ANALYSIS OF BATTERY ENERGY STORAGE MANAGEMENT IN LOW-VOLTAGE CONSUMER AGGREGATION ZONES

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ABSTRACT

The opening of the energy market has been encouraged in several countries. In extensive distribution networks, the aggregation of consumers can create a competitive market that benefits consumers and distribution companies. Consumers with photovoltaic systems can see a more significant decrease in their electricity bills if they install battery energy storage systems in their homes. However, small-scale battery storage systems are still expensive, making them unfeasible for some consumers. The economic viability of battery energy storage systems becomes favorable when the system's power is increased. Thus, a centralized battery energy storage system in an aggregation zone may reduce energy billing better. This work analyzes the management of aggregation zones with distributed and centralized battery energy storage systems. A mixed integer linear optimization model was used to reduce the energy purchased from the distribution company, using the type of battery energy storage system installed and hourly rates. The analysis was carried out on a low-voltage network in Denmark with 45 consumers, four aggregation zones and four different cases. The results show an average variation of 23.38% in energy credits concerning the centralized battery system. This information can help the representative of the aggregation zone to make their decisions.

Keywords: DERs Optimization, LV Networks, Retail Electricity Market, Storage Systems.

Introduction

With the increase of Distributed Energy Resources (DERs) and the modernization of distribution networks, new electric market structures are rising. These structures encourage consumers to participate in the market and manage their DER [1]. To this end, the opening of the market for low-voltage (LV) consumers is considered a viable alternative by implementing aggregation zones to establish a competitive market [2]. Aggregation zones consider the participation of a trading agent representing a group of consumers. The aggregator has to optimize the use of DERs to reduce electrical losses and improve the voltage profile of the electrical network [3], besides negotiating better prices for consumers.

The use of aggregators is widely discussed in the literature. In [4], a bidding model for a price-forming microgrid aggregator is presented. The work of [5] presents a methodology for managing DERS and participating in the day-ahead booking market. The management of DERs using energy storage systems and the optimal allocation of these systems is discussed in [6].

Unlike previous studies, this work analyzes aggregation zones with DERs installed non-homogeneous along extensive LV feeders, considering that an aggregator represents each zone. Additionally, it examines the management of centralized batteries installed at the point of connection of the aggregation zone and the use of residential batteries distributed to each consumer within each aggregation zone.

The methodology developed pursues minimizing the net power required by each aggregation zone within the distribution company's concession area by considering hourly rates. The aim is to benefit extensive distribution networks and LV consumers mutually. The DERs included in the zones are photovoltaic systems (PV) and energy storage systems. From the characterization of each zone, it is possible to obtain different forms of negotiation for the tariff value.

Therefore, a novel methodology is proposed to optimize DER in aggregated LV networks. It assesses whether small or large storage systems are better for consumers, based on purchase price. The proposal can be used by agents in the day-ahead retail electricity market.

Proposed Methodology

The methodology is divided into two stages. The first stage analyzed the management of DERs considering residential storage systems distributed along the distribution network where the PV systems are installed. The second stage studied the management of a single centralized three-phase battery storage system installed at the point where the aggregation zone connects to the main grid.The mathematical formulation presented is inspired by [7] and [8], adding restrictions for the number of battery discharges.

A. Mathematical Formulation

The objective function F presented in (1) minimizes the aggregator's costs with energy purchases.

$$F = \min \sum_{t\in\Omega_t} \sum_{i\in\Omega_N} \rho^S_{i,t} \Delta t P^S_{i,t} - \sum_{t\in\Omega_t} \sum_{i\in\Omega_N} \rho_{i,t} \Delta t P^{\text{Load}}_{i,t} + \sum_{t\in\Omega_t} \sum_{i\in\Omega_N} \rho^{\text{PV}}_{i,t} \Delta t P^{\text{PV}}_{i,t} - \sum_{t\in\Omega_t} \sum_{i\in\Omega_N} \rho^{\text{str}}_{i,t} \Delta t (P^{\text{ch}}_{i,t} - P^{\text{dis}}_{i,t}) \quad (1)$$

Where, Ω_t represents the set of analysis intervals, and Ω_N is the set of nodes. The electricity price in the retail market ($/kWh) at the i node and time t is represented by $\rho^S_{i,t}$ and $\rho_{i,t}$ represents the electricity price ($/kWh) at the i node and time t . $P^{Load}_{i,t}$ is the predicted demand in kilowatts (kW) at the i node and time t . The remuneration rate for PV system generation ($/kWh) at the i node and time t is $\rho^{PV}_{i,t}$, the price to be paid for the installed storage system ($/kWh) at the i node and time t is expressed by $\rho^{str}_{i,t}$. $P^{PV}_{i,t}$ is the power generated by the photovoltaic system in kW at the node i and time t . $P^S_{i,t}$, represents the amount of enery bought/sold by the aggregator at the agregation zone S, node i and t time in kW, $P^{ch}_{i,t}$, denotes the stored power in kW at node i and t time and $P^{dis}_{i,t}$ is the injected active power in kW at node i and time t .

