Energy Storage System Sitting and Sizing in the Presence of Responsible Demands in Energy and Reserve Markets

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ABSTRACT
Recently, the cooperation of energy storage systems and demand response programs in providing efficient energy management scheme have attracted enormous attention among researches. Considering the high capital cost of energy storage systems, the optimal economically sizing and sitting in distribution networks is an ineluctable task. In this paper, the optimal allocation of energy storage units in the presence of demand response programs has been studied. This paper is the updated version of our conference paper, in which the participation of responsive demands in both energy and reserve markets via direct and indirect participation is considered. Also, the block order participation modeling for demand response aggregator is formulated. The optimization problem is solved using GAMS optimization software. The results show that integration of demand response programs and energy storage systems in distribution networks can decrease system operation’s annual cost by about 10%.


1. INTRODUCTION
The utilization of renewable-based generation, such as wind turbines and solar systems in distribution networks, is increasing due to environmental and economic reasons. Irrespective of advantages come from renewable energy utilization, due to high penetration of these resources, the frequency stability of the system is becoming a challenging task for system operators. Energy storage systems (ESSs) can support the renewable-based generation expansion by providing time shift ability leads to advanced attainment of produced energy by the RES, decreasing voltage fluctuations, and providing energy arbitrage opportunity [1]. The nonoptimal utilization of ESS in distribution networks can have drawbacks from viewpoint of economic merits and technical aspects. Considering this critical point, up-to-date review papers are published recently regarding optimal sizing, and placement of energy storage systems in distribution networks, for instance, references [2], [3].

2. LITERATURE REVIEW
In this section, some of the technical literature related to the optimal allocation of the ESSs in distribution networks are reviewed from viewpoints of the objective function, constraints, and solution method.

In [4], the optimal size, location, and charging/discharging pattern of ESSs are determined thorough an optimization framework. The objective function of the proposed optimization includes various factors, such as energy arbitrage benefit maximization and loss and congestion management and emission reduction. The voltage limit constraint is considered as a technical constraint for the optimization. The problem is solved using the genetic algorithm (GA).

In [5], battery ESSs are proposed for voltage fluctuation reduction in distribution networks. The problem of ESS allocation, including determination of optimal size and placement of ESSs, as well as lifecycle calculation, is addressed via an optimization problem. The objective function considers the network loss and investment cost of ESS. The voltage and current limits are posed through constraints, and the number of installed devices is also restricted. The non-dominated sorting genetic algorithm-II (NSGA-II) is proposed to solve the problem.

A two-step optimization is presented by [6], in which the problem of ESS siting and sizing is solved in MATLAB software using GA, and the data is transferred to DigSILENT PowerFactory program to analyze the
optimal power flow of the network. The objective is the minimization of the voltage deviation and network loss. A criterion for power loss and bus voltage limits are considered as the constraints.

In [7], the problem is studied via bilevel programming, where the ESS planning decisions are determined in the upper-level, and the lower-level evaluates the effects of them on the operation of the distribution network. The upper-level objective function investigates the costs of investment and maintenance of ESS, and distribution network upgrades while the lower-level objective function considers operational issues. Different kind of constraints, e.g., the security limitations of the network, are considered. The problem is solved using a hybrid heuristic-based method, including particle swarm optimization (PSO) and differential evolution (DE) algorithms.

The optimal siting and scheduling of the ESS are deliberated in [8], in which the daily generation cost minimization is considered as the objective function, and power balance equalities and voltage and lines restrictions, as well as ESS modeling equations, are the constraints of the problem. The optimization problem then solved using an method containing the PSO algorithm.

The optimal sizing and siting of ESS in smart distribution networks, to maximize the profit of energy arbitrage concerning energy loss diminish and upgrade deferring, has been done by [9]. The power flow and voltage limit constraints are considered. The GA and linprog solvers in MATLAB are used to solve the problem.

Concerning the reliability of radial distribution networks, the ESS optimal sizing and siting is addressed by [10]. The objective function contains the costs of ESS investment and energy not supplied. The generation-demand equality, bus voltage bounds, and lines’ limitations are posed via constraints. The problem is solved using PSO algorithm.

An optimization framework for the optimal ESS sizing and siting is proposed by [11]. The maximization of the profit of the distribution system companies in the presence of price volatility and load forecasting errors is considered as the objective function, and the problem satisfies the network constraints. Furthermore, fuzzy PSO is applied for solving the problem.

