Optimizing load variations using demand side management in the presence of SPV generation

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Abstract. Demand Side Management (DSM) is a new concept that provides a viable and more efficient option to alter the net electricity consumption pattern without bringing much discomfort to the consumers. With the development of control and information technology, residential community provides a new potential demand side management entity to the distribution utilities to optimize their load profile. In this paper, the opportunities associated with Solar Photo Voltaic (SPV) integrated distribution utilities residential consumer DSM to minimize the gap between the targeted and actual load profile are investigated. A load deferral DSM model to shift the operation of not so critical residential appliances along with the optimal energy dispatch model from the residential consumer side battery energy storage (BES) is presented. A centrally controlled DSM strategy to optimize the operating time of deferrable devices and BES bidirectional power flow has been proposed. The DSM results considering different scenarios with and without BES and load deferral are compared with the original case of without DSM. It has been observed that the DSM strategy in the presence of SPVs and battery storage can substantially reduce the overall variance of the actual load curve from the predicted load curve.

1. Introduction

The importance of more active participation of consumers’ through various Demand Response (DR) programs in the electricity network operations has been greatly recognized [1]. The grid utility can be benefitted by reducing the peak demand [2], peak to average ratio and smoothening of load profile, thus reducing the system operational cost and investment deferral on network expansion due to increased demand [3]; whereas, the electricity consumers can earn financial profits depending upon the DR policy of the system operator. Incentive based DR program has been implemented to minimize the operational cost and maximize the profit of the utility in hybrid electricity market scenario [4]. Among various consumers, the residential consumers have great potential and can be effectively utilized to modify the real time demand curve [5].

With the technological advancements, developments in the communication networks, smart appliances and increasing deployment of smart electricity metering, the residential community has come up as a new DR participant [6]. The residential consumers can offer a wide range of appliances for DR including deferrable loads, controllable loads (the power consumption level can be adjusted), interruptible loads and battery energy storage (BES). By controlling the operation of the devices having flexibility in their operation, the residential community can help in managing the mismatches arising due to the uncertainties in the demand and Renewable Energy Resources (RER) generation.
Few researchers have studied the application of DR in balancing the RER fluctuations. In most of such studies the DR potential has been modeled as a dispatchable resource. The same approach is not suitable for real time applications. However, in [7] the authors have used control of electric water heaters loads for balancing the fluctuations of wind generation. The control of air conditioning and refrigeration systems have been used to counter the intermittency of solar photovoltaic (SPV) generation in [8] by creating a virtual energy storage capacity. These studies have not explored the full potential offered by a range of residential appliances.

In this paper, we investigate the potential of deferrable residential appliances and the consumer side BES systems in mitigating the aggregated mismatch in the predicted load profile and the real time load profile. The power fluctuations resulting from uncertainties of load and SPV generation are smoothened, using DR of residential appliances and BES operation control. Although only a few devices have considered for the load shifting purpose, but the algorithm used is flexible to accommodate any number of devices. The optimization problem is formulated as mixed integer nonlinear programming and simulations are carried out considering a practical distribution utility having large number of residential consumers using general algebraic modeling system (GAMS) software.

The remainder of the paper is structured as: Section 2 explains problem formulation. Section 3 describes input data and the scenarios considered for simulations. In section 4 simulation results are discussed. The findings are concluded in section 5 and last section acknowledges the funding agency.

2. Problem formulation
Consider the case of a grid connected distribution utility composed of commercial, industrial and residential consumers having solar photovoltaic (SPV) generation as well. To smoothen the mismatch between net predicted load and the net actual power drawl two types of loads; time shiftable loads and BES are considered for DR. The centralized control has been assumed for the DR activation. The objective function for this optimization problem is given in (1).

$$\text{Min } \sum_t \text{abs}(P_{\text{net}}^t - P_{\text{act}}^t)$$  \hspace{1cm} (1)

Here, $P_{\text{net}}^t$ and $P_{\text{act}}^t$ are net predicted load and net actual demand respectively during time interval $t$. These are calculated as (2) and (3) respectively.

$$P_{\text{net}}^t = P_{\text{pre}}^t - P_{\text{tpv}}^t$$  \hspace{1cm} (2)

$$P_{\text{net}}^t = P_{\text{act}}^t - P_{\text{tpv}}^t$$  \hspace{1cm} (3)

Here, $P_{\text{pre}}^t$ and $P_{\text{tpv}}^t$ are forecasted load and forecasted SPV generation respectively during time; whereas, $P_{\text{act}}^t$ and $P_{\text{tpv}}^t$ are the actual load and SPV generation.

