A Robust Feasible-Box Method for Response Power Boundary Verification of DER Stakeholders in the Distribution System

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Abstract. The growth of low-voltage distributed energy resources (DERs) enables users to manage their own generation and demand, forming DER stakeholders at single or aggregated metering points. As these stakeholders join multi-level electricity markets, their actions must remain feasible under local distribution system limits. Existing work either jointly optimizes DERs and the utility grid or verifies DER response capabilities before market participation. The first can yield accurate results but require real-time data exchange and heavy coordination, whereas the second produce more conservative response boundaries but allow DER stakeholders to ignore local distribution constraints during market participation, thereby decoupling their operations from the utility grid and reducing the internal departments coordination need of utility grid. This paper proposes a practical response-power-boundary calculation and verification framework. Each stakeholder computes its maximum and minimum response boundaries and submits them to the regional load management center (LMC), which operates under the marketing department of the regional utility grid. The local distribution system operator (DSO) then checks and adjusts these boundaries using a DistFlow-Second-order cone program (SOCP) distribution system model and a maximum robust feasible-box method to ensure operational security. The verified boundaries guarantee feasible distribution power-flow solutions for any admissible DER stakeholders' response and thus decouple DER stakeholders from local distribution constraints. Simulation results show that the proposed method offers a practical and robust way to manage demand-side DER flexibility under existing organizational structures.

Keywords: Demand-side management (DSM), Distributed energy resources (DERs), DistFlow-second-order cone program (SOCP), Distribution system, Response power boundary, Robust feasible-box method.

This work was supported by National Key Research and Development Program (2022YFB2403100).

1 Introduction

With the rapid growth of low-voltage distributed energy resources (DERs) such as photovoltaics (PVs), energy storage (ES), and flexible loads, many electricity users are gaining the ability to manage their own power consumption and generation[1]. These users take the utility meter as the ownership boundary with the utility grid and form a new type of business entity, referred to as a DER stakeholder.

DER stakeholders generally fall into two categories. One consists of a single stakeholder, forming an electricity marketing account based on a single utility metering point; the other is composed of multiple electricity users aggregated into a unified electricity marketing account by integrating DERs behind multiple metering points, such as virtual power plants (VPPs) or load aggregators[2].

DER stakeholders can participate in multi-level electricity markets, and during such transactions they must also coordinate with the operational management of the regional utility grid. Therefore, in optimizing the operations of DER stakeholders, the constraints imposed by the utility grid cannot be overlooked. Existing studies generally adopt two main approaches:

1) ***Establishing a joint optimization model between DER stakeholders and the utility grid.*** Existing studies include single-agent or globally optimal models solved via centralized[3] or distributed[4] methods, as well as multi-agent optimal models solved using centralized[5] or decentralized[6] approaches.

2) ***Establishing a utility-grid-oriented verification model for DER stakeholders***, which focuses on evaluating and verifying the response capabilities of DERs prior to market participation. For example, the response power boundaries of each DER stakeholder are determined before trading and subsequently checked by the utility grid as part of the market admission process.

In the first approach, DER stakeholders are tightly coupled with the utility grid, and the solution process relies on real-time communication and information sharing. Although it can improve the efficiency of power system operations through more accurate DER power optimization results, it often depends on advanced information infrastructures and requires close coordination among different departments within the utility grid.

In contrast, the second approach yields more conservative power boundaries optimization results for DER stakeholders; however, because it ensures the feasibility of local distribution system constraints, DER stakeholders can ignore these local constraints when participating in subsequent multi-level electricity markets, effectively decoupling the two sides. During verification, this approach only requires DER stakeholders to provide their response capability indices in advance without disclosing additional internal operational constraints. Moreover, the verification can be completed with limited coordination among the utility grid's internal departments, thereby reducing the complexity of internal collaboration.

Considering the inherent difficulties of cross-entity and cross-department coordination, the second approach better aligns with the current operational and management practices of DER stakeholders and the utility grid.

In a typical integrated transmission-distribution management framework, the utility grid divides its operational functions among several departments, including dispatching, distribution, and marketing. Due to constraints such as access voltage levels and ownership boundaries, DER stakeholders are neither directly subject to the technical management of the transmission system operator (TSO) under the dispatching department nor able to participate in or coordinate with transmission-level electricity markets[7, 8].

