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Evaluating the Hosting Capacity of Distributed PV Considering the Impacts of Mobile Energy Storage System

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ABSTRACT

The rapidly increasing penetration of distributed generation (DG) such as photovoltaic (PV) has brought various impacts on distribution network (DN), such as voltage rise and power decline. Considering that, the hosting capacity evaluation of PV in DN is essential to provide useful references for PV development. Meanwhile, the mobile energy storage system (MESS) has proven to have the potential of improving the HC for its ability to provide various grid support services. This paper proposes a multi-scenario-based model to evaluate the hosting capacity of distribuited considering the impacts of MESS. In the proposed model, the transit features of MESS are considered. Besides, the scenarios are generated according to the uncertainties associated with solar irradiance and load demand. The effectiveness of the proposed method is demonstrated using a modified IEEE 33-bus distribution system.

Keywords: Distributed PV generation, mobile energy storage system, distribution network, hosting capacity, multi-scenario analysis, uncertainty.

NONMENCLATURE

Abbreviations

HC	Hosting Capacity
PV	Photovoltaic Generation
DG	Distributed Generation
DN	Distribution Network
MESS	Mobile Energy Storage System

Symbols

N	Total scenario number generated
S	PV capacity accommodated on DN
L	Set of load demand scenarios
W	Set of solar irradiance scenarios
C	System operation cost

1. INTRODUCTION

Renewable energy is considered a promising solution to environmental pollution and energy crisis[1], which is usually accommodated on the DN. On the other hand, high penetration DG brings various impacts on DN planning and operation[2-4], including voltage rise, reverse power flow, loss increase, power quality decline, etc. In order to ensure the DN operation safety with high penetration of DG, many methods have been presented to evaluate the HC of a DN[5], which is defined as the total DG capacity that can be accommodated on a DN without violating severe operational constraints[6]. A maximum DG hosting capacity evaluation method considering the uncertain context of DG power outputs and load demands is proposed in [7]. Based on multi-scenario system operation simulation, reference [8] proposed a probabilistic method for determining grid-accommodable wind power capacity.

Nowadays, MESS has been exploited for providing load shifting, voltage regulation and other services to DN[8], which can reduce the operational risk of DN with high penetration DG[9]. Different from stationary ESS, it can change its position in the power system through the transportation network, as shown in Figure 1, which has better flexibility. Reference [10] proposed a two-stage optimization model for MESS to enhance DN resilience. A rolling integrated service restoration strategy to minimize the total system cost by coordinating the scheduling of MESS fleets is proposed in [11]. However, there are not many studies on the impact analysis of MESS on hosting capacity of distributed PV.

In this paper, a multi-scenario-based PV hosting capacity evaluation model while considering the impacts of MESS is proposed. A MESS operation strategy that aims to minimize the cost of the DN operation is also studied in the section of system operation simulation. Finally, a modified IEEE 33-bus distribution system with PV generations and MESSs is used to demonstrate the effectiveness of the proposed model.

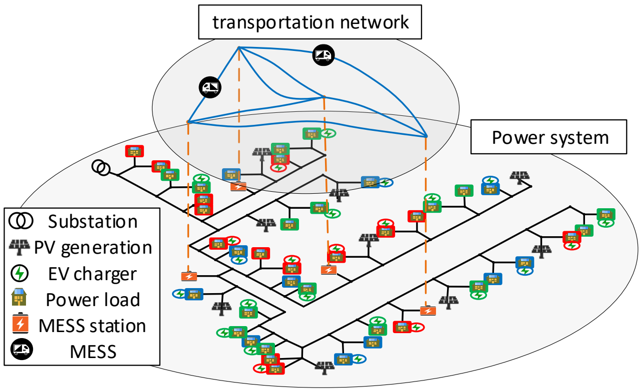


Fig. 1. Interaction between transportation network and power system

2. A MULTI-SCENARIO BASED FRAMEWORK TO DETERMINE THE PV HOSTING CAPACITY

2.1 PV Curtailment Ratio and Penetration Ratio

Before evaluating PV hosting capacity, in (1) and (2) the PV curtailment ratio, which is determined by both the system load and the PV power output, and the PV penetration ratio are defined, which describes the level of utilization of PV, respectively.