In [12], using a fuzzy expert system, the optimal sizing of the ESS in a microgrid with the objective of cost minimization has been carried out. An energy management strategy handled by the GA determines the membership function and rules of the fuzzy system. An estimation of the lifetime of the ESS is also calculated. In this paper, the network constraints are ignored.

A co-optimization framework for optimal allocation of the distributed generators and ESSs are prescribed by [13], in which the objective function is minimization of the investment cost and operational cost of the generators. The problem is addressed just as a sizing problem and network constraints are not considered. The matrix real-coded genetic algorithm (MRCGA) method is used for finding solutions.

The problem of optimal sizing and siting of ESS in low-voltage distribution networks is lectured by [14]. In this paper, firstly, the location of ESSs is determined based on the voltage sensitivity analysis using Clustering and Sensitivity Analysis (CSA). After that, the optimal sizing of the ESS is determined using a multi-period power flow calculation. Network restrictions and ESSs’ behavior are modeled through constraints.

For large-scale distribution networks with numerous connections and consumers, the problem of ESS sizing and siting might be very complicated and being unsolved. With this regard, Refs. [15], [16] propose relaxed formulation for the power flow problem. The ESS sizing and sizing problem is solved mathematically in [15], as a multi-objective optimization with various objectives, e.g., minimizing voltage deviation, network loss, load curtailment, energy procurement cost, and feeder congestion relief, as well as, ESS investment cost. While in [16], the allocation of ESSs has been done with a different objective function consists of investment and maintenance costs related to ESS, energy supply cost and loss payments. Various operational constraints are considered, and a network-based ESS allocation has been done by both works.

On the other hand, in distribution level with a high density of end-users, demand response programs (DRP) can promote practical solutions to manage the usage of electricity and reducing the stress on the power system faced with emergencies by offering incentives for responsible demands. These programs can be divided into different categories regarding their control mechanism, incentive payments rules, and the necessity of them. With this regard, Vardakas et al. [17] have reviewed various DRP models and their applications in smart grids.

ESS and DRP jointly can provide efficient operation in distribution networks. Furthermore, the effects of them on one another is an exciting topic. Only a handful of technical works has investigated the impact of DRPs on the ESS sizing and siting problem. Optimal ESS technology selection problem in the presence of DRP is investigated by [18]. In [19], the problem of sizing of the ESS in a microgrid in the presence of DRP is pondered. The presented framework is a bi-objective optimization which tends to minimize the operational and planning costs of the microgrid and loss of load expectation (LOLE). The problem is solved in the GAMS optimization software. The paper ignores the system power flow calculation. In [20], the research has become more comprehensive, so that, it considers a power
network and its corresponding constraints. Similar to these works, with different objectives, the sizing, and siting problem of the ESS in a smart distribution network in the presence of dispatchable microturbines (MTs), renewable generation and DRP is investigated by [21]. Finally, it is worth mentioning that the conference version of the presented paper [22] had considered a larger test system (i.e., 69-bus IEEE) and DRP incentive payments, in comparison with the abovementioned works.

2.1. Contributions
In this paper, despite our previous conference paper, the direct participation of the responsive demands in DRP is not considered. Instead, the large consumers (LC) and demand response aggregator (DRA) can take part in filling both energy and reserve requirements through DRPs. The DRA is the mediator between small end-users and distribution network operator (DNO). The problem of optimal ESS sizing and siting is then addressed from the perspective of the DNO reducing the operation cost of the network, and the ESS investment cost. Furthermore, in addition to the participation of demands in the energy market, they can take part in reserve provision. The system includes various distributed generators (DGs), i.e., solar systems, wind producers, and MTs. A modified version of the well-known IEEE 33-bus test system has been used to verify the validation of the presented framework. With these explanations, the presented paper includes the following contributions:

• Optimal siting and sizing of the ESSs in distribution networks in the presence of the DRP has been addressed.
• The considered distribution network includes different kinds of dispatchable and non-dispatchable DGs.
• The small responsive demands can take part in both energy and reserve markets with the collaboration of an aggregator, while the large consumers participate independently.
• The aggregator gathers the demand offers and makes a stepwise offering curve to participate in DRPs.

2.2. Paper Organization

The rest of the paper is organized as follows. In Section 3, the problem formulation is presented. In Section 4, the case studies, obtained results, and comparison between them is provided. The essential points of this paper are collected, and the paper is concluded in Section 5.