In practice, DER stakeholders primarily interact with the marketing and distribution departments. The marketing department manages utility meters and users, handling transaction- and operation-related tasks such as electricity metering and financial settlement. Through the load management center (LMC), it also acts as an agent for regional loads, enabling it to guide DER stakeholders to participate in demand-side management (DSM) and to assist them in engaging in multi-level electricity markets associated with the dispatching and distribution departments of utility grid. The distribution department is responsible for the physical infrastructure that supports energy exchange between DERs and the utility grid. As it spans multiple medium- and low-voltage distribution areas, facilities and their technical operations in each area are managed by the corresponding local distribution system operator (DSO).

Building on the above understanding, this paper proposes a response power boundary calculation and verification method for DER stakeholders, developed within the current utility grid framework and assuming that the LMC serves as the agent for regional loads. First, within a given distribution system, each DER stakeholder calculates its maximum and minimum response power boundaries for each time period based on internal operational constraints, and submits the results to the regional LMC. Then, the DSO supports the regional LMC in optimizing, verifying, and adjusting these response boundaries. This paper models the local distribution system using the DistFlow-Second-Order Cone Program (SOCP) method[9, 10] and refines the response power boundaries of DER stakeholders through a maximum robust feasible box optimization approach. The objective is to maximize the sum of the feasible power ranges across all DER stakeholders while ensuring that, regardless of the specific DER power values selected within the ranges, the distribution system can always find a feasible power-flow solution under its own constraints. Finally, the verification results are returned to both the regional LMC and the DER stakeholders. Since the distribution system's feasible operating region becomes robust with respect to any admissible DER power value, the DER stakeholders are operationally decoupled from the local distribution system. Consequently, when participating in subsequent multi-level electricity markets, DER stakeholders can ignore local distribution system constraints. This method provides a practical pathway for efficient demand-side DER management within the existing organizational framework of the utility grid.

The rest of this paper is organized as follows. Section 2 introduces the calculation and verification process of DER stakeholders' response power boundaries. Section 3 presents the calculation model, and Section 4 describes the verification and correction model with its briefly proof. Section 5 provides and analyzes the simulation results. Section 6 concludes the paper.

2 Calculation and verification process of DER stakeholders' response power boundaries

In the current hierarchical management structure of the regional utility grid, the marketing department is responsible for electricity metering and DSM. The regional LMC is an upgraded version of the utility metering management system originally designed for traditional electricity customers. To some extent, it functions as a largest load aggregator on the demand side, guiding DERs to participate in DSM and helping them connect with dispatching, distribution department, and the regional market operator to participate in multi-level and type electricity transactions. The establishment of LMC aligns with the utility grid's gradual and adaptive transition strategy.

Before taking part in electricity transactions, DER stakeholders must submit their response capability data to the LMC to satisfy market entry requirements. Most indicators can be calculated by the DER stakeholders themselves. However, the upper and lower limits of response power must also comply with distribution system constraints and therefore cannot be determined independently. To address this issue, the regional LMC collaborates with the local DSO to assist DER stakeholders in verifying their power boundaries within the distribution system.

Fig. 1 shows the overall structure and steps for calculating and verifying the power boundaries of DER stakeholders connected to a given distribution system.

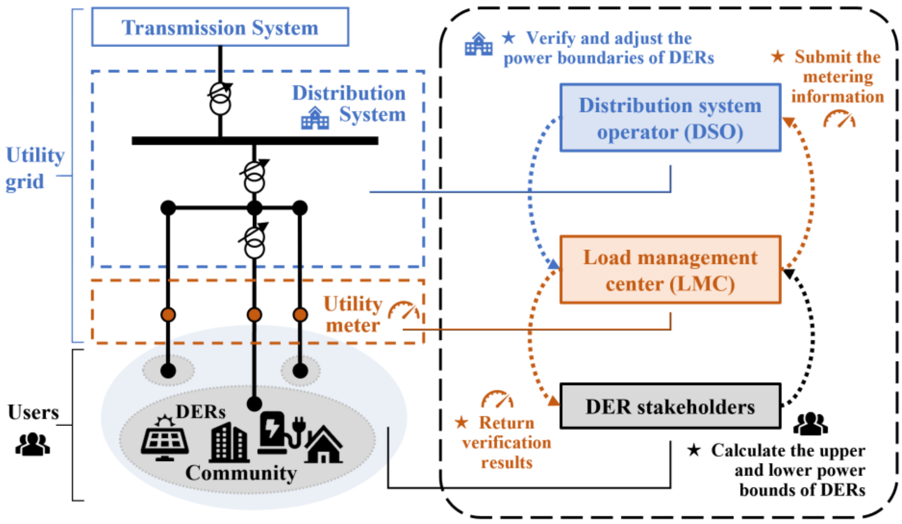


Fig. 1 Overall structure and steps for power boundary calculation and verification for DERs stakeholders