$$\alpha\left(L_n,W_n,S\right)=\frac{Q_{\max}^{C}\left(L_n,W_n,S\right)-Q^{C}\left(L_n,W_n,S\right)}{Q_{\max}^{C}\left(L_n,W_n,S\right)} \tag{1}$$

$$\mu\left(L_n,W_n,S\right)=\frac{Q^{C}\left(L_n,W_n,S\right)}{Q^{\text{total}}\left(L_n,W_n,S\right)} \tag{2}$$

where Q^C represents the actual PV generation electricity imported to the DN, which is determined by the scenario $\left(L_n,W_n\right)$ and PV capacity S. $Q_{\max}^{C}$ represents the maximum electricity that can be imported to the DN without considering any operation constraints, which is the function of the solar irradiance W_n and the PV capacity S. Q^{total} is the total electricity demand during the system operation in a scenario.

It should be noted that the evaluation of PV hosting capacity by the method proposed in this paper is premised on a given PV curtailment ratio $\alpha_{\max}$, which is defined as $S^{\alpha_{\max}}$, and the value of $S^{\alpha_{\max}}$ is positively related to the specified $\alpha_{\max}$.

2.2 The PV hosting capacity based on multi-scenario simulation

The whole PV hosting capacity evaluation framework is presented in Fig. 2. First, the load demand scenario set *L* and solar irradiance scenario *W* are established. Therefore, the system operation scenario used in this paper can be represented by a pair of (L_n, W_n). Second, In the evaluation of each scenario, the PV capacity S is grad-ually increased until it reaches $S_{\max}$, which also indicates that the evaluation of a scenario is completed. Then the system operation simulation model is run with the new system scenario until all the scenarios are considered. Finally, the relationship between PV capacity S and PV curtailment ratio α is obtained, then the HC of the DN can also be calculated. Specifically, for each system simulation, the evaluation of HC is run on a half-hour basis on a day basis, where load demand and solar irra-diance have little correlation for half-hour evaluations.

The error analysis of Monte Carlo method is also considered. The Monte Carlo indicator like (3) can be used as the stop requirement.

With a confidence level of 1−β and error tolerance ε, the amount of sampling $N_{\max}$ should be no less than N, which is shown in (4).

$$\hat{\sigma}=\sqrt{\frac{1}{N}\sum_{k=1}^{N}\left(S_k^{\alpha_{\max}}\right)^2-\left(\frac{1}{N}\sum_{k=1}^{N}S_k^{\alpha_{\max}}\right)^2} \tag{3}$$

$$N=\left(\frac{\lambda_\beta\hat{\sigma}}{\varepsilon}\Big/S^{\alpha_{\max}}\right)^2 \tag{4}$$

where $S^{\alpha_{\max}}$ is defined as the PV capacity under the given $\alpha_{\max}$, $\hat{\sigma}$ is the estimated standard deviation of simulation error, λ_β is the two–tailed 1−β quantile of the standard normal distribution.

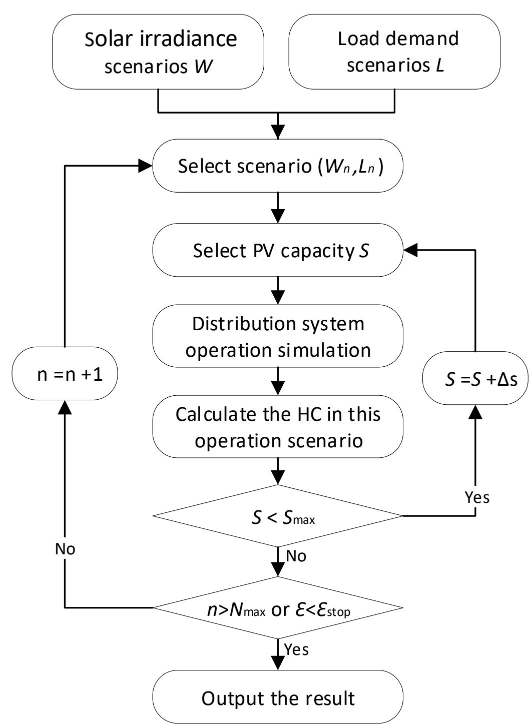


Fig. 2. Framework of the HC evaluation method.

