Renewable Based Hybrid Microgrid Scheduling Incorporating Demand Side Management

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Abstract.

A smart scheduling technique of a renewable integrated microgrid has been proposed and implemented in which generation side and demand side management are simultaneously utilized. Since solar and wind energy sources, which are intermittent in nature, are main energy providers in the microgrid, their variability has also been considered in the scheduling. A natural gas power plant and the grid have been considered as reserve sources. In the demand side management (DSM), a novel area based load shifting technique has been proposed along with voluntary demand reduction as load reserve. The overall aim of the paper has been set to develop a cost effective operation scheduling using generation reserves and DSM so that a balance is maintained between generation and demand over a day. The optimization has been done by cuckoo search algorithm. Simulation results demonstrate the smart scheduling satisfying the operating conditions mentioned in which substantial cost reduction is achieved.

Keywords. Demand Response, Demand Side Management, Energy Scheduling, Scenario Generation, Day Ahead Energy Cost.

1. Introduction

In recent days, environmental impacts and shortages of fossil fuels have increased interest in clean and renewable energy generation, including wind power, photovoltaic, hydroelectric power, natural gas based generation, fuel cells and micro turbines. Wind and solar energy are intermittent and unpredictable in nature and cannot be used for reliable power system operation. In a conventional system, generation follows the load pattern whereas since there is no control over renewable generation, in a renewable integrated system loads are made to follow the generation. To handle variability of renewable power generation effective forecasting method is necessary. Petre et al. described short term wind forecasting by Markov chain and Chapman-Kolmogorov equations [1]. This technique was useful to generate data even if errors may creep in which needs estimation. So, to include this variability in the power system, stochastic models were needed for safe and cost effective operation of power system. In stochastic model, uncertainty was represented by scenarios which could be generated by various methods [2]. Generally, forecast error due to variability and randomness was compensated by energy management from supply side i.e. by using energy storage technologies [3]. The demand side management (DSM) technology is the option to manage the renewable power intermittency from load end. DSM is basically voluntary demand reduction or load shifting from peak load to lean load hours to reduce power consumption during peak load period which improves system reliability. It may also support to increase consumption during high production and low demand period. To accomplish this, the first criterion is to segment the various types of loads. Different types of electricity customer namely industrial, commercial and residential customers with different electricity consumption behaviour and pattern provided operational reserves that have been modelled in separate research work [2]. As per time of the day (TOD) pricing or real time pricing (RTP), customers would pay the highest prices during peak hours and the lowest prices during off-peak hours [4]. Load shifting technique is mainly applied to the usage time of appliances of residential and commercial customers. To shift different appliances from peak load hours (high pricing period) to lean load hours (low price hours), the most important thing is to know the appliance characteristics and their operating time over a day. Different appliances were modelled in a later work whose working hours can be shifted to different time of the day [5].

Although smart energy scheduling has already been proposed in different papers, combined effects of load reduction and load shifting considering the variability of renewable resources and their effects on the cost of energy have not yet been demonstrated. In this paper, a demand side management approach has been undertaken so that difference between load and generation becomes minimized at an optimum cost with minimum computational complexity. Overall day-ahead operational cost is modelled by two-stage stochastic programming method and has been optimized by CSA. The novelty of the work lies in development of area based load shifting technique while implementing this in micro grid scheduling. Appliances are shifted from peak load period to off-peak period according to their consumption. Even if, the variability present in the system will be catered by reserve from source side such as natural gas based generation and grid, participation of load to supply load reserve is also utilized to keep a balance between generation and load. The effect of load shifting and incentive based load reduction on daily total energy cost in day-ahead scheduling of energy is implemented. The demonstrated cost comparison shows substantial reduction in case of DSM based technique.

2. DEMAND SIDE MANAGEMENT

2.1. Load shifting model

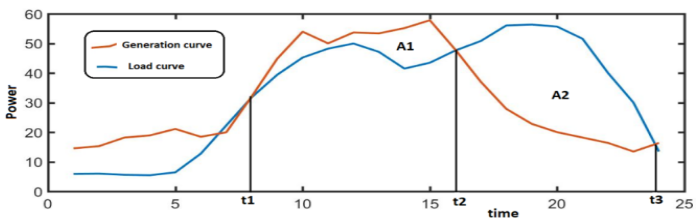

Figure 2.1. Typical generation and load curves for 24 hours

A new approach for load shifting is implemented in this work to consider the variability of renewable generation. In this work only domestic loads have been chosen for shifting with due agreement with the consumers. In Figure 2.1 between t_1 to t_2 hours, generation is more than load whereas between t_2 to t_3 load is much higher than generation. In the proposed technique operation of appliances planned between t_2 to t_3 is shifted to the time slot between t_1 to t_2, such that amount of excess energy between t_1 to t_2 is totally/partially consumed. This will help in utilizing the excess generation between t_1 to t_2 hours and reducing the load between t_2 to t_3 hours. From the figure it is also seen that generation is more than load between 00:00 to t_1 hours. But the consumption of that excess generation is already planned and included in the scheduling. Between t_1 to t_2 hours, solar generation is generally, maximum and loads are lean. Beyond t_2 hours peak load period starts and it may be difficult for the consumers to run some appliances. Rather usage of appliances between t_1 to t_2 hours may be more economically comfortable for the consumers. For that shifting of load from peak load period to lean load period has been chosen. The excess energy F may be written as