3. PROBLEM FORMULATION
The optimal allocation of the ESSs in this paper has been carried out using solving an optimal power flow problem. It is assumed that the installed ESSs will be under the control of the DNO. Hence, the objective function is the minimization of the operational cost of the distribution system, and ESS investment cost. The advantage with the OPF is that it regulates the charging/discharging pattern of the installed ESSs; moreover, DRP’s effect on the ESS allocation and system operation can be assessed straightforwardly.

3.1. Objective Function

The objective function of the optimization problem is minimizing the annual total cost of the distribution network comes from the costs of energy and reserve procurement through the upstream grid and different generation sources, and the diurnal ESS investment cost, as shown in Eq. (1). The presented formulation calculates the daily cost of the distribution network.

\[
\text{Min } \text{OF} = UC + EC + RC + IC
\]  

(1)

\[
UC = \sum_{t=1}^{24} P_{up}(t) \cdot \lambda(t)
\]

(2)

\[
EC = \sum_{t=1}^{24} \sum_{g=1}^{N_g} FC_{DG}(t, g) + STC_{DG}(t, g) + SDC_{DG}(t, g)
\]

\[+ \sum_{d=1}^{N_d} DRC_{DG}(t, d) + \sum_{l=1}^{N_l} DRC_{DG}(t, l) + \sum_{l=1}^{N_l} DRC_{DG}(t, l) + \sum_{l=1}^{N_l} DRC_{DG}(t, l)
\]

(3)

\[
RC = \sum_{t=1}^{24} \sum_{g=1}^{N_g} FC_{DG}(t, g)
\]

(4)

\[
+ \sum_{t=1}^{24} \sum_{g=1}^{N_g} DRC_{DG}(t, l) + \sum_{d=1}^{N_d} DRC_{DG}(t, d)
\]

(5)

3.2. Microturbine Modeling

The fuel cost of MTs is proportional to their power production. This relation can be written as a quadratic formulation as Eq. (6). Moreover, the startup and shut down costs of the MTs are calculated according to (7) and (8) considering their on/off statue changing. The cost of reserve delivery through microturbine is considered as 20% of the marginal cost of the fuel cost, as shown in (9) [23]. The physical limitations of the microturbine are illustrated by (10)-(17). Equation (10) limits the power generation of the microturbine. Equation (11) assures that summation of the power generation in energy and reserve markets should be less than the microturbine’s limit. The concepts of ramp up/down limitation are considered employing constraints (12) and (13). Furthermore, for any microturbine, the minimum up/down times should be observed. This has been accomplished using (14) and (15). The equations (16) and (17) relate the on/off statues of the microturbine to its previous conditions and designates that the microturbine cannot be on and off at the same time.

\[
FC_{DG}(t, g) = a \times (P_{DG}^m(t, g))^2 + b \times P_{DG}^m(t, g) + c
\]  

(6)
3.3. Demand Response Modeling

As previously mentioned, in this paper, two kinds of DRP participants are considered. Small scale responsive loads take part in energy and reserve markets by the help of aggregators, and large consumers can take part independently. In the following, each participant’s behavior modeling is presented.

3.3.1 Demand response aggregator (DRA)

Demand response aggregator (DRA) gathers the load reduction offers from small-scale consumers. Then makes a stepwise load reduction offering curve and submits it to the market. By this way, if the system operator commits them, they should act as their submitted proposal. So, the modeling should contain a counter for the number of steps or blocks. For the first block, the submitted offer should be higher than a threshold and the maximum amount of load interruption at one block, shown in (18). The amount of load curtailment for the rest of the steps should be determined according to the previously submitted blocks, as Eq. (19) shows it. Regarding Eq. (20), the total load curtailment for demand at bus d in time t is equal to the summation of load curtailment amounts during all steps. The DRA’s revenue in the energy market (system’s energy cost) is calculated by (21) according to the price of each accepted block. Similar to the microturbine, the summation of the curtailed load in energy and reserve markets should be less than the total load interruption, which is observed by (22). The DRA’s revenue in reserve provision (system’s reserve cost) is also obtained from (23).

\[ \tilde{d}_{\text{min}}(t,d) \leq D(t,d,k) \leq \tilde{d}(t,d,k), k = 1 \]  

\[ 0 \leq D(t,d,k) \leq \tilde{d}(t,d,k+1) - \tilde{d}(t,d,k), \forall k = 2,3,...,K \]  

\[ P_{\text{DRA}}^e(t,d) = \sum D(t,d,k) \]  

\[ DRC_{\text{DRA}}^r(t,d) = \sum \mathcal{G}^r(t,d,k) \times D(t,d,k) \]  

