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Independent Energy Storage Power Limitations for Secured Power System Operation

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Abstract. This paper presents a tool to robustly allocate the allowable operating zones of active and reactive power trading margins for multi energy storage systems (ESSs) without violating typical distribution system constraints. This tool helps the distribution network operator (DNO) to facilitate ESS safe participation in day-ahead active and reactive power markets. It estimates the required ESS reactive power support to keep safe voltage margins. In order to avoid conservative results, an uncertainty budget designed by a fuzzy expert is imposed on the uncertainty domain. Case studies on one hundred different uncertainty scenarios are conducted on a real 41-bus Canadian system. Simulation results have shown that the proposed algorithm provides robust operating zones for ESSs with less conservatism.

Keywords: Energy storage system (ESS), particle swarm optimization (PSO), uncertainty budget, wind power uncertainty, worst-case power flow.

1 Introduction

Day after day, the world witnesses an increasing penetration level of renewable energy resources (RESs) in power systems. As RESs are indispatchable, combining energy storage systems (ESSs) with RESs is a necessity for enhancing profitability and ensuring system stability. In addition to renewable integrations, ESSs have many other power applications [1], [2], and it participates in ancillary services markets [3], e.g. voltage support in weak grids [4].

Unfortunately, the lack of regulatory rules and grid codes for ESSs in different applications is one of the main challenges facing effective integration of ESSs in grid systems [1], [5]. While ESS acts as an electrical load or generator, the DNO needs to define the safe dispatchability zones of each ESS in case of charge or discharge modes. Within these zones (named hereinafter as robust operating zone (ROZ)), the DNO should guarantee that system operational limits are respected under renewable generation and load uncertainties, and possible contingencies. On the other hand, as each ESS has a different stakeholder with different profit portfolios and dispatching agendas (e.g. energy arbitrage or renewable integration), the DNO should not interfere in ESS commitment or impose a certain dispatching strategy on other assets.

In addition to the aforementioned challenges, load and RES uncertainty makes ROZ identification for ESS a complicated problem.

Energy management system (EMS) of ESSs has different strategies related to the industrial application's nature. For instance, in [6], an intelligent EMS for a battery and a fuel cell in a high frequency microgrid is proposed, while in [6] EMS dispatches the Battery for cost minimization, meanwhile the authors of [7] uses a fuzzy expert to optimize both environmental and economic cost functions. EMS is especially more important with hybrid vehicles (V2G) research [8], [9]. However, none of the aforementioned works considered the AC power flow constraints with the EMS which is the main motive for this PhD research. This paper is arranged as follows. Section 2 explains the main contributions of this work while Section 3 briefly describes the problem formulation, whereas Section 4 explains the different stages for ROZ generation. Section 5 presents a case study on a radial feeder for results validation. Finally, the conclusions are drawn in Section 6.

2 Contribution to Cyber-Physical Systems

This work proposes a framework to facilitate ESS participation in day-ahead markets under distribution system uncertainty taking the power flow constraints into consideration. This is possible via defining ROZ for each ESS. The proposed framework has the following contributions to the research field in general:

1- It combines the merits of stochastic programming and robust optimization (RO) as it is applicable with or without uncertainty distribution availability.
2- For reducing RO conservatism, a fuzzy expert is designed to calculate the uncertainty budget limits according to the uncertainty probability and its risk level.
3- Developing the ROZ concept that draws the charge and discharge margins for each ESS taking into account RES, load uncertainties and possible system contingency.

The main contribution to Cyber-physical system (CPS) is that ROZ can facilitate a distributed trading framework between ESSs and renewable energy resources using Multiagent systems. This is possible since ROZ decentralizes the optimal power flow problem into a distributed economic one and a centralized technical problem (finding ROZ). When each ESS entity knows his feasible operating zone (ROZ), a decentralized trading system for services between ESS and renewable energy owners can be conducted easily via internet or an available local communication network.

3 Problem Formulation

In distribution system, we have two sides that control ESSs dispatch. Firstly, the ESS owner aims at maximizing his profit from market. Secondly, the DNO is a non-profit organization that keeps system reliability and guarantees its secure operation. As ESSs participate in various services, the DNO must guarantee that ESS dispatching decisions will not impair the system operation. Further, the DNO may require reactive power support from different ESSs in case of RES or load uncertainty. The ESS owner is paid for this reactive power support in the reactive power market [10], [11].

