An available capacity evaluation method for photovoltaic generation considering hydrogen storage

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Abstract—With the rapid development of global photovoltaic applications in recent years, it is crucial to evaluate the photovoltaic generation capacity to achieve a secure and efficient utilization of photovoltaic resources. This paper proposes an available photovoltaic evaluation method for generation capacity in distribution networks. The evaluation model is based on the optimal power flow model, considering operational constraints with reactive power and voltage limits. A novel multi-segment boundary approximation method is proposed to solve the model and obtain the available photovoltaic generation capacity explicitly. In addition, the effect of hydrogen storage is explored to host the photovoltaic generation capacity of the distribution network. The accuracy and calculation speed of the proposed method is greatly improved compared with traditional methods. Furthermore, the proposed method can promote the utilization of photovoltaic generation and help dispatching, which guarantees security and improves economics in the distribution network. Simulations on the modified IEEE 33-bus system demonstrate the effectiveness of the proposed evaluation method.

1. Introduction
To address the effects of climate change and meet current energy demands, the wave of promoting the development of renewable energy is gradually sweeping across the world [1]-[3]. By 2021, renewable energy continued to grow, with photovoltaics (PVs) recording its largest-ever increase [3]. However, the maximum accommodation and utilization of PVs are limited due to the unreasonable PVs consumption and the serious curtailment [4]. To make full use of PVs, it is necessary to evaluate the available capacity for photovoltaic (PV) generation in the distribution network. An accurate evaluation can help carry out PV capacity planning and configuration more effectively, ensuring the efficiency and safe operation of the power system [5].

For the past few years, considerable efforts have been made to study the available photovoltaic capacity evaluation methods for the distribution network operation. In [6], a bi-level programming model was built to calculate the maximal capacity for PV generation while considering load uncertainty. Ignoring the uncertainty of PV generation results in a biased result. Owing to the random nature of PV generation, researchers preferred to carry out evaluations based on Monte Carlo simulations. In [7], Monte Carlo stochastic simulation method was adopted to obtain the available PV generation capacity.
of a distribution system considering the network constraints based on the operational data. Due to the heavy computation, this approach has not been widely adopted by utilities. A boundary optimization method was further proposed in [8] to overcome the problem of heavy computation. A set of boundaries were obtained by solving optimization models to calculate the available renewable energy generation capacity. However, the accuracy of this method needs to be improved. Based on multi-parametric programming, the available renewable energy generation capacity was identified accurately by exploring combinations of active and inactive constraints [9]. Unfortunately, this method has difficulty in solving large-scale problems. To overcome this defect, a vertex search method was proposed to search the boundary point of the renewable energy generation region based on the linear optimal power flow (OPF) model [10]. This method is only applicable to linear models, which sacrifices the precision.

Besides, energy storage systems can effectively promote the PV generation capacity. Hydrogen storage (HS), one of the energy storage systems, is an attractive choice as it can achieve a large capacity and long-term storage[11]. In [12], the maximum capacity for PV generation was promoted by improving the operational flexibility of the system through combined the HS. However, the available PV generation capacity imposed by HS was not quantitatively characterized.

With this regard, this paper proposes an accurate evaluation method considering the HS. The contributions of this paper are summarized as follows: 1) A multi-segment boundary approximation method is proposed to efficiently evaluate the available PV generation capacity considering nonlinear constraints. The obtained available PV generation capacity can provide dispatching decision supports and feasibility analyses. 2) A method of quantifying the impact of the HS on the available PV generation capacity is proposed. The hydrogen storage model is further embedded into the evaluation model to improve the flexibility of the available PV generation capacity.

The remainder of this paper is organized as follows: Section II describes the evaluation model based on the OPF model considering the HS. The available PV generation capacity evaluation method for distribution networks is formulated in Section III. Various simulations are conducted in Section IV to verify the effectiveness and benefits of the proposed model. Conclusions are drawn in Section V.

2. Evaluation model based on the OPF model considering the HS

The proposed evaluation model is based on the nonlinear OPF model considering the HS. In this section, the objective function and constraints are constructed and explained.

2.1. Objective functions

The objective function is to minimize the operational cost, price for the renewable energy curtailment, and the utilization costs of hydrogen storage system.

$$\min \sum_{i=1}^{NG} \left[ a_g P_{G,i}^2 + b_g P_{G,i} + c_g \right] + K_F \sum_{i=1}^{NR} \left[ P_{PV,i}^f - P_{PV,i} \right] + c_{P2H}$$

(1)

where $P_{G,i}$ represents the active power output of the conventional generator at bus $i$; $P_{PV,i}^f$ denotes the point forecast output of the PV generator; $P_{PV,i}$ denotes the scheduled real power output of the renewable energy generator; $a_g, b_g$ and $c_g$ represent the generator production costs coefficients; $c_{P2H}$ is the hydrogen storage costs; $K_F$ is the cost coefficient of renewable energy curtailment penalty; NG is the number of conventional generators; NR is the number of the PV generators.