First, DER stakeholders calculate their upper and lower power boundaries for each time period based on their internal constraints, and submit these results and metering data to the regional LMC.

Second, the regional LMC reviews the metering data, conducts an initial check, and forwards the relevant information to the local DSO.

Next, the local DSO verifies the reported boundaries against network topology, line capacity, and voltage limits to ensure they satisfy local distribution system requirements. The verified results are then sent back to the LMC.

Finally, the LMC returns the verification results to the DER stakeholders, who then update their power boundary constraints for subsequent market use.

3 Calculation of response power boundaries for DER stakeholders based on internal operating constraints

This paper considers a distribution system consisting of a set of nodes ***N*** and a set of branches ***B***. The set of DER stakeholders is denoted as $\boldsymbol{R} = \{1, 2, ..., r, ..., R\}$, each connected to node $\pi(r)$ in the distribution system. In this study, the DER stakeholders are set as BTM communities that includes distributed PV generation, residential users with transferable loads, and distributed ES.

Distributed PV systems are typically mounted on rooftops, ground surfaces, or other suitable locations. They can supply electricity to the utility grid or support self-consumption within the community. The model is given as follows:

$$P_{r,t}^{\text{PV,min}} \le P_{r,t}^{\text{PV}} \le P_{r,t}^{\text{PV,max}} \le 0 \tag{1}$$

where $P_{r,t}^{\text{PV,min}}$ and $P_{r,t}^{\text{PV,max}}$ denote the minimum and maximum PV power output of DER stakeholder r at time t, respectively.

In residential users, unlike fixed loads $P_{r,t}^{\text{Load,f}}$, transferable loads $P_{r,t}^{\text{Load,move}}$ can be shifted across different time periods in response to electricity prices. The residential user model is formulated as:

$$\sum_{t=1}^{T} P_{r,t}^{\text{Load,move}} \Delta t = 0 \tag{2}$$

$$P_{r,t,\min}^{\text{Load,move}} \le P_{r,t}^{\text{Load,move}} \le P_{r,t,\max}^{\text{Load,move}} \tag{3}$$

$$P_{r,t}^{\text{Load}} = P_{r,t}^{\text{Load,f}} + P_{r,t}^{\text{Load,move}} \tag{4}$$

where $P_{r,t,\min}^{\text{Load,move}}$ and $P_{r,t,\max}^{\text{Load,move}}$ denote the minimum and maximum load of DER stakeholder r at time t, respectively.

Distributed ES refers to battery systems installed near electricity users or other DERs, used to store and release electrical energy.

$$0 \le P_{r,t}^{\text{ES,ch}} \le P_{r}^{\text{ES,ch,max}} \tag{5}$$

$$0 \le P_{r,t}^{\text{ES,dis}} \le P_r^{\text{ES,dis,max}} \tag{6}$$

$$P_{r,t}^{\text{ES,ch}} \cdot P_{r,t}^{\text{ES,dis}} = 0 \tag{7}$$

$$E_{r,\min}^{\text{ES}} \le E_{r,t}^{\text{ES}} \le E_{r,\max}^{\text{ES}} \tag{8}$$

$$E_{r,t}^{\text{ES}} = E_{r,t}^{\text{ES}} + \left(\eta_{\text{ES,ch}} P_{r,t}^{\text{ES,ch}} - \frac{1}{\eta_{\text{ES,dis}}} P_{r,t}^{\text{ES,dis}} \right) \Delta t \tag{9}$$

