^-(t) \geq D(t) - \sum_{l=1}^{L} IDE(l,t) - \sum_{h=1}^{H} HDE(h,t) \quad (9)$$

where $D(t)$ is the predicted demand of whole MG at tth period, $P_B^+(t)$ and $P_B^-(t)$ are battery discharge and charge power at tth period. The efficiency coefficient of battery is considered by η. Power balance equation is the most important constraint in operation planning. If the total generation be less than consumption, the frequency of grid will be decrease and it is undesirable.

- DG unit output constraint

$$PG(i,t) \geq PG_i^{min}.u(i,t) \quad (10)$$

$$PG(i,t) + R_{DG}(i,t) \geq PG_i^{max}.u(i,t) \quad (11)$$

where PG_i^{min} and PG_i^{max} are the minimum and maximum limitation of ith DG output and $u(i,t)$ shows the on/off state of DG. The spinning reserve that is procured by ith DG is shown by $R_{DG}(i,t)$. The conventional DG like micro turbine, diesel generator and fuel cell may prepare spinning reserve, and WT and PV do not offer reserve.

- Battery charge and discharge constraints

The battery used in MG cannot charge and discharge arbitrary. The below constraint should be considered for scheduling program of battery:

$$SOC(t) = SOC(t-1) + P_B^-(t) - P_B^+(t) \quad (12)$$

$$SOC_{Min} \leq SOC(t) \leq SOC_{Max} \quad (13)$$

where $SOC(t)$ is the battery state of charge that shows how much electricity is reserved in it, SOC_{Min} and SOC_{Max} are the minimum and maximum capacity of battery, respectively. Also the charge and discharge limitation should be considered as follows:

$$P_B^-(t) \leq P_{B\_Max}^- \quad (14)$$

$$P_B^+(t) \leq P_{B\_Max}^+ \quad (15)$$

$$X(t) + Y(t) \leq 1; \qquad X, Y \in \{0,1\} \quad (16)$$

where $X(t)$ and $Y(t)$ are the binary variables that show battery charge and discharge state in each period.

- Reserve requirement

The reserve requirement is determined based on renewable generation forecast error as given by (17):

$$\sum_{l=1}^{L} IDR(l,t) + \sum_{h=1}^{H} HDR(h,t) + \sum_{i=1}^{I} R_{DG}(i,t) \geq R(t) \quad (17)$$

where $R(t)$ is the minimum reserve requirement at period t that is calculated by (18):

$$R(t) = \alpha.PG(w,t) + \beta.PG(pv,t) \quad (18)$$

where $PG(w,t)$ and $PG(pv,t)$ are output power from wind turbine and photovoltaic unit, α and β are the forecast error coefficients which are used to determine how much the output power of wind and solar units may unexpectedly change. These coefficients are calculated based on historical data and the geographical condition of MG.

Augmented ε-Constraint Method

The method that has been used in this paper is augmented ε-constraint method [8]. In order to properly apply the augmented ε-constraint method we must have the range of every objective function at least for the $p-1$ objective functions.

In some conditions, there is a challenge between reducing operation cost and amount of air pollutants emission produced by conventional generators. In order to overcome this dilemma, augmented ε-constraint method is used in this model.

For this model, only the range of the objective function $F^{Emission}$ is calculated in the augmented ε-constraint method, since $F^{\cos t}$ is the main objective function. Then, the range of the objective functions $F^{Emission}$ is divided to k equal intervals. Therefore, there are in total ($k+1$) grid points for $F^{Emission}$. Thus, ($k+1$) optimization sub-problems must be solved where some of these sub-problems may have infeasible solution space. The problem has the following form:

$$\min \left(F^{cost} - \delta \times \left(\frac{S_2}{r_2}\right)\right) \quad (19)$$

subject to:

$$F^{Emission} + S_2 = \varepsilon_i$$

Where (20)

$$e_i = F_{\max}^{Emission} - \left(\frac{F_{\max}^{Emission} - F_{\min}^{Emission}}{k}\right) \times i, i = 0,1,...,k$$

$F_{\max}^{Emission}$ and $F_{\min}^{Emission}$ represent the maximum and minimum values of the individual objective function, total air pollutants emission, based on the payoff table, respectively. r_2 is the range of the total air pollutants emission($F_{\max}^{Emission} - F_{\min}^{Emission}$).

In solving each of the sub-problems all the constraints of the model should be also considered. By solving each optimization sub-problem, one Pareto-optimal solution is obtained.

When the Pareto-optimal solution is obtained, one of the solutions should choose as the best compromise solution. Fuzzy set is introduced here to handle the problem [9].

NUMERICAL RESULT

The proposed operational planning model was tested on a typical MG in low voltage distribution network. This test system is depicted in Fig. 1. Two types of loads are considered in MG: three residential and two medium industrial workshops loads. A variety of DERs, such as two diesel generators, a directly coupled wind turbine (WT), and five Photovoltaic (PV) arrays are installed in MG. The minimum and maximum operating limits of DERs as well as their cost function coefficients are taken from [1], [10]. Data of actual wind and PV production and the hourly energy price of open market are taken from [10]. The capacities of DGs are presented in Table 1. The residential loads reduction offers for each house can be found in Table 2. The diesel generator fuel consumption and emission level is taken from [11-12]. The WT and PV generation forecast errors are taken as 20% of their hourly forecasted outputs. The proposed model is solved using mixed-integer linear programming solver CPLEX 9.0 under GAMS on a Pentium IV, 2.6 GHz processor with 4 GB of RAM.