3. SYSTEM OPERATION SIMULATION MODEL

A system operation simulation model is studied in this section to evaluate the PV capacity that can be accommodated by DN and analyze the impact of MESS on HC in one scenario, which can be divided into 2 subsystems[12]:

1) the MESS operation model that states the MESS operating states and constraints.

2) the system power flow model that relates to the MESS power output and positions.

3.1 MESS operation model

The MESS operation model includes two parts, the transit model and the power model.

The transit model mainly describes the MESS commute time between two stations and the transit logic of MESS, For a set of stations NS, the distance between stations is described by the matrix $D \in R^{NS \times NS}$, element $d_{mn} \forall m, n \in NS$ represents the distance between station m and station n. and τ_{mn} is the commute time (in samples) from station m to station n that depends on d_{mn}, and an assumption is $\tau_{mn} = \tau_{nm}$.

The Boolean matrix $Z \in R^{NS \times T}$ and $X \in R^{T \times 1}$ are also defined to describe the transit logic of MESS, respectively, where each element $z_{m,t}$ equals one if MESS exists at station m at sample time t, and x_t is the stationary location variable, which equals one if the MESS moves at sample time t.

Base on the transit model, the MESS power model are shown as follows[13]:

$$p_{s,t}^{ch} + p_{s,t}^{dh} = p_{s,t}^{S} \tag{5}$$

$$\left(p_{s,t}^{S}\right)^2 + \left(q_{s,t}^{S}\right)^2 \le \left(S_{\max}^{MESS}\right)^2 \tag{6}$$

$$0 \le p_{s,t}^{ch} \le p_{\max}^{ch} \cdot z_{s,t} \tag{7}$$

$$-p_{\max}^{dh} \cdot z_{s,t} \le p_{s,t}^{dh} \le 0 \tag{8}$$

$$-q_{\max}^{MESS} \cdot z_{s,t} \le q_{s,t}^{S} \le q_{\max}^{MESS} \cdot z_{s,t} \tag{9}$$

$$0 \le \sum_{s \in NS} z_{s,t} \le n_{MESS} \tag{10}$$

$$z_{m,t} + z_{n,t+\tau_{mn}} \le 1 \qquad \forall m, n \in NS \tag{11}$$

$$x_t \ge \sum_{s \in NS} z_{s,t+1} - \sum_{s \in NS} z_{s,t} \tag{12}$$

$$0 \le x_t \le 1 \tag{13}$$

$$E_{t+1}^{MESS} = E_t^{MESS} + \Delta t \cdot \frac{\left(\eta^{ch} p_{s,t}^{ch} + \eta^{dh} p_{s,t}^{dh}\right)}{E_{\text{rate}}^{MESS}} \tag{14}$$

$$E_{\min}^{MESS} \le E_t^{MESS} \le E_{\max}^{MESS} \tag{15}$$

where $S_{\max}^{MESS}$ is the MESS converter rated apparent power, $q_{\max}^{MESS}$ represents the reactive power upper limits for MESS. (19) states that the MESS truck can only be at n_{MESS} stations at any sample t. (20) describes the transmission logic of MESS from station m to station n. (23) describes the MESS energy state over time, E_t^{MESS} is the MESS energy at sample t in MW·h, E_{rate}^{MESS} represents the MESS rated energy. η^{ch} and η^{dh} represent the efficiency of charging and discharging, respectively.