$$E_{r,T}^{\text{ES}} = E_{r,0}^{\text{ES}} \tag{10}$$

Where $P_{r,t}^{\text{ES,ch}}$, $P_{r,t}^{\text{ES,dis}}$, $P_r^{\text{ES,ch,max}}$, $P_r^{\text{ES,dis,max}}$, $E_{r,t}^{\text{ES}}$, $E_{r,\min}^{\text{ES}}$, $E_{r,\max}^{\text{ES}}$, $E_{r,0}^{\text{ES}}$, $E_{r,T}^{\text{ES}}$ represent the charging power, discharging power, maximum charging power, maximum discharging power, stored energy, minimum stored energy, maximum stored energy, initial energy, and final energy of the distributed storage of DER stakeholder r at time t, respectively. $\eta_{\text{ES,ch}}$ and $\eta_{\text{ES,dis}}$ denote the charging and discharging efficiencies. Previous studies have shown that when charging and discharging efficiencies are below 100%, simultaneous charging and discharging does not occur; therefore, constraint (7) is omitted in this paper[11].

Based on the above, the DER stakeholder response power boundary calculation model is established under internal operating constraints (1)-(10) The objective function is given as:

$$P_{r,t}^{\min} = \min P_{r,t}, t \in [1, T] \tag{11}$$

$$P_{r,t}^{\max} = \max P_{r,t}, t \in [1, T] \tag{12}$$

$$P_{r,t} = \boldsymbol{I}_r^{\text{PV}} P_{r,t}^{\text{PV}} + \boldsymbol{I}_r^{\text{Load}} P_{r,t}^{\text{Load}} + \boldsymbol{I}_r^{\text{ES}} \left(P_{r,t}^{\text{ES,ch}} - P_{r,t}^{\text{ES,dis}} \right) \tag{13}$$

where $P_{r,t}^{\min}$ and $P_{r,t}^{\max}$ represent the maximum and minimum exportable power achievable at each time period. $\boldsymbol{I}_r^{\text{PV}}$, $\boldsymbol{I}_r^{\text{Load}}$, $\boldsymbol{I}_r^{\text{ES}}$ respectively denote the indicator functions that specify whether the corresponding superscripted DER type is included or not (1 or 0).

4 Verification and correction of DER stakeholders' response power boundaries considering distribution system constraints

4.1 Verification constraints of local distribution system

Given the independently calculated power range $P_{r,t} \in \left[P_{r,t}^{\min}, P_{r,t}^{\max}\right]$ without considering distribution system constraints, the result is often overly wide and therefore requires further verification and correction by the DSO.

For a DER stakeholder connected at node $i = \pi(r)$, the power balance at node $i \in \boldsymbol{N}$ can be written as:

$$P_{i,t} = P_{i,t}^{\text{load}} + \sum_{r:\pi(r)=i} P_{r,t} \tag{14}$$

$$Q_{i,t} = Q_{i,t}^{\text{load}} + Q_{i,t}^{\text{comp}} \tag{15}$$

where $p_{i,t}^{\text{load}}$ and $q_{i,t}^{\text{load}}$ are the fixed loads at node *i*, and $q_{i,t}^{\text{comp}}$ represents local reactive power compensation. Since DERs are generally equipped with inverters capable of reactive power regulation or power factor control, local voltage can be maintained through local control. Thus, the reactive power injection of DERs can be treated as self-balanced, and only active power variations are explicitly modeled.

The distribution network power flow is described using the Baran-Wu DistFlow model[9]:

$$P_{ij,t} = \sum_{k:(j,k)\in \boldsymbol{B}} P_{jk,t} + P_{j,t} + r_{ij} l_{ij,t} \tag{16}$$

$$Q_{ij,t} = \sum_{k:(j,k)\in \boldsymbol{B}} Q_{jk,t} + q_{j,t} + x_{ij} l_{ij,t} \tag{17}$$

$$v_{j,t} = v_{i,t} - 2\left(r_{ij} P_{ij,t} + x_{ij} Q_{ij,t}\right) + \left(r_{ij}^2 + x_{ij}^2\right) l_{ij,t} \tag{18}$$

$$l_{ij,t} = \frac{P_{ij,t}^2 + Q_{ij,t}^2}{v_{i,t}} \tag{19}$$

where $i, j \in \boldsymbol{N}$, $(i,j) \in \boldsymbol{B}$, r_{ij} and x_{ij} are the resistance and reactance of line (i,j), $l_{ij,t}$ is the squared branch current value $I_{ij,t}$, and $v_{i,t}$ denotes the squared voltage magnitude $V_{i,t}$ at node *i*.

