OPTIMAL BATTERY SIZING FOR A DISTRIBUTION NETWORK IN AUSTRIA TO MAXIMISE PROFITS AND RELIABILITY

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Keywords: Battery sizing, distribution network, reliability, second-order cone programming.

Abstract

Energy Storage Systems (ESS) can benefit distribution networks by providing multiple services to the Distribution System Operator (DSO) and contributing to system reliability. Given the high capital costs of ESS, it is beneficial to optimally design them for their intended applications; however, this can be computationally expensive due to the non-convex formulation of the AC power flow, the complexity of business use cases, and the simulation of multi-period operations. This paper develops a comprehensive model to size the ESS to minimize the system lifetime costs and maximise reliability. The non-convex AC power flow model is modified using a convex relaxation, which yields efficient and globally optimal results. The battery degradation is simulated by a global wear coefficient considering the effect of Depth of Discharge (DOD). The sizing study is implemented to fulfil multiple applications on the Güssing distribution network in Austria.

1 Introduction

Distribution Networks face challenges driven by increasing penetration of renewable generation and changes in electricity demand due to the decarbonisation of heat and transport. These challenges can be addressed in part by employing a Battery Energy Storage System (BESS) to provide services to the Distribution System Operator (DSO) including demand peak shaving and other ancillary services [1]. The BESS can also improve the reliability of some sections of network by enabling islanded operation during the system faults.

Reliability is an important topic for Distribution Networks, which are usually radial, so the failure of a single element may cause the disruption of an entire feeder [2]. However, in microgrids with the capability to island, reliability may be driven not only by network failures but also by generation adequacy and the capability to provide a power unbalance response, which can be mitigated using a BESS. Neglecting these aspects when designing the BESS might hinder the optimal operation of the grid.

Optimal planning and design of BESS in distribution systems can benefit the investor and DSO. The BESS's energy capacity and power rating should be optimally set considering the capital cost, potential business use cases, and operation cost. BESS sizing studies in distribution networks have been extensively investigated, for example [3] proposes a Model Predictive Control (MPC) scheme to optimal plan the battery with Benders decomposition technique and [4] presents a two-stage MPC, and employs chance-constrained programming to size the battery considering the uncertain wind generation. The BESS is assumed to provide reactive power support in [5], and is sized considering day-ahead and real-time electricity markets. In the above literature, the BESS sizing is carried out considering different objectives and functions, but the non-convex AC power flow model is either fully simulated, linearized, or completely ignored, leading to inaccurate results.

Standard optimisation solvers struggle to solve BESS sizing problems for distribution networks, because they require massive computational effort and fail to guarantee global optimality due to the non-convex form of the power flow equations and the multi-period formulation of the sizing problem. This paper employs a convex formulation of the radial network model [6] to transfer the non-convex AC power flow model via Second Order Cone Programming (SOCP). This enables commercially available solvers to efficiently solve the multi-period sizing problem with high accuracy.

The contributions of the paper are:

i) Applying SOCP to model the AC power flow in sizing studies for a BESS in a real distribution network in Austria.
ii) A method to assess the distribution network reliability considering multiple renewable generators, BESS, and island operation.
iii) A comprehensive model to size the BESS to maximise network profits and reliability, while considering battery degradation. The BESS provides electricity price-based arbitrage, frequency response, and improves reliability.

The rest of the paper is organised as follows. Section 2 models the power flow and BESS. Section 3 presents the reliability evaluation and formulates the sizing problem. The case study is investigated in section 4. Section 5 concludes the paper.

2. Distribution Network Modelling

2.1 Convexification of Power Flow Model

In a distribution network, the active and reactive power balance at bus i are expressed as

$P_{\text{net},i} = \sum_{k=1}^{N}|V_i|\,|V_k|[G_{ik}\cos(\theta_i-\theta_k)+B_{ik}\sin(\theta_i-\theta_k)]$, and (1)

$Q_{\text{net},i} = \sum_{k=1}^{N}|V_i|\,|V_k|[G_{ik}\sin(\theta_i-\theta_k)-B_{ik}\sin(\theta_i-\theta_k)]$, (2)

where V_i and θ_i are the voltage and phase angle at bus i, N indicates the number of buses connected to bus i, G_{ik} and B_{ik} mean the real and imaginary parts of the corresponding element Y_{ik} in the admittance matrix. $P_{\text{net},i}$ and $Q_{\text{net},i}$ are the net active and reactive power injections at bus i.