2.2. Operational constraints of distribution network

$$V_j \sum_{i=1}^{V_j} \left[ V_j(G_i \cos \theta_j + B_i \sin \theta_j) + P_{L,i} + P_{D,i} \right] = P_{G,i} + P_{PV,i} + P_{C,i}, \forall i, j \in \overline{G}$$

(2)

$$V_j \sum_{i=1}^{V_j} \left[ V_j(G_i \cos \theta_j - B_i \sin \theta_j) + Q_{L,i} + Q_{D,i} \right] = Q_{G,i}, \forall i, j \in \overline{G}$$

(3)

$$P_j = V_j \left[ V_j(G_i \cos \theta_i + B_i \sin \theta_i) - G_i V_j^2 \right], \forall i, j \in \overline{G}$$

(4)

$$Q_j = V_j \left[ V_j(G_i \sin \theta_i + B_i \cos \theta_i) + B_i V_j^2 \right], \forall i, j \in \overline{G}$$

(5)

$$P_j^{\min} \leq P_j \leq P_j^{\max}$$

(6)
\begin{align*}
Q_G^\min \leq Q_G & \leq Q_G^\max & (7) \\
P_{pr}^\min \leq P_{pr} & \leq P_{pr}^\max & (8) \\
V_i^\min \leq V_i & \leq V_i^\max, \ i = 1, 2, \ldots, \ NB & (9) \\
\theta_j^\min \leq \theta_j & \leq \theta_j^\max, \ i = 1, 2, \ldots, \ NB & (10) \\
(P_j)^2 + (Q_j)^2 & \leq S_j^\max & (11)
\end{align*}

where \(P_G\) and \(Q_G\) are the active and reactive output of the conventional generator, respectively; \(P_{PV}\) is the active output of the PV generator; \(P_{LD}\) and \(Q_{LD}\) are the active and reactive load demand, respectively; \(P_{EL}\) is the supplied electric power; \(P_{FC}\) is the power output of fuel cell; \(G_{ij}\) and \(B_{ij}\) are the element at the \(i\)th row and \(j\)th column of the bus admittance matrix; \(\theta_{ij}\) denotes the voltage angle difference between buses \(i\) and \(j\); \(V\) and \(\theta\) represent the magnitude and phase angle of the voltage, respectively; \(P_{ij}\) and \(Q_{ij}\) are the active and reactive power flow from bus \(i\) to bus \(j\); \(S_{ij}^{\max}\) is the apparent power limitation from bus \(i\) to bus \(j\); superscripts \((\cdot)^\min\) and \((\cdot)^\max\) represent the upper and lower limits of the variables, respectively; \(NB\) is the branches number in networks.

Constraints (2) and (3) represent the active and reactive power flow constraints of the distribution network, respectively. Constraints (4) and (5) denote the active and reactive transmission constraints, respectively. Constraints (6) and (8) are the active capacity limits of the conventional generators and the PV generators, respectively. Constraints (7) represent the reactive capacity limits of the conventional generators. Constraints (9) and (10) give the limitations of voltage magnitude and phase angles. Constraints (11) represent the capacity limits of the lines.

2.3. Hydrogen storage system

\begin{align*}
n_{H_{i,El}} & = \eta_{El} P_{El} \over \text{LHV}_{H_2} & (12) \\
n_{H_{i,FC}} & = \eta_{FC} P_{FC} \over \text{LHV}_{H_2} & (13) \\
P_{H_{i}} & = P_{H_{i,0}} + \frac{Y}{T_{H_2}}(n_{H_{i,El}} - n_{H_{i,FC}}) & (14) \\
P_{El}^\min & \leq P_{El} \leq P_{El}^\max & (15) \\
P_{FC}^\min & \leq P_{FC} \leq P_{FC}^\max & (16) \\
P_{H_2}^\min & \leq P_{H_2} \leq P_{H_2}^\max & (17)
\end{align*}

where \(n_{H_{i,El}}\) represents the hydrogen molar flow of the electrolyzer; \(\text{LHV}_{H_2}\) is the lower heating value of hydrogen (240 MJ/kmol); \(\eta_{El}\) is electrolyzer efficiency, which takes into account electro-chemical, thermodynamic and ancillary losses; \(n_{H_{2,FC}}\) represents the hydrogen consumption of the fuel cell; \(\eta_{FC}\) is fuel cell efficiency, which takes into account electro-chemical, thermodynamic and ancillary losses; \(P_{H_{2,0}}\) represents the initial hydrogen tank pressure; \(P_{H_{2}}\) represents the final hydrogen tank pressure; \(Y\) is the gas constant; \(T_{H_2}\) is the mean temperature inside the vessel; \(V_{H_2}\) is the overall tank volume. Specific data can be obtained from references [13]-[14].