Additionally, $\rho_{i,t}$ can take on three values: $\rho_{i_{max}}$ is the energy price to node i within the three consecutive hours of highest demand from the electrical grid; $\rho_{i_{normal}}$ is the energy price at node i when consumption is carried out within the intermediate period; $\rho_{i_{min}}$ is the energy price at node i when the demands are outside the period of most significant demand and intermediate level of demand of the distribution network. The objective function F is subject to energy balance restrictions, physical and operational limits of the system,and operation of storage equipment. Regarding storage systems, the restrictions should ensure loading and unloading from coinciding. The model run was performed for each aggregation zone separately.

Case Studies

The network used in this study case has 15 nodes, 45 consumers, 12 PV systems of 2.5 kVA and 12 storage systems. The transformers are 400 kVA and the feeder is 571 A. The network topology and aggregation zones represented by AZ_n are shown in Fig. (1).

Fig. 1 shows that there are 12 PV systems distributed among the phases. Five of them are allocated in phase A, four in phase B, and three in phase C.

B. Results and Discussion

The following section presents the obtained results. The simulations are carried out using OpenDSS and Python. For the mathematical model, the Pyomo library and Couenne solver are used. Four different generation profiles are considered to better accommodate the unpredictable nature of solar resources Case 1, Case 2, Case 3, Case 4. These profiles are created by using the k-means clustering technique [9] with irradiance and temperature measurements. The results are presented separately for distributed batteries connected to nodes with PV systems and concentrated batteries connected each aggregation zone. The tariff adopted for both cases is $0.014.

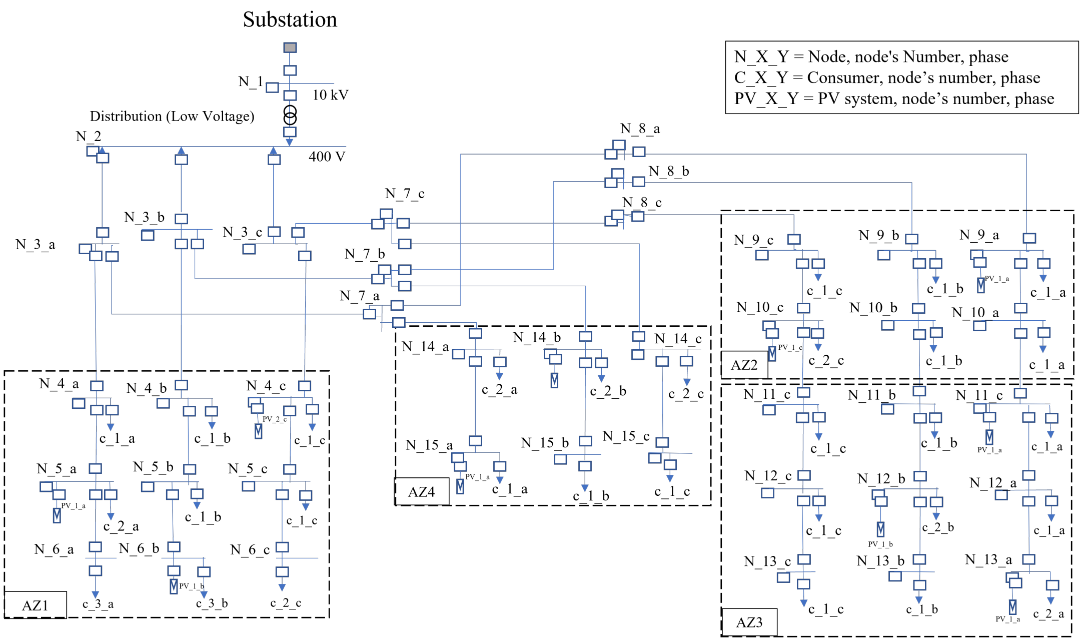

Figure 1: 15 Nodes Network Topology

a) Results Using Distributed Storage Systems

Fig. 2 shows the energy purchased by aggregators in each of the analyzed cases. It can be seen that the most significant purchase of energy occurs in Case 3, which has the worst conditions for the solar resource. On the other hand, Case 2 has better conditions for photovoltaic generation, which results in the lowest value found for energy purchase.