$$F = min\{area1 - area2\} \tag{2.1}$$

$$area1 = \int_{t_1}^{t_2} (f_1(t) - f_2(t))\, dt \tag{2.2}$$

$$area2 = \sum_{t=t_2}^{t_3} \sum_{app} \sum_{h=1}^{H} N^{shift}(app, h, t) \times KWhr(app, h) \tag{2.3}$$

$$P^{solar}(t) + P^{wind}(t) = P^{load}(t) \pm \sum_{app} \sum_{h=1}^{H} N^{shift}(app, h, t) \times KWhr(app, h) \times U^{shift}(app, h, t) \tag{2.4}$$

$$\sum_{t=t_s}^{t_e} U^{shift}(app, h, t) = T_{run} \tag{2.5}$$

$$\sum_{app} \sum_{h=1}^{H} N^{shift}(app, h, t) \leq N_{max}^{shift} \tag{2.6}$$

The objective for load shifting is to minimize the difference between excess generation and excess load and is formulated by (2.1). Equations (2.2) and (2.3) represent each term of the objective function where $f_1(t)$ and $f_2(t)$ are considered as load curve and generation curve respectively. The number of appliances of type app to be shifted from t^{th} hour is represented by $N^{shift}(app, h, t)$ and $KWhr$ is the consumption of each type of appliance. Equation (2.4) is included to check the balance between load and total renewable generation. Run time of each appliance is described by (2.5) where U^{shift} is the on-off status and T_{run} is the run time of each appliance. If a appliance starts from t_s hour it will stop at t_e hour without any interruption.

2.2. Load shifting model

Incentive based demand reduction is one of the easiest ways to support the intermittency of solar and wind. Equations (2.7) to (2.9) are used to calculate the incentives paid to different customers for participating in the demand reduction programs.

$$IC_{ind}^{E}(i, t) = IP_{ind}^{E}(i, t) \times incen^{ind} \tag{2.7}$$

$$CC_{com}^{E}(cc, t) = CP_{com}^{E}(cc, t) \times incen^{com} \tag{2.8}$$

$$R_{res}^{E}(r, t) = RP_{res}^{E}(r, t) \times incen^{res} \tag{2.9}$$

here, i, cc, r, are the index of industrial, commercial and residential customers respectively. Demand reduction of different customers have been given by $IP_{ind}^{E}, CP_{com}^{E}, RP_{res}^{E}$.

$$IP_{ind}^{max}(i,t) \geq IP_{ind}^{s}(i,t,s) - IP_{ind}^{E}(i,t) \tag{2.10}$$

$$CP_{com}^{max}(cc,t) \geq CP_{com}^{s}(cc,t,s) - CP_{com}^{E}(cc,t) \tag{2.11}$$

$$RP_{res}^{max}(r,t) \geq RP_{res}^{s}(r,t,s) - IP_{res}^{E}(r,t) \tag{2.12}$$

Boundary conditions for amount of load reductions are determined by (2.10) to (2.12).

3. MATHEMATICAL FORMULATION

3.1. *Objective function*

The main objective of this study is to optimize the total operating cost considering variability associated with renewable generations and loads and maintaining the balance between the load and generation with an uninterrupted power supply over a day. A two stage stochastic program is developed for optimization problem and is mathematically formulated by (3.1). First stage variables are called *here-and- now* variable i.e. the optimization variables that are common to all scenarios and indicate the day-ahead energy transaction. The second stage variables or *wait-and-see* variables are the variables those take on different values in each scenario considering the real time operation with wind and solar power variability. One hundred scenarios have been generated by Latin hypercube sampling-Cholesky decomposition (LHS-CD) method and reduced into two scenarios by k-means clustering method [6]. Now the total cost *TC* can be written as