To preserve convexity, a second-order cone relaxation is introduced[10]. Under the radial structure of a distribution system, this relaxation is typically tight and can accurately represent power flow relationships. This yields the DistFlow-SOCP model for the distribution system.

$$\left\| \begin{matrix} 2P_{ij,t} \\ 2Q_{ij,t} \\ v_{i,t} - l_{ij,t} \end{matrix} \right\| \leq v_{i,t} + l_{ij,t} \tag{20}$$

To capture operational limits of distribution system facilities, line thermal capacity constraints, branch current limits and voltage magnitude limits are additionally incorporated.

$$P_{ij,t}^2 + Q_{ij,t}^2 \leq \left(S_{ij}^{\max}\right)^2 \tag{21}$$

$$\left(I_{ij}^{\min}\right)^2 \leq l_{ij,t} \leq \left(I_{ij}^{\max}\right)^2 \tag{22}$$

$$\left(V_i^{\min}\right)^2 \leq v_{i,t} \leq \left(V_i^{\max}\right)^2 \tag{23}$$

where: $S_{ij}^{\max}$ is the rated apparent power capacity of branch (i,j). $I_i^{\min}$, $I_i^{\max}$ denote the allowable current range at node *i*. $V_i^{\min}$, $V_i^{\max}$ denote the allowable voltage range at node *i*.

4.2 Correction of active power adjustment ranges based on upper–lower boundary scenarios

Let the power range of DER stakeholder *r* at time *t* be denoted as $P_{r,t} \in \left[P_{r,t}^{\mathrm{L}}, P_{r,t}^{\mathrm{U}}\right]$. Define the matrix $P = \left[P_{r,t}\right] \in \mathbb{R}^{R\times T}, \forall r,t$, and then their joint range can be written as a box set (24).

$$A\left(P^{\mathrm{L}}, P^{\mathrm{U}}\right) := \left\{P \mid P_{r,t}^{\mathrm{L}} \leq P_{r,t} \leq P_{r,t}^{\mathrm{U}}, \forall r,t\right\} \tag{24}$$

Treat P as the parameter variables, and let Λ be the set of all other decision variables in the DistFlow-SOCP model. All constraints (14)-(23) of this model can be written compactly as (25), which contains affine inequalities and second-order cone inequalities, forming a convex constraint set with respect to (Λ, P).

$$F(\Lambda, P) \leq 0 \tag{25}$$

If (26) holds, we say that the power-flow solution Λ of DistFlow-SOCP is robustly feasible.

$$\forall P \in A\left(P^{\mathrm{L}}, P^{\mathrm{U}}\right), \exists \Lambda : F(\Lambda, P) \leq 0 \tag{26}$$

This means that no matter how the DER stakeholders choose their P values inside $A\left(P^{\mathrm{L}},P^{\mathrm{U}}\right)$, the distribution system can always find a feasible solution Λ. In other words, the DistFlow-SOCP constraints must remain valid under the worst-case combination of parameters. Thus, (26) can be rewritten as (27).

$$\max_{P\in A\left(P^{\mathrm{L}},P^{\mathrm{U}}\right)} F\left(\Lambda,P\right)\le 0 \tag{27}$$

In this case, the set $A\left(P^{\mathrm{L}},P^{\mathrm{U}}\right)$ forms a robust feasible box of the parameter variables P .To find the adjustable power range for each DER stakeholder, we build the following optimization problem that maximizes the robust feasible box of P .

Objective:

$$\max \sum_{t=1}^{T}\sum_{r\in \boldsymbol{R}}\left(P_{r,t}^{\mathrm{U}}-P_{r,t}^{\mathrm{L}}\right) \tag{28}$$

s.t. (27)(29).

$$P_r^{\min}\le P_{r,t}^{\mathrm{L}}\le P_{r,t}\le P_{r,t}^{\mathrm{U}}\le P_r^{\max} \tag{29}$$

Since $F\left(\Lambda,P\right)$ is a monotonic function of P , the case that satisfies $\max_{P\in A\left(P^{\mathrm{L}},P^{\mathrm{U}}\right)} F\left(\Lambda,P\right)$ always appears at the vertices of the R×T dimensional box set, i.e., at $P_{r,t}^{\mathrm{L}}$ or $P_{r,t}^{\mathrm{U}}$. The above observation can be supported by a straightforward derivation based on the Karush-Kuhn-Tucker (KKT) conditions, and the proof is omitted here for brevity.

