frontiers | Frontiers in Energy Research

TYPE Opinion
PUBLISHED 14 September 2022
DOI 10.3389/fenrg.2022.1019352

Check for updates

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted
to Smart Grids,
a section of the journal
Frontiers in Energy Research

RECEIVED 15 August 2022
ACCEPTED 23 August 2022
PUBLISHED 14 September 2022

CITATION
Yu X, Ling X, Zhou X, Li K and Feng X (2022), Flexibility evaluation and index analysis of distributed generation planning for grid-source coordination. *Front. Energy Res.* 10:1019352. doi: 10.3389/fenrg.2022.1019352

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Flexibility evaluation and index analysis of distributed generation planning for grid-source coordination

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KEYWORDS

flexibility evaluationl, distributed generation, demand response, technology index, economic index

1 Introduction

Electric energy has a critical impact on the consumer's life, which is mostly based on centralized generation at present. However, the centralized generation has caused high power transmission and distribution losses. Meanwhile, the high combustion cost of fossil fuels and the environmental pollution caused by the greenhouse effect has become the problems that have to face. Reasonable planning sizing and location of distributed generations (DGs) to the distribution network (DN) may overcome the above limitations such as reducing power loss and environmental pollution. Therefore, access to DGs at the DN has been widely adopted (Rana et al., 2017; Ali and Qiang, 2018). Nowadays, due to the ability to maximize the use of renewable energy such as wind, solar, wave, hydro, and hydrogen the penetration rate of DGs has increased.

The optimal location and capacity of DGs properly may reduce power loss, cost and enhance the reliability of the power grid. A large number of DG connections have a great impact on DN such as power flow, voltage profile, power loss, and power grid stability of the DN. Therefore, it is valuable to quantitatively evaluate the comprehensive impact of DG connections on the DN (Francisco et al., 2020; Li et al., 2021). In order to evaluate whether the location and capacity of the DGs connected to the power grid are correct, various evaluation indexes are proposed mainly including economy, technology, and environment. Reference (Wang et al., 2019) has defined the voltage stability index based on the power flow calculation results of the DN and studied the influence of the DG connection on the voltage stability of the DN. Literature (Su, 2010) has considered the uncertainty of the operation of the distribution system, including the daily variable load, the random DG generation, the grid configuration, and the voltage control device, and analyzes the influence of the distributed power supply connected to the distribution network on the voltage deviation. Currently, various literatures proposed several methods for optimal location and capacity of DGs, literature (Koutsoukis et al., 2014; Magadum and Kulkarni, 2015) separately proposed tabu search (TS), and fuzzy logic to minimize power loss and cost of DGs. Moreover, artificial neural networks (ANN) have either been designed to minimize energy loss, and it no need for flow calculations (Semic et al., 2019).

However, the above literature both ignores the users' demand response (DR) about the DGs accessing, and just consider the DGs' impact on the grid. Meanwhile, there is no review paper evaluating and analyzing the index of DGs. Hence, this paper has mainly evaluated and analyzed the economic index, and technology index of DGs. Furthermore, the advantages/limitations, applications, and objective function of each index have been proposed. Finally, valuable perspectives and challenges for future researchers are proposed.

2 Analysis of economic indexes

Generally, to decrease the environmental pollution and power loss caused by the traditional centralized generators, installing DGs in DN as far as possible is a conventional method to solve. However, how to not only decrease the investment, operation, and maintenance cost but enhance the reliability of the power grid is a critical challenge for the current researchers. Currently, several approaches have been proposed to solve this problem, as follows:

- By optimizing the location and capacity, the voltage quality can be improved and the loss of the grid will be reduced with less investment cost. Moreover, investment costs can be recovered by actively participating in DN management based on a price control mechanism, and investment costs can be recovered by appropriately increasing electricity prices. Meanwhile, by adding robots to make equipment intelligent to reduce operation and maintenance costs;
- Establish an incentive scheme to help the company and government to install DGs. These incentive plans may include government subsidies on the generator side and taxes on customers (e.g., environmental taxes);
- Active DN (ADN) mechanism should be more widely used in the current new power system. Based on the resident DR, combine the resident and generation to create more ADN.