$$TC = \sum_{t=1}^{T}[C^{solar}(t) + C^{wind}(t) + \sum_{m=1}^{M}\{C^{gas}(m,t) + SU^{gas}(m,t)\} + \sum_{i=1}^{I}\{IC_{ind}^{E}(i,t) + \sum_{cc=1}^{CC}\{CC_{com}^{E}(cc,t) + \sum_{r=1}^{R}\{R_{res}^{E}(r,t) \pm C^{grid}(t)] + [\sum_{s=1}^{S}Prob^{s}\{\sum_{t=1}^{T}C_{s}^{solar}(t,s) + C_{s}^{wind}(t,s) + \sum_{m=1}^{M}\{C_{s}^{gas}(m,t,s) + SU_{s}^{gas}(m,t,s)\} + \sum_{n=1}^{N}C_{s}^{gen_{res}}(n,t,s) + \sum_{i=1}^{I}IC_{ind}^{s}(i,t,s) + \sum_{cc=1}^{CC}C_{com}^{s}(cc,t,s) + \sum_{r=1}^{R}C_{s}^{res}(r,t,s) \pm C_{s}^{grid}(t,s)] \tag{3.1}$$

where, C^{solar}, C^{wind}, C^{gas}, C^{grid} are cost of solar, wind, scheduled gas reserve, power generation and selling or buying price of power to or from the grid respectively. Start up cost of the gas generator is SU^{gas}. C_{s}^{solar}, C_{s}^{wind}, C_{s}^{gas}, C_{s}^{grid} are cost of solar, wind, scheduled gas reserve, power generation and selling or buying price of power to or from the grid for each scenario.

3.2. *System constraints*

Maintaining balance between load and generation is the main constraint of this program. Equations (3.2) and (3.3) give information about load balance in day-ahead condition and in each scenario condition. Therefore, the equation of balance can be expressed as

$$P^{solar}(t) + P^{wind}(t) + \sum_{m=1}^{M}P^{gas}(m,t) \pm P^{excess}(t) = P^{load}(t) - \sum_{i=1}^{I}IP_{ind}^{E}(i,t) - \sum_{cc=1}^{CC}CP_{com}^{E}(cc,t) - \sum_{r=1}^{R}RP_{res}^{E}(r,t)\ \ b \tag{3.2}$$

$$P_{s}^{solar}(t,s) + P_{s}^{wind}(t,s) + \sum_{m=1}^{M}P_{s}^{gas}(m,t,s) \pm P_{s}^{excess}(t,s) = P^{load}(t) - \sum_{i=1}^{I}IP_{ind}^{s}(i,t,s) - \sum_{cc=1}^{CC}CC_{com}^{s}(cc,t,s) - \sum_{r=1}^{R}RP_{res}^{s}(r,t,s) \tag{3.3}$$

Hourly forecasted power outputs from solar and wind are P^{solar}, P^{wind} and are calculated as in [2]. Scheduled power output is P^{gas} and P_s^{gas} gas power output in scenario. Hourly load demand connected to the microgrid is represented by P^{load}. Excess power to be sold or buy to or from grid is expressed by P^{excess}. Now we can also write

$$F^{gas}(m,t) = [\alpha + \beta \times P^{gas}(m,t) + \gamma \times \{P^{gas}(m,t)\}^2] \times U^{gas}(m,t) \quad (3.4)$$

$$F^{gas}(m,t) \le F_{max}^{gas}(m) \quad (3.5)$$

$$SU^{gas}(m,t) \ge sc^{gas} \times (U^{gas}(m,t) - U^{gas}(m,t-1)) \quad (3.6)$$

Equation (3.4) represents the relationship between gas fuel and power output of the plant. Amount of fuel required for power generation of m^{th} unit at t^{th} hour is $F^{gas}(m,t)$. The on/off status of the gas unit is U^{gas}: 1 is considered on, 0 is off. Gas unit system constants are α, β, γ. The availability of the fuel over the day is calculated by (3.5). Start-up cost $SU^{gas}(m,t)$ of gas unit is determined by (3.6). Start-up cost of each gas plant unit is sc^{gas}.

4. Results

4.1. *Day-ahead energy scheduling without demand side management*

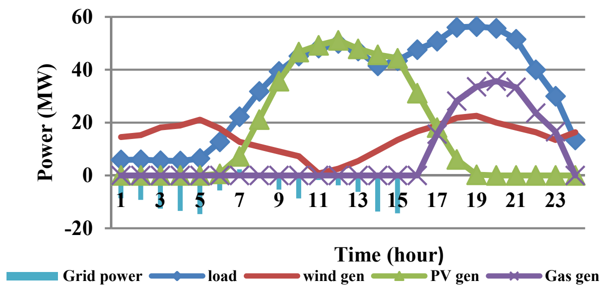

Figure 4.2. Day ahead energy scheduling without DSM

Day-ahead energy scheduling without demand side management program has been shown in Figure 4.1. In day time, e.g. at 10:00 am, as the renewable generation mainly the solar generation is high, excess 8.74 MW generation is sold to grid. In evening time, for example at 8:00 pm, the load is much higher than renewable generation because of zero solar output. Mainly gas reserve takes up the excess load of 35.68 MW and hence increases the fuel cost which in turn increases the total operating cost.