Constraints (12) give the relationship of \(n_{H_{i,El}}\) and \(P_{EL}\). Constraints (13) give the relationship between \(n_{H_{2,FC}}\) and \(P_{FC}\). Constraints (14) are the function of \(P_{H_{2}}\) about \(n_{H_{i,El}}\) and \(n_{H_{i,FC}}\). Constraints (15) and (16) give unit generation limits. Constraints (17) are the storage limits.

3. Evaluation method based on multi-segment boundary approximation method

In this section, a novel evaluation method based on the multi-segment boundary approximation is proposed to obtain the available PV generation capacity, which can be regarded as the region characterization of the PV generation capacity. The basic idea of the multi-segment boundary approximation algorithm is searching for new boundary points by outward translating facets of the obtained approximation region of PV generation capacity. Repeat the process of facets translating of the
obtained approximation region until the difference between the obtained approximation region and the original region of PV generation capacity ($\Omega$) under a preset value. The approximation of $\Omega$ is completed. The detailed procedure of the evaluation method is as follows.

1) Initialization of the PV generation capacity region

Explore along the upper and lower limits of each variable in $P_{PV}$ to determine primary boundary points. Based on the optimization theory, the determination process of $i^{th}$ renewable energy generator output $P_{PV}^i$ can be formulated to two optimization problems as below:

$$\max_{\ell_i, \bar{n}_i, \tilde{n}_i} P_{PV}^i, \ s.t.(l) - (17).$$

$$\min_{\ell_i, \bar{n}_i, \tilde{n}_i} P_{PV}^i, \ s.t.(l) - (17).$$

The optimal solutions of above formula can be recorded as a set of boundary points to construct a primary region $\Omega \triangleq \{A_P \leq B\}$, where $A$ and $B$ are the coefficients of facets of $\Omega$.

2) Searching boundary points by moving the facets

Suppose the $k^{th}$ facet of the bounded closed region $\Omega$ is formulated as (20).

$$A_k P_{PV} \leq B_k$$

where $A_k$ is the $k^{th}$ row sub-matrix of $A$; and $B_k$ is the $k^{th}$ element of column vector $B$.

Construct the optimization problems based on (20), all boundary points can be obtained.

$$\max_{\ell_i, \bar{n}_i, \tilde{n}_i} A_k P_{PV}^i, \ s.t.(l) - (17).$$

Suppose the optimal solution is $P_{PV|k}$, the new set of boundary points for the feasible region is $V_{new} = \{V \cup P_{PV|k} (\forall k)\}$. Based on the new and previous boundary points in the region, a new region of PV generation capacity can be obtained as $\Omega_{new} \triangleq \{A_{new} P_{PV} \leq B_{new}\}$.

3) Accuracy indices

Repeat the above process until the difference between the new region and the previous region is less than a preset threshold. The boundary points search can terminate because small difference indicates that the new region is similar to the $\Omega$.

4. Case studies

4.1. System Information and Comparison Methods

IEEE 33-bus system is used to demonstrate the effectiveness of our proposed method. Three conventional generators are connected at bus 1, bus, 12 and bus 33, respectively. Two PV generators combined with the HS system are located at bus 6 and bus 18. Following four methods are compared in this paper:

- M0: Monte Carlo sampling method.
- M1: Maximum PV generation capability method.
- M2: Proposed multi-segment boundary approximation method.
- M3: Proposed multi-segment boundary approximation method considering the HS.

All simulation results are calculated under MATLAB R2015b and performed on a laptop equipped with Intel Core i7-10700F 2.90GHz CPU and 16.00GB of RAM. The program was solved by an embedded IBM CPLEX 12.6 solver with the YALMIP interface in MATLAB.

4.2. Analysis of results

The available PV generation capacity using M0-M2 is shown in Fig. 1. The available capacity of M0 shown in Fig. 1(a) is constructed by plenty of sampling points, which can be regarded as a reference. The available capacity of M1 depicted in Fig. 1(b) is significantly less than the reference. For example, the PV generation point (1.5, 2) MW is infeasible in Fig. 1(b), while is feasible actually. The evaluation result from M1 is overoptimistic and amplifies the risk of system operation. The available capacity of M2 is basically identical with the reference, as shown in Fig. 1(c). With enough sampling points, the
region obtained M2 method should be basically the same as Fig. 1(a). The accuracy of the proposed evaluation method is proved valid.

![Fig. 1 Available PV generation capacity using M0-M2.](image)

As for the computational time, the M0 method takes the longest time—604800.5 seconds. Although M0 can obtain an accurate available PV generation capacity, the most time-consuming process dooms it unable to apply in practice. In contrast, M1 takes the least time—5.2 seconds. However, in terms of accuracy, the M1 method produces large errors. For M2, the computational time is 14.3 seconds. The retention of non-linear information in M2 provides a more accurate available PV generation capacity with a sacrifice of slight computational efficiency. Consequently, the M2 method can achieve a better tradeoff between computational accuracy and efficiency.