To sum up, the ESSs dispatch decision must fulfills the following techno-economic objectives:

1- The DNO must guarantee sound system operation and security for all dispatchability levels of ESS.
2- The ESS provides adequate reactive power support to overcome any uncertainties for a fair compensation from the local reactive power market.
3- The ESS owner has the freedom of dispatching his assets to participate in different electricity markets (given that condition 1, 2 are satisfied).

Condition 1, 2 are the DNO conditions in each ESS dispatch decision taken by the ESS owner. These conditions are easily embedded as a constraints (limits) on the dispatch power (charge and discharge) at each time, known here as ROZ. As depicted in Fig. **1**, firstly, the DNO calculates the day-ahead ROZ and sends it to all ESS stations. Secondly, each ESS owner dispatches his own assets in different markets such that his profit is maximized. As given in (1), each owner dispatches his ESS to maximize his profit, given the network constraints embedded in the ROZ and other dynamical operational constraints for the ESS (e.g., state-of-charge, number of charging cycles, etc.).

$$\begin{array}{c} \underset{p_s}{\text{Max}}(profit_s)\ S.t. \\ p_s \epsilon ROZ_s\ \ ,ESS\ \text{Operational constraints} \end{array} \tag{1}$$

The ROZ is defined as the allowable margins of charging and discharging for each ESS to participate in different active power markets, such that the grid system constraints are respected and the ESS can provide adequate reactive power support for compensating uncertainties.

$$ROZ_{sk} = \left[\underline{p_{sk}}, \overline{p_{sk}}\right] \forall\, s \epsilon N_s, \forall\, k \epsilon N_k \tag{2}$$

$$ROZ_s = \bigcup_k ROZ_{sk}, ROZ_s \subset \mathbb{R}^{2 \times n_k} \tag{3}$$

$$ROZ = \bigcup_s ROZ_s, ROZ \in \mathbb{R}^{2 \times n_k \times n_s} \tag{4}$$

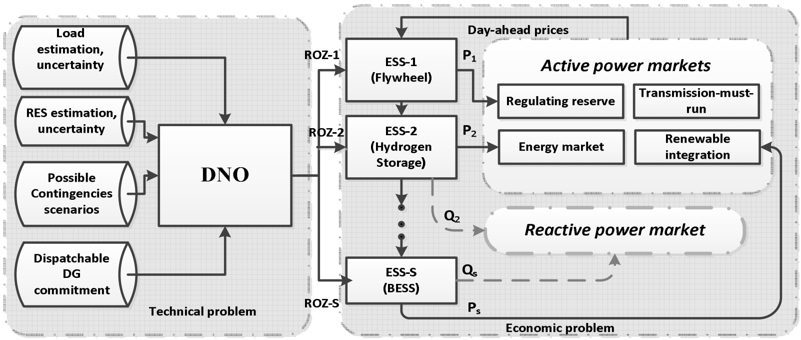

Fig. 1. Proposed ESS dispatch framework.

As given in (2), the ROZ is defined by the allowable upper and lower limits for each ESS *s* over the time horizon *k*. for a set of time horizon n_k, and a set of ESSs n_s, ROZ is defined by the sets given in (3), (4). Given the uncertainty domain $\mathcal{D}$, the possible contingencies, the dispatchable units' commitment and RES and load expected values, two optimization problems define the ROZ. First, the ROZ upper limit $\overline{p_{sk}}$ is defined via (5). The objective function **Error! Reference source not found.** aims at maximizing the per-unit active power participation of all ESSs. The resulting ESS active power represents the ROZ upper limits $p_{sk-ref} = \overline{p_{sk}}$. The reason for dividing each ESS active power on the apparent power (C_s) is the fair participations for reactive power support from the different ESSs as they have different sizes; otherwise, the large ESS units will have higher weights in the objective function. However, it should be noted that reactive power support is also location-based power; we can't guarantee equal VAR participation from different ESSs. Constraints **Error! Reference source not found.**, **Error! Reference source not found.** represent the power flow models set $PF_k^m(\dot{d})$ for active and, reactive powers, respectively. These are uncertain models as function in uncertainty set $\mathcal{D}$. While in **Error! Reference source not found.**, each branch current $(I_{ik})$is calculated and the power loss (p_{loss_k}) is estimated in **Error! Reference source not found.**, constraints **Error! Reference source not found.-Error! Reference source not found.** represent the DNO different technical constraints. First, the bus voltage limits are defined in **Error! Reference source not found.**, while each branch ampacity constraint is limited by **Error! Reference source not found.**. In **Error! Reference source not found.**, the maximum power loss is limited (e.g., 5%). Equation **Error! Reference source not found.** limits the exchange power with the grid to avoid un-allowed reversal power flow or extra loading on the main grid. On the other hand; **Error! Reference source not found.** and **Error! Reference source not found.** define the apparent and discharge powers margins. Finally, **Error! Reference source not found.** represents the discharging power losses in each storage in order to consider the ESS efficiency [12],where