Theoretically, in this case, each element of P can potentially reach different extreme values in different directions, we would need to examine each constraint separately, checking the sign of each coefficient in the parameter matrix to decide which vertex each of the R×T parameter variables $P_{r,t}$ should take.

However, in this paper, all elements of P have the same monotonicity within $F\left(\Lambda,P\right)$. Thus, for any specific constraint in (27), all elements $P_{r,t}$ will take the vertices in the same direction to maximize $F\left(\Lambda,P\right)$. Therefore, we only need to check the two extreme cases, $P=P^{\mathrm{L}}$ and $P=P^{\mathrm{U}}$, to guarantee the constraints (25) hold for all possible P in $A\left(P^{\mathrm{L}},P^{\mathrm{U}}\right)$. Hence, we introduce two copies (30)(31) of the DistFlow-SOCP constraints to replace the original (25).

$$F\left(\Lambda^{\mathrm{L}},P^{\mathrm{L}}\right)\le 0 \tag{30}$$

$$F\left(\Lambda^{\mathrm{U}},P^{\mathrm{U}}\right)\le 0 \tag{31}$$

So, the final optimization model is built, with objective (28) and subject to (29)-(31).The resulting maximum robust feasible box gives the active-power response bounds of DER stakeholders under distribution-network constraints.

5 Case Study

5.1 Parameters setting

Taking four BTM communities as an example, each community acts as a DER stakeholder and connects to bus nodes 2, 9, 19, and 33 of the IEEE-33 distribution system, with a utility meter installed at each access point, respectively. The DER setups of the four stakeholders are shown in Fig. 2: Stakeholders 1 and 3 both have PV and residential users (RU); Stakeholder 2 includes only RU; Stakeholder 4 combines RU with distributed ES. Each DER stakeholder uses an independent electricity marketing account and is under DSM from the regional LMC, as well as technical management from the local DSO.

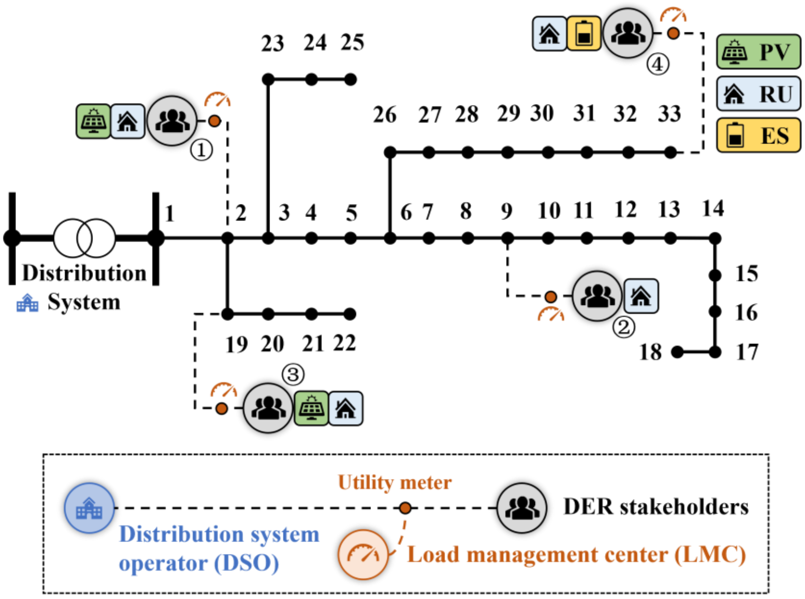


Fig. 2 Four BTM communities connects to an IEEE-33 distribution system.

5.2 Results of DER stakeholders' response power boundary calculation

Without considering distribution system constraints, each DER stakeholder independently calculates its response power boundaries for each time period based solely on the operating characteristics of its local DERs, and submits the results to the regional LMC. As shown in Fig. 3, the response characteristics of the four BTM communities differ significantly.