3.4. Renewable Generation Modeling

In addition to the upstream grid, MTs and demand-side generation, two kinds of renewable resources are considered, namely, photovoltaic (PV) systems and wind turbines. However, it is assumed that the generation and curtailment of these resources are cost-free, and they can only produce active power. The power generation of the wind turbine is proportional to the wind velocity, and the corresponding relation is formulated in (27). The precious modeling of PV production is behind the scope of this paper and using a simple equation (28), the power production of the PV system is considered as the multiplication of PV’s rated capacity by the hourly forecasted constants.

\[ P_{\text{PV}}(t,p) = PV_{\text{rated}}(p) \times \Omega(t) \]  

3.5. Power Flow Calculation and Network Constraints

In this paper, a multi-period ac power flow ensures the optimal generation dispatch as well as DRP planning and the ESS allocation. The advantage of using power flow calculation is that it can find the optimal size and placement of the ESSs simultaneously by exploiting a precise mathematical formulation and solution method.

The active and reactive balances between generation and
consumption are guaranteed by (29) and (30). The reserve balance is held by (31). The bus voltage limit is observed in (32). In Eq. (33), the apparent exchanged power between connected buses is calculated, and the thermal limit of the lines is considered in (34).

\[
P_{v(t,g)} + P_{v(t,d)} + P_{v(t,l)} + P_{v(t,s)} - P_{v(t,c)} = 0
\]

\[
P_{v(t,g)} + P_{v(t,d)} + P_{v(t,l)} - P_{v(t,s)} - P_{v(t,c)} = 0
\]

\[
\sum_{j=1}^{N_{bus}} V(t,i) \times V(t,j) \times Y_{ij} \times \cos(\theta_{ij} + \delta(j,t) - \delta(i,t)) \]

\[
Q_{v(t,g)} - Q_{v(t,c)} = 0
\]

\[
-P_{g(t,g)} - P_{g(t,d)} + P_{g(t,l)} \geq 0
\]

\[
0.2 \times P_{s(t,g)} + 0.1 \times P_{s(t,d)} \geq 0
\]

\[
V_{min} \leq V(t,i) \leq V_{max}
\]

\[
S_{ij} = \begin{cases} 
\sum_{j=1}^{N_{bus}} V(t,i) \times V(t,j) \times Y_{ij} \times \cos(\theta_{ij} + \delta(j,t) - \delta(i,t)) \times 2 \\
-\sum_{j=1}^{N_{bus}} V(t,i) \times V(t,j) \times Y_{ij} \times \sin(\theta_{ij} + \delta(j,t) - \delta(i,t))
\end{cases}
\]

\[
S_{ij} \leq S_{ij} \leq S_{ij}
\]

3.6. Energy Storage System Modeling

In this section, the physical limitation and behavior modeling of the ESSs are explained. First of all, the initial and final state-of-charge (SOC) of the ESS is determined by (35). For the rest of the day, the hourly SOC is computed using (36). Only one variable is used to show the charging and discharging powers of the ESS, and there is no need for abundant binary variables for preventing simultaneous charge and discharge. According to the Eq. (36), the positive amounts for the variable indicates the charging process and vice versa. The hourly SOC and charging/discharging powers are bounded in (37) and (38), respectively.

\[
SOC(t,s) = SOC_0
\]

\[
SOC(t,s) = SOC(t-1,s) + \eta \times P_{r}(t,s)
\]

\[
SOC_{min}(s) \leq SOC(t,s) \leq SOC_{max}(s)
\]

\[
-P_{s} \leq P_{s}(t,s) \leq P_{s}
\]

4. CASE STUDIES AND RESULTS

The well-known IEEE 33-bus test system connected to different generation resources is implemented to check out the validation of the presented optimization. Figure 1 shows the single line diagram of the distribution network and connected resources. The information regarding test system technical characteristic, microturbines cost functions, the forecasts of power generation of the wind turbines and PV systems are available in Ref. [21]. The load demand data, forecasted hourly electricity prices, the offering of responsive LCs as well as DRAs’ stepwise offering information could be found in [23]. From Fig. 1, the DRA 1 supports demands at buses 26 to 33, and the DRA 2 supports demands at buses 9 to 18.