According to the convex relaxation method in [6], by introducing variables $u_i = V_i^2/\sqrt{2}$, $R_{ik} = V_iV_k\cos(\theta_i-\theta_k)$, $I_{ik} = V_iV_k\sin(\theta_i-\theta_k)$, (1) and (2) can be expressed as:

$P_{\text{net},i} = \sqrt{2}G_{ii}u_i + \sum_{k=1, k\neq i}^{N}[G_{ik}R_{ik}+B_{ik}I_{ik}]$, and (3)

$Q_{\text{net},i} = -\sqrt{2}B_{ii}u_i - \sum_{k=1, k\neq i}^{N}[B_{ik}R_{ik}-G_{ik}I_{ik}]$. (4)

It can be derived that the variables R_{ik} and I_{ik} satisfy:

$2u_iu_k = R_{ik}^2 + I_{ik}^2$, (5)

which can be further relaxed to

$2u_iu_k \geq R_{ik}^2 + I_{ik}^2$. (6)

Equations (3), (4) and (6) represent a convex formulation of a SOCP to model the non-convex AC power flow model. Commercially available solvers can therefore efficiently locate the global optimal solution.

2.2 BESS Model

The BESS exchanges power with the distribution network by either gaining energy (charging energy E_{ch}) or losing energy (discharging energy E_{dis}). The energy stored within the BESS E_{b} at time step t is formulated as

$E_{\text{b}}(t) = E_{\text{b}}(t-1) - E_{\text{b}}^{\text{stb}} + E_{\text{ch}}(t)\cdot\eta_{\text{ch}} - E_{\text{dis}}(t)/\eta_{\text{dis}}$, (7)

where η_{ch} and η_{dis} are the charging and discharging efficiencies, $E_{\text{b}}^{\text{stb}}$ means the BESS standby loss.

The BESS degrades as it is used, which should be appropriately modelled within a sizing study. The most influential factor driving BESS degradation is the operating Depth of Discharge (DOD). The influence of DOD is explicitly simulated in this paper based on the degradation model proposed in [7], which is summarized here:

The exploitable energy capacity loss, ΔE, through a single charge/discharge action is

$\Delta E = E_0\left|D_{\text{ini}}K_{D_{\text{ini}}} - D_{\text{fin}}K_{D_{\text{fin}}}\right|$, (8)

where D_{ini} and D_{fin} are the initial and final DODs of the charge and discharge actions, respectively; E_0 denotes the exploitable energy capacity at the beginning of the action. K_D is a coefficient formulated, which indicates the relationship between the BESS's achievable life cycles and the operating DOD formulated as:

$K_D = \frac{1}{2D}\left(1-0.8^{\frac{1}{N_{\text{ACC}(D)}}}\right)$, (9)

where $N_{\text{ACC}(D)}$ indicates the number of cycles the BESS can achieve before the exploitable energy capacity drops to 80% of its initial capacity for an operating DOD of D.

By computing (8) with all possible initial and final State of Charges (SOCs), the capacity loss in terms of all SOCs is derived as an approximately linear surface. A global wear coefficient, K_{w}, is substituted to approximate K_D and (8):

$\Delta E = K_{\text{w}}E|D_{\text{ini}} - D_{\text{fin}}|$. (10)

For a lithium-ion battery, whose life cycles $N_{\text{ACC}(D)}$ vary between 15000 and 6000 with the operating DOD changing between 0 and 100%, the best approximation of K_{w} is obtained as 1.04×10^{-5} by comparing the root mean square errors of using all possible initial and final SOCs to compute (8) and (10). The value means that the battery capacity reduces by 1.04×10^{-5} kWh when the BESS charges or discharges by 1 kWh.