4.2. *Day-ahead energy scheduling with demand side management*

Figure 4.2 shows, the renewable generation is excess from 8:00 am to 4:00 pm and load is excess between 4:00 pm to 9:00 pm. Hence load is shifted from the later period to excess generation period. As for example, load of 9.36 MW is shifted from 7:00 pm and load of 3.43 MW is added to the load at 12:00 pm as the renewable generation is excess. This load shifting is implemented by the developed method explained in section 2.

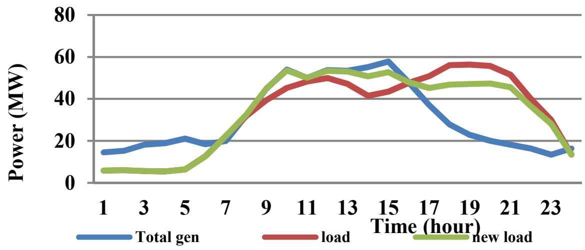

Figure 4.2. Load curve comparison for DSM

The combined effects of load shifting and incentive based demand reduction in day-ahead scheduling are presented in Figure 4.3. As at 12:00 pm some load has been shifted, there is no surplus generation to be sold to grid. At 7:00 pm shifted demand of 9.363 MW and incentive based load reduction of 16.11 MW allow gas unit to generate only 13.55 MW instead of 33.55 MW as in the case of without demand side management.

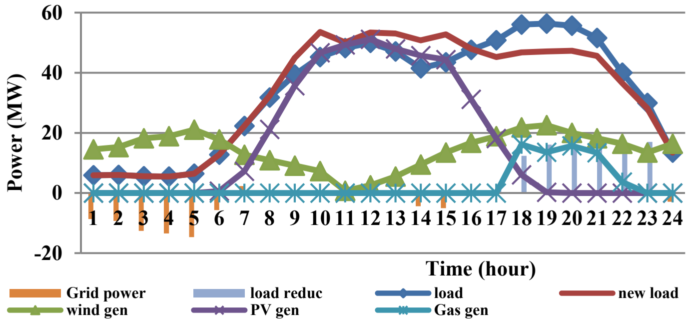

Figure 4.3. Day ahead energy scheduling with DSM

4.3. Cost comparison

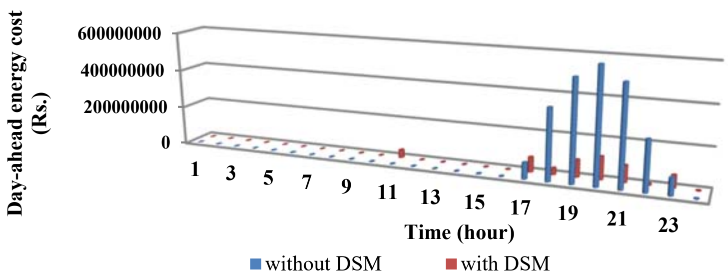

Figure 4.4. Comparison of Hourly energy cost

Figure 4.4 shows hourly cost of energy which clearly shows that reduction in operating cost using DSM occurs during the peak load period. At 8:00 pm the energy cost is Rs. 514996506.3 in case of without DSM whereas with DSM this cost has been reduced to Rs. 86401732.08. It also reveals that, since with DSM loads are shifted to the excess renewable generation period to consume maximum amount of renewable generation it reduces the amount of load in peak load hour. Reserve from load side helps to reduce the amount of demand in peak load with less renewable generation period and hence reduction in operating cost from Rs. 2398829115 to Rs. 505529445.3 is achievable within a day.

5. CONCLUSION

A novel demand side management technique has been developed and implemented in a microgrid. Microgrid considered in this paper utilizes solar and wind as major supply sources and grid and natural gas based generation serve as reserve sources. The energy scheduling of the microgrid is done considering the variability of solar and wind sources. Hourly cost comparison is done to demonstrate the cost reduction period. The total daily cost reduction due to use of DSM and smart scheduling has also been established. For a futuristic approach, demand side management considering appliances with different characteristics can be analyzed.

6. REFERENCES

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Biography

Arnab Ghosh is the 1st author and the corresponding author of this paper. He received the B. Tech degree in Electronics and Instrumentation Engineering from West Bengal University of Technology, Kolkata, India, in 2012, M.E. degree in power engineering from Jadavpur University, Kolkata, India, in 2014. He completed his PhD (Engineering) in the Department of Power Engineering, Jadavpur University, Kolkata, India in 2019. Presently, he is serving as the Assistant Professor in Electrical Engineering Department of UEM Kolkata. His area of research includes wireless sensor network, smart grid and demand side management. His contact email address is: arnab281290@yahoo.com.