$$\eta_{dcs} \geq 1$$

$$\max_{p_{sk-ref},q_{sk}} \left(\sum_{k=1}^{n_K} \sum_{s=1}^{n_S} \frac{p_{sk}}{C_s}\right) \; s.t. \tag{5}$$

$$PF_k^m(\tilde{d}) \begin{cases} \hat{p}_{ik} + \tilde{p}_{ik} = \sum_{j=1}^{n_b} |v_{ik}^m||v_{jk}^m|\left(G_{ij}^m \cos\left(\delta_{ijk}^m\right)\right) + \left(B_{ij}^m \sin\left(\delta_{ijk}^m\right)\right) & (6) \\ \hat{q}_{ik} + \tilde{q}_{ik} = \sum_{j=1}^{n_b} |v_{ik}^m||v_{jk}^m|\left(G_{ij}^m \sin\left(\delta_{ijk}^m\right)\right) - \left(B_{ij}^m \cos\left(\delta_{ijk}^m\right)\right) & (7) \\ I_{tk}^m = \left|v_{ik}^m - v_{jk}^m\right| \left|G_{ij}^m + jB_{ij}^m\right| & (8) \end{cases}$$

$$p_{loss_k}^m = \sum_{t=1}^{n_T} {I_{tk}^m}^2 Z_t^m \tag{9}$$

$$v_{min} \leq v_{ik}^m \leq v_{max} \tag{10}$$

$$I_{tk}^m \leq \bar{I}_t \tag{11}$$

$$p_{loss_k}{}^m \leq \bar{p}_{loss_k} \tag{12}$$

$$\underline{p}_{grid} \leq p_{grid_k}^m \leq \bar{p}_{grid} \tag{13}$$

$$p_{sk-ref}^2 + q_{sk}^2 \leq {C_s}^2 \tag{14}$$

$$0 \leq p_{sk-ref} \leq C_s \tag{15}$$

$$p_{sk} = \eta_{dcs} p_{sk-ref} \tag{16}$$

$$\forall\, i, j \epsilon \mathcal{N}_b, k \epsilon \mathcal{N}_k, t \epsilon \mathcal{N}_t, s \epsilon \mathcal{N}_s, m \epsilon \mathcal{N}_c, [\tilde{P}_{ik}, \tilde{q}_{ik}] = \tilde{d}_{ik} \epsilon \mathcal{D}$$

Second, the charge power maximization is driven by **Error! Reference source not found.**.

$$\min_{p_{sk-ref},q_{sk}} \left(\sum_{k=1}^{n_k} \sum_{s=1}^{n_s} \frac{p_{sk}}{C_s}\right) \tag{17}$$

$$s.t. (6) - (14)$$

$$-C_s \leq p_{sk-ref} \leq 0 \tag{18}$$

$$p_{sk} = \eta_{chs} p_{sk-ref} \tag{19}$$

Unlike **Error! Reference source not found.**, in **Error! Reference source not found.**, ESSs act as a load and the objective is to minimize their active power (maximizing charge power). The resulting ESS power in this case represents the lower ROZ limit($p_{sk-ref} = \underline{p}_{sk}$). This problem has the same constraints as **Error! Reference source not found.** plus constraints**Error! Reference source not found.**,**Error! Reference source not found.** and the first constraint guarantees that all ESSs act as load, whereas the second constraint represents the charging losses in each ESS-s , where $\eta_{chs} \leq 1$. Since the problem **Error! Reference source not found.** aims at maximizing the discharge power of all ESS,

4 Roz Generation Framework

We assume a power flow model where all ESSs participate with their maximum discharge power and a zero reactive power support; thus, the PF linearization is conducted around the ESS power coordinates $\lfloor p_{sk}, q_{sk} \rfloor = [c_s, 0] \forall s \in \mathcal{N}_s, k \in \mathcal{N}_k$. The voltage sensitivity matrix $\Lambda_{ip}, \Lambda_{iq}$ is derived for this special power flow to obtain this linearized model; however, the problem still uncertain; thus, a possible framework is summarized in these three steps:

1- Relax the uncertainty domain from $\mathcal{D}$ into $\mathcal{D}_f$.