Fig. 1. Test system schematic.

For the sake of ease, the operation of a single day is tested, and the results are multiplied by 365 to show the annual total costs. For this purpose, the prorated investment cost of ESSs is assumed to be 225 $/MWh/day in Eq. (5). The charging/discharging efficiency considered 90%. The minimum and maximum SOC of the ESS is equal to 20% and 100% of its rated capacity. The lower and upper limits of the bus voltages are 0.9 per unit and 1.0 per unit, respectively. It is assumed that the total installed number of the ESS on the system should be less than 10, and each of which has no more than 1 MWh rated capacity. The presented optimization problem, i.e., Eqs. (1)-(38), formulated as mixed-integer non-linear programming and solved using GAMS optimization software [24] via DICOPT solver [25].

4.1. Results

The proposed optimization approach for optimal sizing and siting of the ESSs has been tested over four case studies. In case 1, without considering neither DRP nor ESS, the power flow calculation has been done to find the optimal dispatch and the minimum operating cost of the distribution system over one year. In case 2, without considering responsive loads and DRAs, the problem of the optimal ESS allocation has been investigated, and the effects of ESS on the operation of the distribution system has been studied. In case 3, the effects of DRP on the system operation, without
considering ESS allocation is investigated. In case 4, considering DRP, the problem of the optimal ESS allocation is deliberated, and the results are compared with earlier cases.

Table 1 shows the total cost of the system in one year for four cases. It should be reemphasized that total cost for case 1 is the net operation cost for one year, while for other cases given the assumptions of each case, the ESS investment cost or DRP incentive cost is also added.

Bearing on the objective function, the optimal sizing and placement of the ESSs are determined as in Fig. 2. Due to high penetration of renewable generation at far-end buses (i.e., 26 to 33), a massive amount of capacity has been installed at these buses. Cases 2 and 4 are relatively the same in term of optimal sizing of the ESSs. However, in case 2, two ESSs are placed at buses 5 and 6, where, in case 4, the recommendation is buses 23 and 24.

From Table 1, it can be concluded that regarding cost saving, case 4 which takes the advantages of ESS beside DRP has the least annual cost, i.e., more than 10% saving is achieved in this case. Comparing the cost of cases 2 and 3, it is clear that DRP outperforms ESS in energy management purpose in the considered distribution network, so that, the cost saving in case 2, with optimal sited and sized ESSs is insignificant. The main reason for cost saving might be less power purchasing from the upstream grid. Figure 3 illustrates the drawn active power from the utility, in which the imported power during peak times in case 1, is relatively higher than that in the other cases that has led to higher operating cost. Reactive power importance is the same for all cases; thus, the corresponding curve has not been plotted.

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual energy cost</td>
<td>23.336</td>
<td>23.098</td>
<td>20.838</td>
<td>20.612</td>
</tr>
<tr>
<td>(million $)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual reserve cost</td>
<td>0.500</td>
<td>0.500</td>
<td>0.585</td>
<td>0.585</td>
</tr>
<tr>
<td>(million $)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total operational</td>
<td>23.836</td>
<td>23.599</td>
<td>21.423</td>
<td>21.197</td>
</tr>
<tr>
<td>cost (million $)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investment cost of</td>
<td>--</td>
<td>0.61</td>
<td>--</td>
<td>0.61</td>
</tr>
<tr>
<td>the ESSs (million $)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incentive cost of</td>
<td>--</td>
<td>--</td>
<td>0.386</td>
<td>0.386</td>
</tr>
<tr>
<td>DRPs in energy market (million $)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incentive cost of</td>
<td>--</td>
<td>--</td>
<td>0.483</td>
<td>0.483</td>
</tr>
<tr>
<td>DRPs in reserve</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>market (million $)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net profit</td>
<td>--</td>
<td>0.237</td>
<td>2.413</td>
<td>2.639</td>
</tr>
<tr>
<td>compared with base</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>line (million $)</td>
<td></td>
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</table>