The application of DR modifies $P_{\text{pre}}^t$ in two ways: (i) increase the drawl ($\text{DR}_{\text{inc}}^t$) (ii) decrease the drawl ($\text{DR}_{\text{dec}}^t$). The modifications $\text{DR}_{\text{inc}}^t$ and $\text{DR}_{\text{dec}}^t$ are computed as given in (4) and (5). Here, $\text{bat}^t_{\text{ch}}$ and $\text{bat}^t_{\text{dis}}$ represent total load increment/decrement by BES charging/ discharging respectively. The variables $a_P^t_{\text{on}}$ and $a_P^t_{\text{off}}$ represent total load increment/decrement by switching on/off deferrable devices.

$$\text{DR}_{\text{inc}}^t = \text{bat}^t_{\text{ch}} + a_P^t_{\text{on}}$$  \hspace{1cm} (4)

$$\text{DR}_{\text{dec}}^t = \text{bat}^t_{\text{dis}} + a_P^t_{\text{off}}$$  \hspace{1cm} (5)
2.1. SPV system

The power output from the SPV panels is computed from the forecasted solar irradiation data using (6). The available minute wise solar irradiation forecast data is used to simulate the power output of the solar PV panels by computing the average PV output over the 15 minute time slot [9].

\[
P_{t}^{PV} = \begin{cases} \frac{P_{t}^{PV} R_{t}}{R_{std} R_{c}} & \text{for } 0 < R_{t} < R_{c} \\ \frac{P_{t}^{PV} R_{t}}{R_{std}} & \text{for } \forall R_{t} > R_{c} \end{cases}
\]

(6)

Here, \( P_{t}^{PV} \) is the SPV generation, \( P_{t} \) represents equivalent power output rating of the PV panel, \( R \) denotes the forecasted value of solar irradiance in W/m\(^2\) and \( R_{std} \) denotes the solar irradiance under standard conditions. This value is set as 1000 W/m\(^2\). The radiation point \( R_{c} \) has been assumed as 250 W/m\(^2\) in the present study. Under practical conditions, the actual SPV output is also affected by the PV cell temperature and inverter efficiency. There impact on the SPV power output has been accounted for by multiplying the calculated SPV generation with a factor 0.8.

2.2. BES system and Load deferral

The operation of the deferrable appliances and power exchange with the consumers’ BES is scheduled by the central controller in real time such that the gap between the targeted and actual drawl is minimized. Consumers’ convenience should be guaranteed so as to ensure the increased customer DR participation. This is achieved by constraining the optimization algorithm to schedule the deferrable devices to operate within the specified time. Also the level of discharge and the rate of discharge are required to be within the specified limits. The detailed mathematical model of the deferrable loads and BES charging/ discharging control used in the optimization process is the same as discussed in our earlier publication [10].

3. Input data and scenarios

For the simulation studies the realistic data of Chandigarh, a city in the northern India is considered. The actual data of solar irradiance forecasting, PV power generation by a 1kW solar photo-voltaic panel, predicted power drawl from the grid and actual power drawl data of June 7, 2017 of the city have been used for the study [11]. For computing the total actual generation from the SPV, the scaled up value of power generation data from SOLAX inverters recording system of the 1kW rooftop SPV panel at the college building has been used. There are total 187687 residential electricity consumers in the city [12]. The scaled down values of various power parameters for 1000 consumers have been used in the simulations. The aggregated predicted load profile has been obtained from the forecasted load profile and the forecasted SPV radiations and similarly aggregated actual load profile has been calculated from the actual SPV radiations and actual load demand figure 1 and figure 2. The parameters of the appliances participating in load deferral and BESS parameters are given in table 1 and table 2 respectively. The time period granularity is kept as 15 minutes in line with the grid time granularity prevalent in India.