3.2 Power flow model of distribution network

Considering the fact that power DN typically features radial topology, the complex power flow at each node is described by the DistFlow equations, these linearized power flow equations has been widely used in DN analysis[14]. The linearized DistFlow model that ignores network losses are represented as follows.

$$P_{i+1,t} = P_{i,t} - p_{i+1,t} \tag{16}$$

$$Q_{i+1,t} = Q_{i,t} - q_{i+1,t} \tag{17}$$

$$p_{i,t} = p_{i,t}^{L} - p_{i,t}^{G} - p_{i,t}^{S}, q_{i,t} = q_{i,t}^{L} - q_{i,t}^{G} - q_{i,t}^{S} \tag{18}$$

$$V_{i+1,t} = V_{i,t} - \left(R_i P_{i,t} + X_i Q_{i,t}\right) / V_{1,t}^2 \tag{19}$$

where $P_{i,t}$ and $Q_{i,t}$ are the active and reactive power flow from node i to node i+1 at sample time t, respectively. $p_{i,t}$ and $q_{i,t}$ are the active and reactive power demand at node i, respectively, which are determined by the load demand (superscripted L), PV generator output (superscripted G) and MESS power output (superscripted S) at node i. V_i represents the voltages at node i, R_i and X_i are resistance and reactance of the branch from node i to node i+1, respectively.

The constraints considered here include over-voltage and feeder ampacity.

$$V_{i\min} \le V_{i,t} \le V_{i\max} \tag{20}$$

$$0 \le P_{i,t} \le P_{i\max} \tag{21}$$

3.3 System optimal operation model with MESS

The mathematical formulation of the system optimal operation in one scenario can be formulated as follows.

The objective function is to minimize DN operation cost C, which includes the cost of PV curtailment, the cost of buying electricity and the cost of MESS operation.

$$\min C = \left[PC \cdot Q^{cur} + \lambda_{MESS} \cdot C^{MESS} + \lambda_{sub} \cdot C^{sub}\right] \tag{22}$$

$$\begin{aligned} Q^{cur} &= \sum_{t \in T} \sum_{i \in NG} \left(p_{i,t}^{G\max} - p_{i,t}^{G}\right) \cdot \Delta t \\ C^{MESS} &= \sum_{t \in T} \sum_{s \in NS} c_{s,t}^{MESS}, C^{sub} = \sum_{t \in T} EP \cdot p_t^{sub} \end{aligned} \tag{23}$$

$$c_{s,t}^{MESS} = \max(D) \cdot FC \cdot x_t + CP \cdot \left| \frac{\gamma}{100} \right| \cdot \left(p_{s,t}^{sh} + p_{s,t}^{dh} \right) \quad (24)$$

where λ_{MESS} and λ_{sub} are the weighting factors of the MESS operation cost and imported electricity cost, Q^{cur} is the total curtailment of electricity generated by PV, Δt is the duration of one simulation time period in h, NG and NS are the sets of PV generators and MESS stations, respectively. PC and EP are the penalty factor of curtailment and electricity price, respectively. (12) describes the cost of MESS, it includes truck operation cost, which is modeled as the worst case, and ES degradation cost, which is the function of charging ($p_{s,t}^{ch}$) and discharging ($p_{s,t}^{dh}$) decision variables at time t for station s, γ and CP are the technology-specific degradation slope parameter[15] and Charge/discharge cost factor, respectively.

The constraints of the problem include the MESS operation constraints shown in (5)-(15) and DN operation limits shown in (20)-(21).

4. CASE STUDY

4.1 Modified IEEE 33-bus test system

In the section of case study, the modified IEEE-33 distribution network, the diagram of which is shown in Fig.3, is applied as the test system. 6 PV generators, whose parameters are shown in TABLE I, and 4 MESS stations, between which the distance matrix has been modeled, are added to the DN. And the parameters of the MESS are shown in TABLE II.

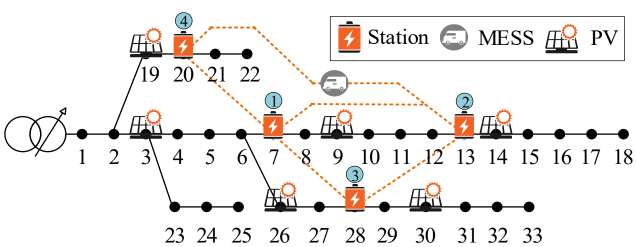


Fig.3. Diagram of the modified distribution network

It should be noted that the parameters of the simulation model are taken from MATPOWER6.0, and other parameters are shown in TABLE III. Evaluation is running for the day 7:00-17:00, we analyzed the daily power load data and solar energy data in a certain place in China and normalized it to get the proportion of the load on each bus and the solar for each area at different sample time period. The electricity price EP in a day is considered as a constant value.