3 Sizing Problem Formulation

3.1 Reliability Evaluation

For a power system, reliability describes its ability to adequately supply demand with few interruptions over a long period of time [8]. Modelling the failure probabilities of each element enables enumeration of the likelihood of each operational state, assuming all failures are independent of the network loading, generator output, and each other. In this paper, Sequential Monte-Carlo Simulation [2] has been chosen to preserve the relationship with the annual load demand and generation output of the grid.

The probabilities related to failure of the main incoming supply to the network have been calculated from real indices related to the Austrian distribution system [9]. These indices were also used to model branches, fuses, circuit-breakers, and transformers to reproduce the stochastic behaviour of the system. Distributed generators and loading points were represented by real data provided by an Austrian utility with hourly load demand and generation curves available for a whole year. A simulated outage history for each element within the system was generated using the Mean Time To Failure (MTTF) and Mean Time To Repair (MTTR) for each network element [2].

The reliability indices for each load point were calculated individually based on analysis of the outage history of the elements between the load point and the generators. For a radial system, and considering the generator m, such indexes can by assessed by:

$\lambda_k^m = \sum_i \lambda_i$ [failures/year], (11)

$U_k^m = \sum_i \lambda_i \cdot r_i$ [hours/year], (12)

$r_k^m = \frac{U_k}{\lambda_k}$ [hours]. (13)

where λ_i, U_i and r_i stands for the failure rate, annual unavailability and repair time of the element i, while k indicates the analysed load point.

The key output for the performance evaluation of a distribution system is Expected Energy Not Supplied (EENS). For the whole system, it can be calculated by:

$$EENS = \sum_k U_k \cdot L_k \text{ [MWh/year]} \quad (14)$$

where L_k is the active power demand for load point k.

3.2 Problem Formulation

The objective function of the sizing problem is to minimize the annual cost of the distribution system as:

$$C_{\mathrm{T,an}} = \left(\frac{365}{D_{\mathrm{T}}} \cdot \sum_{t=1}^{T} C_{\mathrm{e}}(t) - R_{FR}(t)\right) + C_{\mathrm{RC}} + CC_{\mathrm{BESS}} \cdot \frac{d(1+d)^{LT_{\mathrm{BESS}}}}{(1+d)^{LT_{\mathrm{BESS}}-1}}, \quad (11)$$

where $C_{\mathrm{T,an}}$ indicates the annual cost including the annualised BESS capital cost, T is the number of time steps in the analysed period D_{T}, $C_{\mathrm{e}}(t)$ denotes the electricity procurement cost at time step t, $R_{FR}(t)$ means the revenue of providing frequency response at time step t, C_{RC} denotes the reliability cost. CC_{BESS} is the battery capacity cost annualised by the discount factor d and the battery lifetime LT_{BESS}. The investment on battery is expressed as:

$$CC_{\mathrm{BESS}} = C_{\mathrm{BESS}}^{\mathrm{en}} \cdot E_{\mathrm{BESS}} + C_{\mathrm{BESS}}^{\mathrm{pwr}} \cdot P_{\mathrm{BESS}}, \quad (12)$$

where E_{BESS} is the battery capacity, P_{BESS} is the power rating, $C_{\mathrm{BESS}}^{\mathrm{en}}$ and $C_{\mathrm{BESS}}^{\mathrm{pwr}}$ are their unit costs.

The frequency response revenue $R_{\mathrm{FR}}(t)$ is quantified by the availability payment $A_{\mathrm{FR}}(t)$ multiplied by the power rating of the battery system and hours committed to provide frequency response T_{FR}, the relation is shown as:

$$R_{\mathrm{FR}}(t) = A_{\mathrm{FR}}(t) \cdot P_{BESS}(t) \cdot T_{\mathrm{FR}}. \quad (13)$$

The reliability cost C_{RC} in the objective function is calculated by the multiplication of Expected Energy Not Served (EENS) and Value of Loss Load (VOLL) as:

$$C_{\mathrm{RC}} = EENS \times VOLL \quad (14)$$

The inclusion of reliability cost in (11) means that the optimisation aims to maximise both the profits and system reliability.