| Type               | Power Rating (kW) | Operating Steps |
|--------------------|-------------------|-----------------|
| Washing Machine    | 1.5               | 6               |
| Dish Washer        | 2                 | 6               |
| Microwave Oven     | 1                 | 1               |
| Food Processor     | 0.35              | 1               |
Table 2. BES parameters [13]

| Description                  | Unit          |
|------------------------------|---------------|
| Battery Capacity             | 2.4kWh        |
| Depth of discharge limited   | 2kWh (80%)    |
| Current limit                | <20% of rated AH |
| Round Trip efficiency        | 80%           |

Figure 1. Aggregate predicted and actual load profile

Figure 2. Predicted and actual PV generation

4. Simulation results

To investigate the effectiveness of the proposed DR methodology; five cases have been analyzed as described in table 3. In the base case the aggregated actual load variation with the PV integrated system from the predicted aggregated load profile is studied. The impact of load deferral and BES control when implemented alone and together has been analyzed in the subsequent scenarios as per details given in table 3. In the last two scenarios, it has been assumed that the battery state of charge at the end of the simulation period is either greater than or equal to its value at the start of the day.

Table 3. Scenario description and result comparison

| Scenario       | Considered DR options | Participation level | Total variation throughout the day | Reduction in variation |
|----------------|------------------------|---------------------|------------------------------------|------------------------|
|                | Load deferral | BES                  |                                     |                        |
| Without DR     | --            | --                   | 16815.69                           | ----                   |
| Excl. load deferral | Yes         | --                   | 16640.11                           | 01.04%                 |
| Excl. BES      | --            | Yes                  | 6304.80                            | 62.50%                 |
| Incl. both     | Yes           | Yes                  | 4849.77                            | 71.16%                 |
| Inc. BES       | Yes           | Yes                  | 3219.00                            | 80.85%                 |

4.1. Effectiveness of load deferral in reducing load profile deviations

In this scenario the effectiveness of load deferral DR program in reducing the aggregate load profile mismatch from the predicted load profile has been analyzed. The results indicate that there is a little improvement in the overall deviations of the actual load profile from the predicted load pattern by considering load deferral DR strategy alone figure 3, table 3.
4.2. Effectiveness of BES control in reducing load profile deviations
In this scenario it has been assumed that 60 percent of the total residential consumers’ BESs participate in the DR program. The simulation results show that by the charging/discharging control of the batteries the deviations can be reduced greatly figure 4. Almost all the peak deviations have been reduced and deviations have also been reduced largely during other intervals as well. However, there is creation of one additional deviation peak during time intervals 68-69. The results reveal that the aggregate load deviation has been reduced almost to zero during the interval 72-96. The aggregate load mismatch computed over the whole day is reduced by 62 percent in this case table 3.

4.3. Impact of both load deferral and BES control on aggregate load deviation
In this scenario the effectiveness of both BES and load deferral acting together on the load mismatch is investigated. It is clear that the application of both the DR programs further improves the results figure 5. The aggregate deviations have nearly reduced to zero in the time interval range from 46 to 88. Also it has been smoothened in the interval range from 33 to 45. Although the new deviation peak which was created in the previous scenario has been removed here, but a new negative deviation peak of lesser duration have been created at interval number 30 in this case.

Also, with increased BES participation level from 60 to 70 percent, not only the overall aggregate variations have reduced by over 80 percent; also the all the variation peaks have come down without formation of new peaks figure 6, table 3. In figure 7, the time intervals and the amount of power exchange with BES and under load deferral have been shown.

![Figure 3. Impact of Load shifting](image3)

![Figure 4. Impact of BES](image4)

![Figure 5. Impact of BES and load shifting](image5)

![Figure 6. Effect of increased BES participation](image6)
5. Conclusion
In this paper, the potential of residential demand response to reduce the mismatch between the predicted and the actual aggregated demand pattern has been investigated. The net load fluctuations get more pronounced with the installation of roof top SPV panels by the consumers. The effectiveness of BES control and load deferral DR techniques to optimize these variations has been discussed. The results demonstrate that while the BES control is quite effective in smoothening the variations; the load deferral helps to reduce the mismatch only slightly when applied alone. This is because its participation is restricted by several technical constraints. However, when used in conjunction with the BES, its’ effectiveness increases. To sum up, residential DR is an effective measure to balance the aggregated demand uncertainties enhanced by the integration of RER.

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