Fig. 2. Optimal size and location of the ESSs.
From Table 1, the differences of the annual cost of reserve procurement among four cases are not notable; however, in cases 3 and 4, this cost has increased slightly because of extra incentive costs of the DRP in the reserve market, but in total the operation cost of the distribution system has been decreased. Comparing to cases 1 and 2, the presence of DRP in the system scheduling in cases 3 and 4, has changed the commitment strategy of the MTs. As it is clear from Fig. 4, the integration of the DRP in cases 3 and 4, increases the cumulative active power generation of the MTs in the energy market and decreases that in the reserve market, see Fig. 5. In fact, the optimization problem compares MT generation cost and DRP incentive cost for both energy and reserve markets, and finds out that under the optimal scheduling of the system, the DRP should have more share for reserve provision, while MTs should generate more power in the energy market (in cases 3 and 4). As it was mentioned before, the DRP participation of the responsive loads is available in two ways- by the help of an aggregator and direct participation for LCs. Figure 6 displays the contracted load reduction of the LCs placed at buses 6 and 23, in Fig. 1, in both energy and reserve markets. From Fig. 6, the industrial load located at bus 6, participates only in energy market considering his price offers, while the consumer at bus 23 takes part in both markets, even provides more load reduction in reserve market. That is in line with the previous discerption regarding MTs generation strategy in cases 3 and 4. Furthermore, there are two DRAs in the distribution network, which the first one covers the loads at buses 23 to 33, and the second one covers the loads at buses 9 to 18. The optimal power flow calculation has selected the loads at buses 13 and 30 as winner DRP participants. The load reduction scheduling for the group of consumers at buses 13 and 30 are demonstrated by Fig. 7, for energy and reserve markets. It is clear that the consumers are requested to participate actively in reserve provision, and only at hours 11, 12, 15, and 16, they have been scheduled in the energy market. It is worth mentioning, the curtailed loads in cases 3 and 4 are similar, hence, Figs. 6 and 7 are enough to show the performance of the DRP.

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**Fig. 3.** Imported power from the upstream grid.

**Fig. 4.** Microturbines cumulative active power generation for energy procurement
**Fig. 5.** Microturbines cumulative active power generation for reserve procurement.

**Fig. 6.** Large consumers participation in energy and reserve markets.

**Fig. 7.** Demand response contracts by DRAs.
Finally, Fig. 8 shows the daily average voltage profile. It should be pointed out that the objective function does not include the cost for voltage deviation restraint. From Fig. 8, the average amount of the bus voltages never set below 0.95 per unit, and the average amounts in cases 3 and 4 with the implementation of DRP has improved significantly in the shoulder times, i.e., hours 8 to 17. Moreover, the voltage profile differences between case 1 and 2, and between cases 3 and 4 are minor.

5. CONCLUSION

The problem of optimal allocation of the ESSs in smart distribution networks in the presence of renewable generation and dispatchable MTs has been addressed in this paper. As practical solutions, DRPs have shown successful operation in energy management of distribution networks. The problem of optimal sizing and siting of ESSs in the presence of the DRPs is further examined. The DRP implementation has been carried out in two ways- using direct contracts and by the intercession of aggregators. Four case studies are considered, and the results revealed that the integration of DRP in distribution network operation, even without considering ESSs, can achieve satisfying optimal dispatch that leads to lower operational costs. However, the optimal siting and siting of the ESSs can further lessen the operational cost of the system. By solving the presented optimization problem, the optimal size and placement of the ESSs are obtained, and the load reduction scheduling of the responsive loads for both energy and reserve procurement market has been found. The results show that integration of demand response programs and energy storage systems in distribution networks can decrease system operation’s annual cost by about 10%.

REFERENCES


[8] F. Mohammadi, H. Gholami, G. B. Gharehpetian,


Appendix

Nomenclature

<table>
<thead>
<tr>
<th>Sets</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t$</td>
<td>Time index</td>
</tr>
<tr>
<td>$i, j$</td>
<td>Sets of networks bus</td>
</tr>
<tr>
<td>$k$</td>
<td>Block counter</td>
</tr>
<tr>
<td>$g$</td>
<td>Set of buses includes DG</td>
</tr>
<tr>
<td>$l$</td>
<td>Set of buses includes large consumer</td>
</tr>
<tr>
<td>$d$</td>
<td>Set of buses includes demand response aggregator (DRA)</td>
</tr>
<tr>
<td>$s$</td>
<td>Set of buses includes ESS</td>
</tr>
<tr>
<td>$w$</td>
<td>Set of buses includes wind turbine</td>
</tr>
<tr>
<td>$p$</td>
<td>Set of buses includes photovoltaic</td>
</tr>
<tr>
<td>$c$</td>
<td>Set of buses includes consumers</td>
</tr>
</tbody>
</table>