2- Search for the worst case uncertainty (WCU) within the domain $\mathcal{D}_f$to detect d^* and pick up the worst contingency power flow structure.

3- Solve optimization problems **Error! Reference source not found.** using semi-definite programming given the WCU-power flow. The ROZ generation is formalized in a three stages framework as explained next.

The proposed framework finds the ROZ for each ESS on three stages: Stage (A), given the uncertainty range for both RES and load $\mathcal{D}$, it is relaxed using an uncertainty budget to get a new set $\mathcal{D}_f$.

This work proposes a new method for uncertainty budget determination based on the uncertainty risk and associated probability (if available). In Stage (B), PSO detects WCU by scanning $\mathcal{D}_f$. As a result, Stage (A) draws the search domain for PSO. Finally, in Stage (C), first, the full active power participation of all ESS in both full charge and full discharge scenarios with the WCU are tested. In case of any grid code violation, a semi-definite programming technique calculates the required reactive power support from each ESS such that no system violation occurs at the WCU. Fig. 2 shows the ROZ generation process.

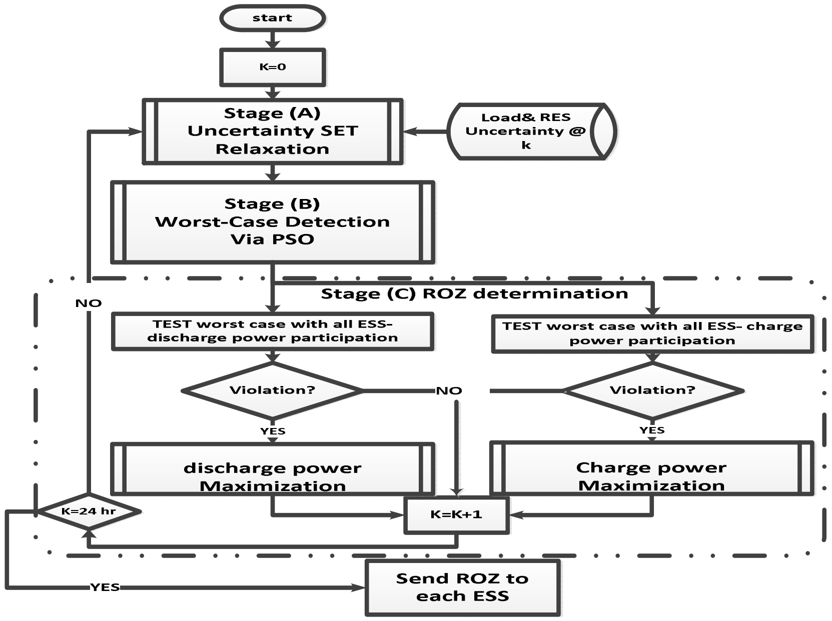

Fig. 2 Flowchart for ROZ generation.

5 Case Study

This study tests the proposed framework on a 41-bus real radial feeder in Ontario, Canada [13]. This medium-voltage (20 MVA, 16 kV) radial feeder is depicted in Fig. 3. The load represents real case residential profiles as stated in [14]. The feeder has five RESs with a gross penetration of 30% (6 MVA). Further, it has two BESS represented in a PEV parking lot (BESS1) and a storage station (BESS2). The total storage penetration is (15%) and aims at providing enough reactive power support if needed. The RES and storage allocation is optimized in [13] in order to minimize power losses, while RES profiles are historical data from Alberta system operator (AESO). Simulations study the effect of uncertainty domain choice $\mathfrak{D}$ on the ROZ and voltage violation. Four cases with different conservatism degrees are compared here:

- **Deterministic case** (D1)**:** the RES and load uncertainty are unconsidered
  Uncertainty budget D2**;** in this case, the fuzzy expert defines the uncertainty budget and uses 95% probability confidence level.
- **No-budget case (D3);** same as D2 without uncertainty budget

- **Six-sigma case (D4);** most conservative but highest robustness case considering 99.99% of the uncertainty domain under the famous six-sigma rule. No uncertainty budget is assumed here. This emulates the robust optimization.