The electricity cost $C_{\mathrm{e}}(t)$ in (11) contains the cost of importing electricity from the grid $P_{\mathrm{G}}(t)$ and the i^{th} local renewable generator $P_{\mathrm{re},i}(t)$ at time step t. By using the electricity prices of the grid $\Pi_{\mathrm{G}}(t)$ and i^{th} renewable generator $\Pi_{\mathrm{re},i}(t)$, $C_{\mathrm{e}}(t)$ is formulated as:

$$C_{\mathrm{e}}(t) = P_{\mathrm{G}}(t) \cdot \Pi_{\mathrm{G}}(t) + \sum_{i=1}^{R} P_{\mathrm{re},i}(t) \cdot \Pi_{\mathrm{re},i}(t). \quad (15)$$

To ensure the battery exploitable energy is higher than 80% of its initial capacity before the anticipated lifetime, the global wear coefficient K_{w} is employed as:

$$LT_{\mathrm{BESS}} \cdot \left(\frac{365}{D_{\mathrm{T}}} \cdot \sum_{t=1}^{N} E_{\mathrm{ch}}(t) + E_{\mathrm{dis}}(t)\right) \cdot K_{\mathrm{w}} < 0.2 \cdot E_{\mathrm{BESS}}. \quad (16)$$

The decision variables for the sizing problem contain the active and reactive power injections from the grid and renewable generators, ancillary variables $u_i(t)$, $R_{ik}(t)$ and $I_{ik}(t)$, battery charging energy, discharging energy, battery energy level, battery capacity and power rating.

$$u = [u_i(t), R_{ik}(t), I_{ik}(t), P_G(t), P_{\mathrm{re},i}(t), E_{\mathrm{ch}}(t), E_{\mathrm{dis}}(t), E_{\mathrm{b}}(t), E_{\mathrm{BESS}}, P_{\mathrm{BESS}}] \quad \forall i, \forall k, \forall t \quad (17)$$

In conclusion, the optimisation problem is formulated as:

Objective function: Minimise (11)

Subject to: (3), (4), (6), (7), (12)-(16), (18-20)

$$0 \le E_{\mathrm{ch}}(t)/t \le P_{\mathrm{BESS}} \quad (18)$$

$$0 \le E_{\mathrm{dis}}(t)/t \le P_{\mathrm{BESS}} \quad (19)$$

$$\frac{V_{i,\min}^2}{\sqrt{2}} \le u_i(t) \le \frac{V_{i,\max}^2}{\sqrt{2}} \quad (20)$$

Where (18) and (19) indicate the charging and discharging energy for all time steps should be less than the optimal battery power rating, (20) regulates the line voltage restrictions.

4 Case Study

4.1 Summary of Güssing distribution network

The proposed battery sizing has been demonstrated on the Güssing distribution network in Austria as part of the Merlon project [9]. The schematic of the network is shown in Fig. 1.

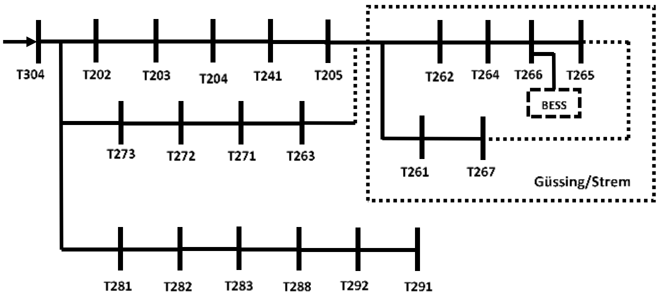

Fig. 1. Güssing distribution network

The 20-kV distribution network is supplied by a feeder connected with bus T304. The Strem area will be modelled for the case of operation as an Island Local Energy System (ILES) which can be disconnect from the grid due to system requirements or fault and continue to operate in islanded mode. The BESS, providing grid-forming functionality during islanded operation, will be installed at bus T266. The BESS will provide electricity price-based arbitrage and frequency response during grid-connecting mode. BESS availability has been assumed to be 96% when evaluating reliability. Austrian network regulations state that the voltage at each bus should be within the ±2% of the nominal value [10]. The branch parameters, historic demand and generation data were provided by the DSO, Energie Güssing. The demand uncertainties of each bus were modelled through the Two-Point Estimate Method (2PEM). Eight representative days – a weekday and a weekend day for each season – were used to implement the battery sizing study. The duration and times of providing frequency response are taken from [11]. Other input parameters are listed in Table 1.