Table I the technical and economical features of DERs

units	Min power (kW)	Max power (kW)
Diesel 1	6	100
Diesel 2	5	70
WT	0	30
PV1	0	5
PV2	0	5
PV3	0	5
PV4	0	5
PV5	0	5
Battery	-30	+30

Table II Typical load data of the study case network

hour	Demand(kW)	hour	Demand(kW)
1	52	13	72
2	50	14	72
3	50	15	76
4	51	16	80
5	56	17	85
6	63	18	88
7	70	19	90
8	75	20	87
9	76	21	78
10	80	22	71
11	78	23	65
12	74	24	56

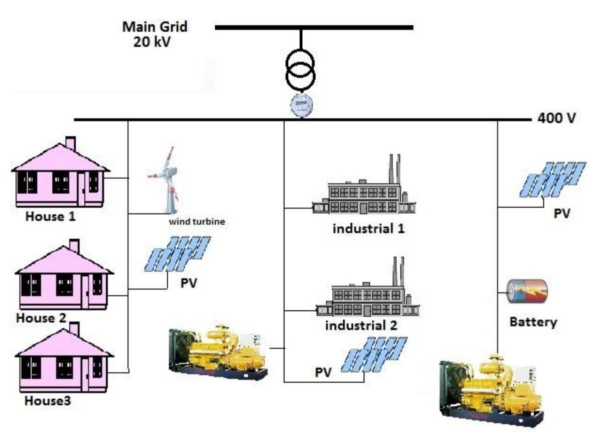

Fig. 1 Typical microgrid test system

Applying the augmented ε-constraint method, the obtained Pareto-optimal set has been shown in Fig. 2.

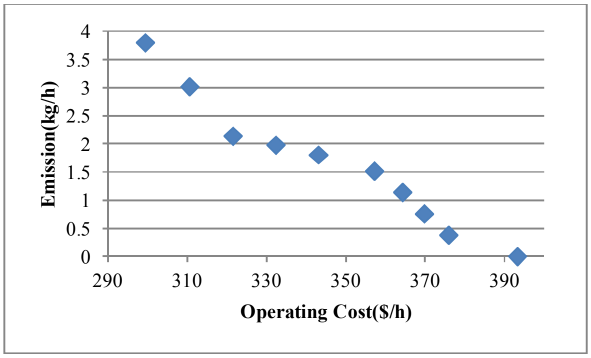

Fig.2 Pareto-optimal front of the proposed approach

After the Pareto-optimal solution is obtained, one of the solutions is chose as the best compromise solution using Fuzzy set. In this case, 5th solution has been chose.

The operational planning is performed by running multiple demand response programs. The generation scheduling of DERs and demand participation are shown in Fig. 3a and 3b. While loads participate in energy and reserve scheduling, the MT and FC scheduled power are changed. The demand participation in energy scheduling was presented in Fig. 3b. The results emphasize that the demand response in the hours with high energy price is higher than low energy price hours. That means the MGO intends to purchase load curtailment when the hourly energy price is high. The results also show that MGO plans to arrange loads to prepare reserve; in some hours that the grid energy price is higher than DGs offer, it prefers to use all capacity of DGs for delivering energy.

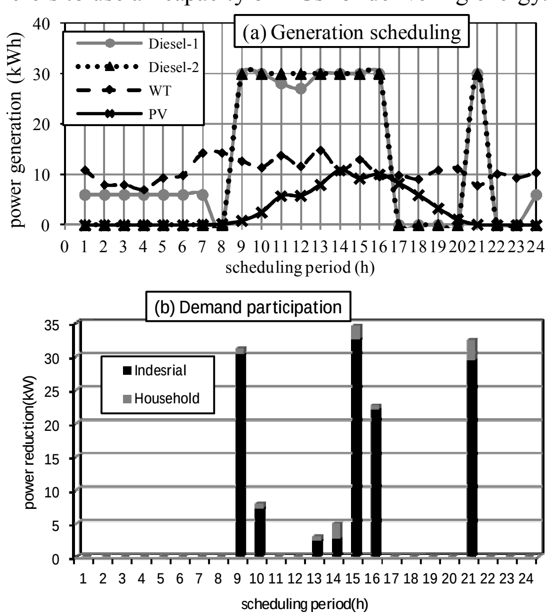

Fig. 3 Energy scheduling in scenario 2: (a) Generation scheduling, (b) Demand participation

CONCLUSION

In this paper, an energy and reserve scheduling approach, that manages generation and consumption through a MG by running multiple DR programs was proposed. The operating cost and emission level are considered as objective functions. This approach allows load to participate in both energy and reserve operational scheduling. The results show that minimizing emission level may increase operational cost and vice versa. In addition, the renewable uncertainty will also be covered by reserve scheduling through the operational planning program.

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