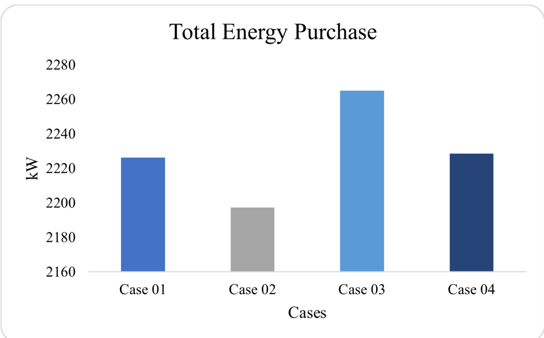

Figure 2: Energy Purchase by aggregators for the Distributed Storage Systems scenario

Table 1: Sale of Energy by the aggregator for the Distributed Storage Systems scenario

Cases	Sale Energy ($)
Case 1	25.74
Case 2	29.51
Case 3	22.34
Case 4	25.42

Through energy storage systems, aggregators can reduce their need to buy energy from the distribution company. For this analysis, 4 kW batteries are used. The stored energy is credited to the aggregator, in monetary terms. This stored energy means there was a more significant injection of energy into the network than imports. The energy credits, that is, the receipt from the sale of energy, are then passed on to each aggregation zone and divided among the included consumers. This transfer considers the energy imported from the main grid and the use of DERs. The credits obtained by consumers in each case are presented in Table 1.

When considering the same load profile for each case, there was a higher average energy sale in aggregations zones 1 and 3. The reason for this is that these areas have a higher presence of PV systems.

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b) Results Using Centralized Large Storage Systems

Fig. 3 shows the energy purchased by aggregators in each of the analyzed cases. Similar to the case of distributed batteries, Case 3 has the highest purchase price and Case 2 the lowest. For this analysis, 20 kW batteries are used. The credits obtained are shown in Table 2. In relation to credits for the sale of energy by aggregators, cases with a higher concentration of PV systems have more credits.

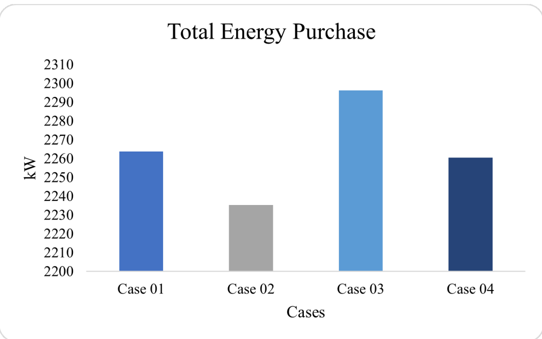

Figure 3: Energy Purchase by aggregators for the Centralized Storage Systems scenario

Table 2: Sale of Energy by the aggregator for the Centralized Storage Systems scenario

Cases	Sale Energy ($)
Case 1	21.08
Case 2	24.85
Case 3	18.34
Case 4	19.42

Conclusion

This study presents a methodology for optimizing the management of Distributed Energy Resources (DERs) in aggregation zones for low-voltage consumers. Considering hourly tariffs, the objective is to minimize the net power requirement per aggregation zone in the distributor's concession area. The analysis compares centralized and distributed storage systems integrated into the grid alongside various photovoltaic generation profiles. The study is conducted per zone for granularity.

The results of Table 1 and 2 demonstrate varying degrees of improvement depending on the specific case when comparing different generation profiles. These objective function values represent the economic savings obtained by the aggregator and the economic savings to be transferred to each aggregation zone. Case 1 showed a reduction of 22.08%, Case 2 demonstrated an 18.73% decrease, Case 3 experienced a 21.85% improvement, and Case 4 achieved the most significant reduction, with a reduction of 30.86%. These variations can be attributed to the choice between centralized and distributed storage systems.

Regarding energy importation by aggregators, variations in energy are minimal during periods of high load demand or increased PV generation. The average variance in energy imports between centralized and distributed storage systems was 1.6%. When comparing the highest and lowest important Case 2 and Case 3, the variation was 2.65%. These results are shown in Fig. 2 and 3. Therefore, both storage methods maintained relatively constant grid energy imports. These findings provide valuable insights that could foster mutually beneficial arrangements for DER owners and electricity system operators, ultimately fostering a competitive retail market.

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