Table 1: Input parameters for the sizing problem

BESS parameters	
Capacity unit cost	316 €/kWh
Power rating unit cost	200 €/kW
Maximum investment on BESS	200,000 €
Charging/discharging efficiency	95 %
Operating limits	0≤SOC≤100 %
VOLL	10,000 €/MWh
Lifetime	15 years
Discount rate	6 %
Frequency response	
Participation time of providing FR	12:00 am-06:00 am
Availability payments	22.01 €/MW/h

4.2 Sizing results

The optimal battery configuration is derived as 0.295 MWh with 0.533 MW. The optimal scheduling of the BESS operations over the 8 simulated days is shown in Fig. 2.

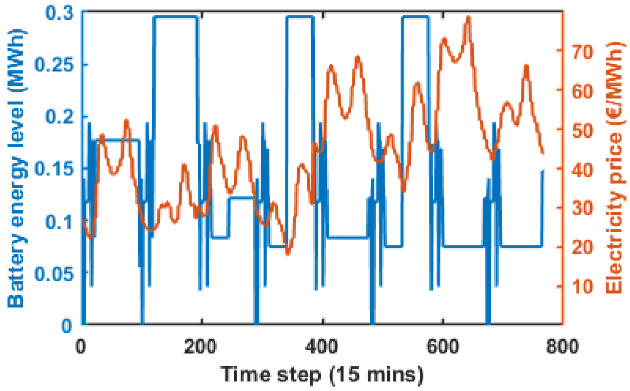

Fig. 2. Scheduling of BESS operations

The BESS provides frequency response as required between 00:00-06:00 each day through rapid charge and discharge actions. Electricity price-based arbitrage is only carried out in a small number of time steps because the BESS is constrained by its lifetime number of cycles by (16). The frequency response service represents much greater value for the system than the variable energy price, so its budget of cycles is primarily allocated to this.

The anticipated BESS lifetime significantly affects the BESS behaviour and optimal sizing results. Table 2 shows the sizing results and annualized network cost for different anticipated BESS lifetimes. The annualised cost remains approximately the same, which indicates higher annual profit because of the reduction in anticipated BESS lifetime. Meanwhile, the optimal power rating tends to decrease, and the capacity increases due to limited investment budget for the BESS. According to (16), the BESS operations are more constrained when the BESS lifetime increases, hence the investor should increase the BESS's capacity and decrease the power rating to extend the BESS lifetime which ensures profitable operations when providing different services.

Table 2: Optimal BESS configurations

Lifetime	Power rating (MW)	Capacity (MWh)	Annualised cost (€)
10	0.581	0.265	5.949×10^5
12	0.581	0.265	5.922×10^5
15	0.533	0.295	5.920×10^5
20	0.470	0.335	5.927×10^5

5 Conclusions

This paper presents a comprehensive model to size BESS in distribution networks maximise profit and reliability. The model considers the BESS's degradation and is implemented on a real distribution network in Güssing, Austria. The model benefits from efficient computation and the ability to reach global optimality with the convex-relaxed AC power flow model. The proposed model can be employed by BESS investors to carry out sizing studies for their objectives and business use cases. The major findings are:

i) For an anticipated 15 years of battery lifetime, the optimal configuration of the BESS is 0.295 MWh with 0.533 MW for the Güssing distribution network.
ii) The optimal capacity of the BESS increases, and the power rating decreases when the BESS lifetime is increased.

6 Acknowledgement

This work was supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No 824386.

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