TABLE I. Parameters of PV generators

Number	Location	Capacity	Power factor
1	3	23%·S	1
2	9	23%·S	0.9
3	14	19%·S	0.9
4	19	12%·S	0.9
5	26	23%·S	1

TABLE II. Parameters of MESS

Type	Value	Type	Value
n_{MESS}	1	$E_{\max}^{MESS}$	1 MW·h
η^{ch}	0.75	$E_{\min}^{MESS}$	0.2 MW·h
η^{dh}	1.33	E_{rate}^{MESS}	0.8 MW·h
$p_{\max}^{ch}$	0.5MW	E_0^{MESS}	0.5 MW·h
$p_{\max}^{dh}$	0.5MW	$q_{\max}^{MESS}$	0.075MW

TABLE III. Basic Parameters of the model

Type	Value	Type	Value
EP	800$/ MW·h	$N_{\max}$	100
CP	1000$/ MW·h	ε	0.05
PC	100$/ MW·h	T	21
FC	10$/km	Δt	0.5h
λ_{MESS}	1	$S_{\max}$	2.5MW
λ_{sub}	0.1	ΔS	0.125MW

The proposed MILP problem is solved in cplex12.10. We use MATLAB R2018a to formulate the desired model which is then linked with cplex solver. The result will be shown and discussed in section 4.2.

4.2 Results and discussion

Fig.4 shows the relationship between the PV capacity S and the PV curtailment ratio α. It can be seen that, for the DN with MESS, there is $S^{0\%}$ = 1.20MW and the corresponding expected PV penetration μ is 29.93%. To analyze the impact of MESS in improving the operation status of DN, the comparison of the evaluation result without MESS is also shown in Fig.4. And the operation cost of DN using MESS (C_1=16562$) has also been shown to be lower than that without MESS (C_2=17626$).

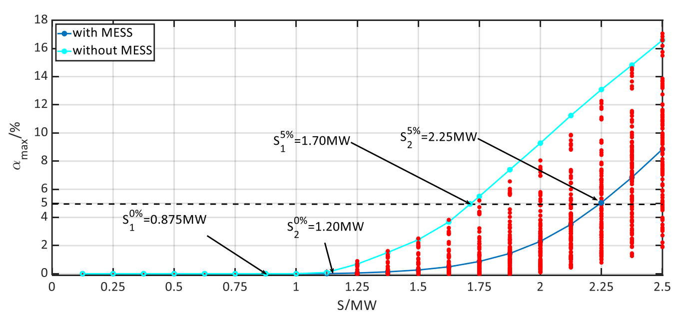
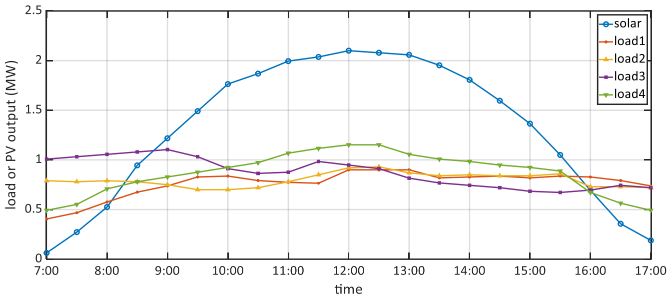
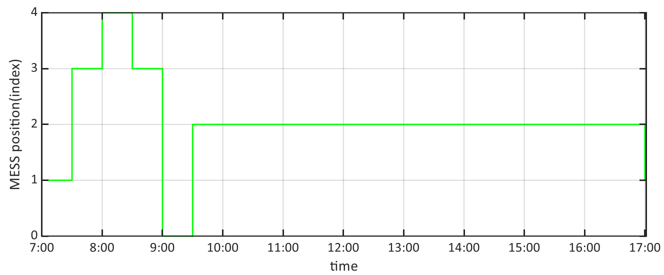