Parameters

- $\lambda(t)$: Hourly energy price forecast
- $\chi_{ESS}$: Capital cost of ESS
- $a, b, c$: Cost coefficients of DGs
- $P_{\text{max}}(g) / P_{\text{max}}(DG)$: Minimum/maximum generation limit of the DG
- $X_{\text{SF}}(g) / X_{\text{SD}}(g)$: Startup/shutdown cost of each DG
- $UPT(g) / DNT(g)$: Minimum up/down time of each DG
- $RU(g) / RD(g)$: Ramp up/down constant of each DG
- $P_{\text{rated}}(w)$: Rated power of each wind turbine
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{cut-in}/V_{rated}$</td>
<td>$FC_{DG}^g(t,g)$</td>
</tr>
<tr>
<td>$V_{cut-out}$</td>
<td>$STC_{DG}(t,g)$</td>
</tr>
<tr>
<td>$P_{cut-out}(P)$</td>
<td>$SUC_{DG}(t,g)$</td>
</tr>
<tr>
<td>$d_{min}(t,d)$</td>
<td>$DRC^a_{LC}(t,l)$</td>
</tr>
<tr>
<td>$d_{i}(t,d)$</td>
<td>$DRC^a_{LC}(t,l)$</td>
</tr>
<tr>
<td>$\delta^a_k(t,d)$</td>
<td>$DRC^m_{DRA}(t,d)$</td>
</tr>
<tr>
<td>$\theta^a_k(t,d)$</td>
<td>$DRC^m_{DRA}(t,d)$</td>
</tr>
<tr>
<td>$\psi^a(t,l)$</td>
<td>$C_{ESS}(s)$</td>
</tr>
<tr>
<td>$\psi^b(t,l)$</td>
<td>$P_{ESS}(t,s)$</td>
</tr>
<tr>
<td>$\psi^c(t,l)$</td>
<td>$SOC(t,s)$</td>
</tr>
<tr>
<td>$P_{max}(t,d)$</td>
<td>$P_{DG}(t,g)$</td>
</tr>
<tr>
<td>$P_{load}(t,c)$</td>
<td>$P_{DG}(t,g)$</td>
</tr>
<tr>
<td>$Q_{load}(t,c)$</td>
<td>$\alpha(t,g)$ / $\beta(t,g)$ / $\gamma(t,g)$</td>
</tr>
<tr>
<td>$\Omega(t)$</td>
<td>$P_{wind}(t,w)$</td>
</tr>
<tr>
<td>$Y_{ij}$</td>
<td>$D_{k}(t,d)$</td>
</tr>
<tr>
<td>$\theta_{ij}$</td>
<td>$P_{LC}^a(t,l)$</td>
</tr>
<tr>
<td>$V^{\min}$ / $V^{\max}$</td>
<td>$P_{LC}^a(t,l)$</td>
</tr>
<tr>
<td>$S_{ij}^{\max}$</td>
<td>$P_{DRA}^a(t,d)$</td>
</tr>
<tr>
<td>$P_{max}$</td>
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</tr>
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<td>$SOC_{i}$</td>
<td>$V(t,i)$</td>
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<tr>
<td>$SOC_{min}/SOC_{max}$</td>
<td>$\delta(t,i)$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>$S_{ij}(t,i,j)$</td>
</tr>
<tr>
<td>Variables</td>
<td>Definition</td>
</tr>
<tr>
<td>$OF$</td>
<td>Objective function</td>
</tr>
<tr>
<td>$UC$</td>
<td>Daily supply cost from upstream grid</td>
</tr>
<tr>
<td>$EC$</td>
<td>Daily energy procurement cost</td>
</tr>
<tr>
<td>$RC$</td>
<td>Daily reserve procurement cost</td>
</tr>
<tr>
<td>$IC$</td>
<td>Prorated daily investment cost of the ESS</td>
</tr>
<tr>
<td>$P_{wp}(t)$</td>
<td>Purchased active power from upstream grid (bus No. 1)</td>
</tr>
<tr>
<td>$Q_{mp}(t)$</td>
<td>Purchased reactive power from upstream grid (bus No. 1)</td>
</tr>
<tr>
<td>$FC_{DG}^{en}(t,g)$</td>
<td>Fuel cost of DG at bus $g$ at time $t$ for energy supply</td>
</tr>
</tbody>
</table>