Stakeholders 1 and 3 are both equipped with PV systems, and their lower response power boundaries reach the maximum at midday when PV output is strongest. Stakeholder 2 consists only of residential users, so its adjustable power range is relatively limited. Stakeholder 4 is equipped with energy storage, which, while meeting user load demand, uses the charging and discharging flexibility to form a more ample and smoother response power boundary than the other stakeholders, with an adjustable range of about ±600 kW.

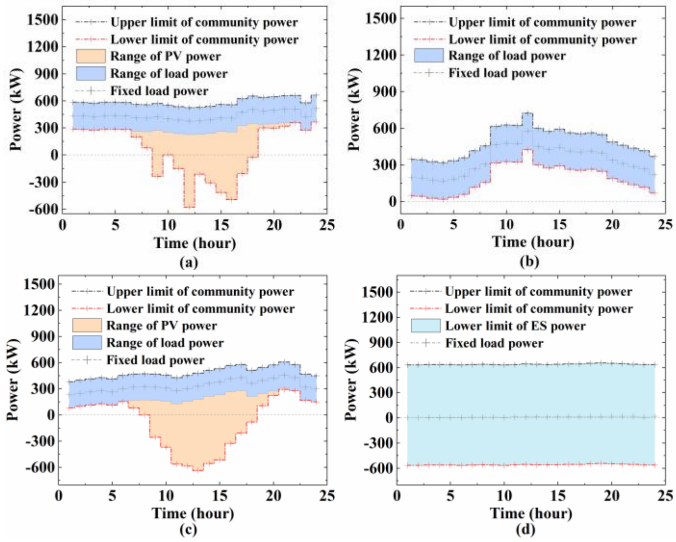
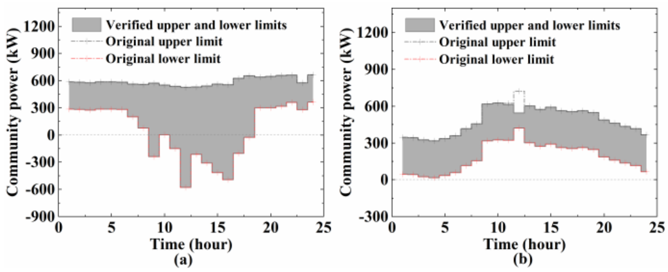


Fig. 3 Results (a)-(d) of Four DER stakeholders' response power boundary calculation.

It should be noted that, because voltage, power flow, capacity, and other distribution system constraints have not yet been included at this stage, the above aggregated boundaries only reflect the theoretical achievable capability submitted to the regional LMC. The DSO will later verify and adjust these boundaries under distribution system constraints to produce the final feasible response boundaries that satisfy grid operation requirements.

5.3 *Results of DER stakeholders' response power boundary verification and correction*



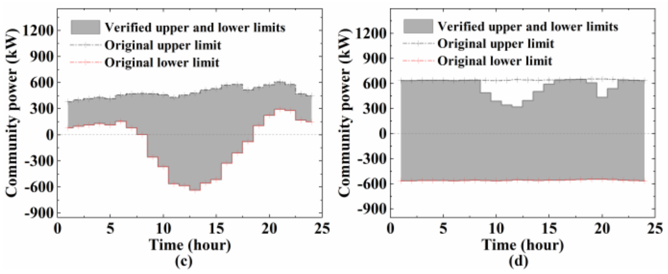


Fig. 4 Results (a)-(d) of Four DER stakeholders' response power boundary verification and correction.

After considering distribution system constraints, the response power boundaries of the four BTM communities shrink to varying degrees, as shown in Fig. 4.

For DER Stakeholders 1 and 3, their adjustable ranges show almost no change after introducing distribution network constraints, indicating that they are essentially unaffected by these limits. The main changes for DER Stakeholder 2 occur at 12:00 noon, where its upper boundary drops by about 180 kW, showing that line power flow during this period is already close to its upper limit and thus cannot fully release its power regulation potential. DER Stakeholder 4, which is equipped with energy storage, maintains its lower boundary after verification, but its upper boundary shrinks significantly at noon and in some evening periods, with a maximum reduction of about 330 kW. This indicates that although the energy storage system has a large adjustable range during these periods, its charging still must meet line capacity and voltage limits.