Fig.4. HC evaluation result and comparison

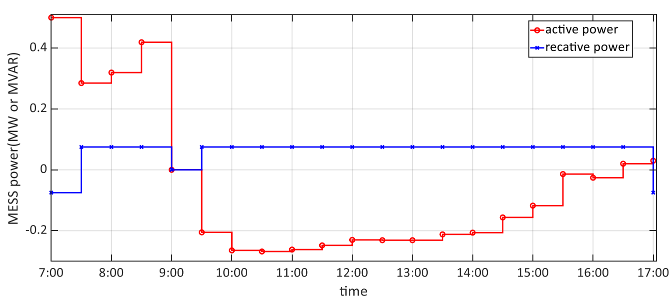
The optimal operation strategy of MESS is illustrated in Fig.5. Fig.5(a) shows the load and PV curve for each area in one simulation scenario, it can be seen that the load trends in different areas are different, which provides a movement direction for the MESS. The mov-ement trajectory and power output of the MESS in this scenario are shown in Fig.5(b) and 5(c), respectively. Fig.5(d) compares the PV curtailment of the DN with and without MESS in this scenario, finally.



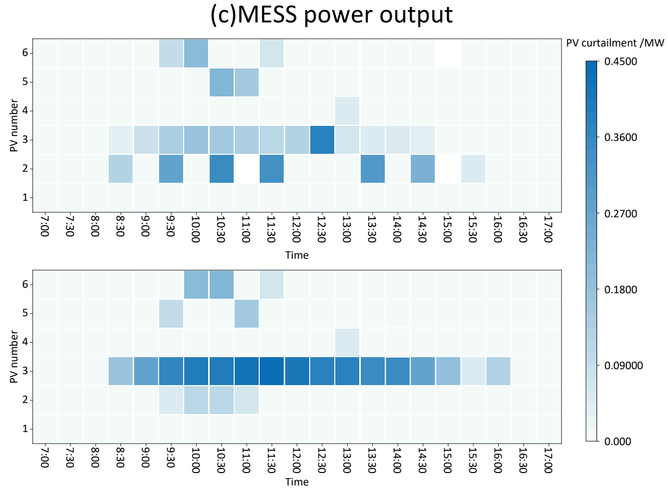
(a) load curve and solar curve



(b)MESS positions



(c)MESS power output



(d) comparison of PV curtailments

Fig.5. simulation result for one certain scenario

As can be seen in Fig.5, in the early morning the output of PV generation is rare, and the MESS acts as a generator to generate electricity at this time. When the solar irradiance is strong at noon and the PV generation output is high, the MESS acts as a load to absorb excess PV power generation to avoid PV curtailment.

The contribution of MESS to improve the PV hosting capacity can be proved obviously. According to Fig. 5(d), in the case of not using MESS, there is a serious problem of PV curtailment on PV 3 at noon. In the case of using MESS, the MESS moves to station 2 that is close to PV 3 at noon and acts as a load. The results show that the problem of PV curtailment on PV 3 has been effectively solved, which also proves the effectiveness of the MESS optimization operation strategy proposed in this paper.

5. *CONCLUSIONS*

This paper proposes an evaluation method for PV hosting capacity of a certain DN while the connected position of PVs in the DN has been determined before evaluation, the analysis of MESS on PV hosting capacity is also studied. The optimal operation strategy of MESS, which aims to minimize the operation cost of DN, is studied in the section of system simulation. Multi-scenario analysis is also applied in this method to deal with the uncertainty of system load demand and solar irradiance. A case study on a modified IEEE-33 distribution system with daily data of PVs and loads is used to validate the results. The proposed method effectively describes the relationship between PV hosting capacity and PV curtailment. The optimal operation strategy of MESS has also been verified to be effective, the HC evaluation result of a DN with MESS is higher than that without MESS, and the system operation cost is also reduced when using MESS.

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