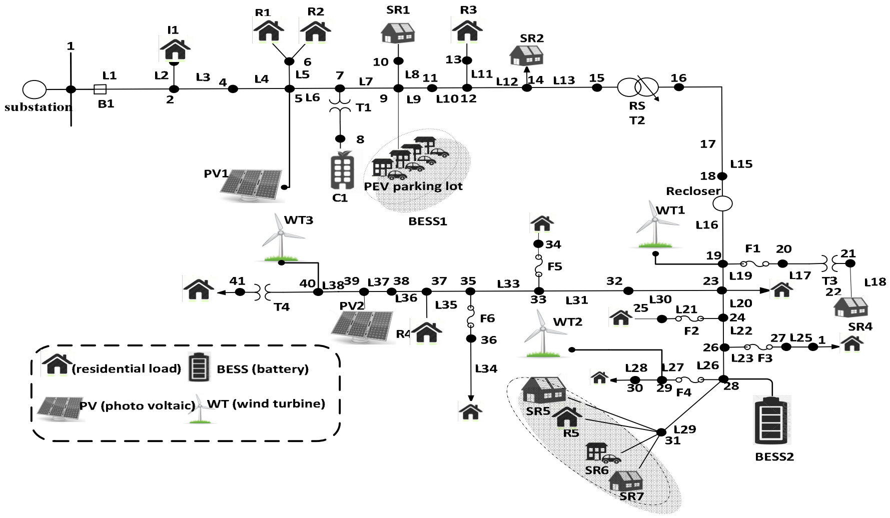

Fig. 3 41-bus radial feeder.

A comparison is conducted between the four cases by testing the 100 different uncertainty scenarios generated from Fig. 6. Further, the comparison is repeated at different RES penetration levels (20, 30 and 40%). No contingency is assumed in all simulations. The results are investigated from two perspectives. First, the DNO cares about the network sound operation represented here by buses' voltage violations. This is represented here by the count of [over-voltage (OV) or under-voltage (UV)] during the 100 scenarios. No ampacity or loss violations occur; thus they are not included in the comparison. On the other hand, The BESS-owner cares about the ROZ size, as a higher ROZ-size means a higher operation margin and profit. Comparison between the gross violations (OV, UV) over the 100 different scenarios is shown in Table 1. It compares the four ROZ cases corresponding to the different uncertainties.

Table 1. ROZ size and voltage violations in 100 scenarios.

	20%-RES			30%-RES			40%-RES		
	OV	UV	ROZ_2	OV	UV	ROZ_2	OV	UV	ROZ_2
D1	133	47	98.2%	88	45	98%	43	41	97.6%
D2	7	3	95.7%	7	1	95.7%	6	1	95.3%

D3	6	2	95%	6	0	95.3%	5	1	94.9%
D4	0	0	92.9%	0	0	92.9%	0	0	92.1%

As expected, the deterministic case D1 achieves the highest ROZ size (best for the owner as less VAR support needed) but with the highest number of violations on all penetrations (all apparent power is committed as active power while reactive power support is not enough to overcome violations resulting from uncertainty). On the other hand, the six-sigma case D4 results in zero violations with the lowest ROZ size for all BESS, As a result, the ESS owner achieves less profit from the active power market; however, the ESS has always had the required reactive power support to overcome the uncertainty effect during the hundred different power flow scenarios. For the proposed uncertainty budget D2 and the no-budget caseD3, the number of violations is very small (a maximum of ten times violations occur during the 100 scenarios in a 41-bus system); however, the ROZ size in the case of D2 is always greater than in D3. As a result, the proposed framework has managed to boost the ROZ size without big sacrifices in the power system security. On the other hand, the RES penetration effect is clear on the ROZ-size, for a higher RES penetration, higher reactive power support is required from the BESS. As a result, the active power limits decreases (ROZ size diminishes with RES penetration).

6 Conclusions

This paper presents a framework to define robust operating zones (ROZ) for independent energy storage units in power systems without imposing unit commitment on the ESSs owners. The technical constraints include permissible voltage level, ampacity, power losses, and reverse power flow limits. Further, RES and load uncertainty are taken into consideration when generating the ROZ. Furthermore, a security constrained-ROZ is possible for any contingences combinations. This tool provides the safe operating zone for each ESS which facilitates a decentralized co-operation between a high number of storages and other renewable facilities. The proposed framework is tested on a real 41-bus radial feeder using 100 different uncertainty scenarios. Four uncertainty sets with different conservatism levels are tested. The results have shown that the designed uncertainty budget managed to boost the ROZ size with a very low violation probability.

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