Overall, the response power boundary reductions mainly occur during periods when the distribution system is under relatively high load, and they mostly appear as reductions in the upper power boundary presenting load characteristics. Thus, through the joint verification and correction by the LMC and DSO, the response power boundaries of each DER stakeholder can be converted from demand-side potential ranges into feasible ranges that account for distribution system operating constraints. This provides boundary conditions that better reflect actual operating conditions for participating in DSM and multi-level electricity markets.

6 Conclusion

This paper presented a practical framework for calculating and verifying DER stakeholders' response power boundaries within the existing marketing-distribution structure of a regional utility grid. The framework lets each stakeholder first compute its theoretical response capability and then allows the DSO to verify and adjust these boundaries using a DistFlow-SOCP model and a maximum robust feasible-box method to meet distribution system limits.

The case study on the IEEE-33 system showed clear differences in the theoretical response boundaries of 4 DER stakeholders. After verification, the feasible boundaries shrank mainly during high-load periods, with the largest reductions appearing in stakeholders whose adjustments stressed line capacity or voltage limits. Stakeholders less affected by network constraints retained most of their flexibility.

These results show that the proposed method can convert theoretical demand-side flexibility into feasible response ranges that respect grid operating conditions, enabling reliable participation in DSM and multi-level markets.

References

1. Mousavi, M., Wu, M.: A DSO Framework for Market Participation of DER Aggregators in Unbalanced Distribution Networks. IEEE Transactions on Power Systems. 37, 2247–2258 (2022). https://doi.org/10.1109/TPWRS.2021.3117571.
2. Gao, H., Jin, T., Feng, C., Li, C., Chen, Q., Kang, C.: Review of virtual power plant operations: Resource coordination and multidimensional interaction. Applied Energy. 357, 122284 (2024). https://doi.org/10.1016/j.apenergy.2023.122284.
3. Li, R., Wu, Q., Oren, S.S.: Distribution Locational Marginal Pricing for Optimal Electric Vehicle Charging Management. IEEE Transactions on Power Systems. 29, 203–211 (2014). https://doi.org/10.1109/TPWRS.2013.2278952.
4. Nguyen, D.H., Azuma, S.-I., Sugie, T.: Novel Control Approaches for Demand Response With Real-Time Pricing Using Parallel and Distributed Consensus-Based ADMM. IEEE Transactions on Industrial Electronics. 66, 7935–7945 (2019). https://doi.org/10.1109/TIE.2018.2881938.
5. Patnam, B.S.K., Pindoriya, N.M.: DLMP Calculation and Congestion Minimization With EV Aggregator Loading in a Distribution Network Using Bilevel Program. IEEE Systems Journal. 15, 1835–1846 (2021). https://doi.org/10.1109/JSYST.2020.2997189.
6. Zhang, J., Che, L., Wan, X., Shahidehpour, M.: Distributed hierarchical coordination of networked charging stations based on peer-to-peer trading and EV charging flexibility quantification. IEEE Transactions on Power Systems. 37, 2961–2975 (2022). https://doi.org/10.1109/TPWRS.2021.3123351.
7. Das, H.S., Rahman, M.M., Li, S., Tan, C.W.: Electric vehicles standards, charging infrastructure, and impact on grid integration: a technological review. Renewable and Sustainable Energy Reviews. 120, 109618 (2020). https://doi.org/10.1016/j.rser.2019.109618.
8. Wu, Y., Wu, Y., Guerrero, J.M., Vasquez, J.C.: A comprehensive overview of framework for developing sustainable energy internet: from things-based energy network to services-based management system. Renewable and Sustainable Energy Reviews. 150, 111409 (2021). https://doi.org/10.1016/j.rser.2021.111409.
9. Baran, M., Wu, F.F.: Optimal sizing of capacitors placed on a radial distribution system. IEEE Transactions on Power Delivery. 4, 735–743 (1989). https://doi.org/10.1109/61.19266.
10. Farivar, M., Low, S.H.: Branch Flow Model: Relaxations and Convexification—Part I. IEEE Transactions on Power Systems. 28, 2554–2564 (2013). https://doi.org/10.1109/TPWRS.2013.2255317.
11. Li, Z., Guo, Q., Sun, H., Wang, J.: Sufficient Conditions for Exact Relaxation of Complementarity Constraints for Storage-Concerned Economic Dispatch. IEEE Transactions on Power Systems. 31, 1653–1654 (2016). https://doi.org/10.1109/TPWRS.2015.2412683.