Besides, the available PV generation capacity before and after considering the HS using the proposed method M3 is shown in Fig. 2. Obviously, the available PV generation capacity is sharply increased after considering the HS. The maximum output is increased from 3.46 MW to 3.84 MW in the y-direction, and the maximum output is increased from 2.87 MW to 3.01 MW in the x-direction. The increased PV generation capacity can promote the PV accommodation effectively.

![Fig. 2 The available PV generation capacity before and after considering the HS.](image)

5. Conclusion

In this paper, an available photovoltaic evaluation method for generation capacity is proposed considering the HS. The advantages of the proposed method include the following: 1) A multi-segment boundary approximation method is proposed to efficiently evaluate the available PV generation capacity. Compared with the Monte Carlo method and the boundary optimization method, the proposed method has higher accuracy and faster solving speed. The evaluation result can help to dispatch and guarantee the secure operation of distribution networks. 2) The effect of the HS on the available PV generation capacity is quantified characterized. With the hydrogen storage system integrated into distribution networks, the peak power supply pressure can be relieved and the PV accommodation can be promoted to alleviate the climate problem and meet current energy demands.
Acknowledgments
This work was financially supported by the Science and Technology Project of Jiangsu Electric Power Co., LTD. (J2021046).

References
[1] C. Byers and A. Botterud. Additional capacity value from synergy of variable renewable Energy and energy storage. IEEE Trans Sustain Energy Apr. 2020; 11(2): 1106-1109.
[2] O. Ogunrinde, E. Shittu and K. K. Dhanda. Investing in renewable energy: reconciling regional policy with renewable energy growth. IEEE Eng. Manag. Rev. Dec. 2018; 46(4):103-111.
[3] British Petroleum (BP). Statistical review of world energy 2021, https://www.bp.com/statisticalreview; 2021 [accessed 24 Jul 2021].
[4] Z. Zhuo, E. Du, N. Zhang, C. Kang, Q. Xia and Z. Wang. Incorporating massive scenarios in transmission expansion planning with high renewable energy penetration. IEEE Trans Power Syst Mar. 2020; 35(2):1061-1074.
[5] S. Wang, Y. Dong, L. Wu and B. Yan. Interval overvoltage risk based PV hosting capacity evaluation considering PV and load uncertainties. IEEE Trans Smart Grid May 2020; 11(3):2709-2721.
[6] K. Liu, Y. Liu, and W. Sheng. Maximal allowable DG penetration capacity calculation considering voltage constraints. Electr. Power Autom. Equip. Jun. 2016; 36(6):81–87.
[7] R. Torquato, D. Salles, C. Oriente Pereira, P. C. M. Meira and W. Freitas. A comprehensive assessment of PV hosting capacity on low-voltage distribution systems. IEEE Trans. Power Deliv. Apr. 2018; 33(2):1002-1012.
[8] J. Yu, J. Liu, R. Xu, W. Yan and X. Zhao. Limit preserving equivalent method of interconnected power systems based on transmission capability consistency. IET Gener. Transm. Distrib. 2016; 10(14): 3547-3554.
[9] W. Dai, B. Shi, D. Zhang, H. H. Goh, H. Liu and J. Li. Incorporating External Flexibility in Generation Expansion Planning. IEEE Trans Power Syst May 2021; 3101700.
[10] W. Lin, Z. Yang, J. Yu, W. Li and Y. Lei. Improving security and economy of interconnected power network through explicit feasible region of tie-line power transfer. Int J Electr Power Energy 2020; 123: 106262.
[11] G. Pan, W. Gu, Y. Lu, H. Qiu, S. Lu and S. Yao. Optimal planning for electricity-hydrogen integrated energy system considering power to hydrogen and heat and seasonal storage. IEEE Trans Sustain Energy Oct. 2020; 11(4):2662-2676.
[12] Li Y, Wang C, Li G, Wang J, Zhao D, Chen C. Improving operational flexibility of integrated energy system with uncertain renewable generations considering thermal inertia of buildings. IEEE Energ Convers Manag 2020; 207: 112526.
[13] M. Trifkovic, M. Sheikhzadeh, K. Nigim and P. Daoutidis. Modeling and control of a renewable hybrid energy system with hydrogen storage. IEEE Trans Control Syst Technol Jan. 2014; 22(1):169-179.
[14] Cau, G., Cocco, D. and Petrollese, M. Energy management strategy based on short-term generation scheduling for a renewable microgrid using a hydrogen storage system. Energy Conver. Manag. 2014; 87(107): 820–831.