The cost of the DG is a complex problem, which includes several uncertain paraments such as the price of the fuel cell, labor cost, inflation rate, tax, raw material cost, government subsidy, and DGs types. Literature (Yang et al., 2020) has comprehensively summarized the types of DGs which are divided into four types including only active power DGs (type-I), reactive power generators (type-II), which generate both active and reactive power DGs (type-III), and generate active power and consume reactive power (type-VI). A variety of uncertain parameters will lead to a very complex problem in calculating the investment and operation cost of the system. In addition to the investment and operation costs, the environmental benefits generated by installing DGs on the DN side should also be considered, which not only alleviates the pollution but better use of renewable energy (Priyanka et al., 2014). Because of its benefit, several researchers have chosen the minimized cost of DGs as the objective to optime the capacity and location. Table 1 comprehensively summarizes the typical economic indexes and analyzes their application, benefits, and limitations.

Drawn from Table 1, typical economic indexes have been adopted for various types of DGs, and most of them are tested in experimental models. However, many researchers ignore the labor cost, tax, and fuel costs at present. Meanwhile, DGs planning is based on experimental models and has not been applied to the real model. Besides, in future research, DGs should be planned based on user experience. The demand side is extremely important. Future researchers should consider how to not only meet the users' power consumption feeling but also reduce the investment and operation costs. In the small-scale power grid, the load on the user side and the daily load fluctuation are relatively low, while in the large-scale power grid, the daily load fluctuation is large and more DGs are required, so it is difficult to ensure the economy. Hence, in the large-scale power grid, the reliability index such as load fluctuation and voltage profile are more important. Moreover, as the increasing penetration of electric vehicles (EVs) has increased, it will cause load fluctuation. The design and selection of economic indexes will face difficulties.

3 Analysis of technology indexes

3.1 Power loss

Before the DGs are connected to DN, the power flow of the DN simply flows from the substation side to the load side. However, with the incorporation of the DGs, the direction and magnitude of the system power flow will be affected, thus changing the power loss of the DN. To minimize the power loss, the most ideal method is to install DGs locally at each power node. However, due to the investment cost and the limitation of the number of generators installed, this method is not feasible. In general, the value of DGs power factor is equal to the total load of the electric power system network, but there are equality constraints to prevent power flow reversal. In practice, the power factor of most DGs operates according to their rated power value, reducing power loss on the premise of maintaining voltage stability. The value of DGs power factor will be different in different periods (Quezada et al., 2006; Hengsritawat and Tayjasanant, 2012). During the peak off hour, to limit voltage fluctuation and reduce active power loss, the value of DGs power factor is generally chosen as the leading power factor. Besides, during the peak hour, to compensate for voltage drop and enhance reactive power, the value of DGs power factor is supposed to be chosen for the lagging power factor.

The access of DGs makes the DN change from a simple radiation network to a multi-power supply system. Before DGs are connected, the direction of feeder power flow is always unidirectional. When DN is connected to the DGs, the unidirectional power flow mode of the system is changed. The power flow of the system is not necessarily unidirectional, and the reverse flow of the power flow may occur. The access to DGs may

TABLE 1 Summary and analyze the evaluation indexes of DGs.

Evaluation index	Objective	Objective function	Type of DG	Parameters	Application	Benefits	Limitations
Economic index	Maximize benefits (He et al., 2019)	$F = f_{\mathrm{Inc}} - f_{\mathrm{Inv}} - f_{\mathrm{Ope}}$	Type-I; Type-III; Type-IV.	f_{Inc} : income of company; f_{Inv} : investment of DG; f_{Ope} : operation cost.	Small-scale power grid.	Consider three types of DG.	Ignore the labor cost, government subsidy, and environmental impact; Ignore DR.
	Minimize system cost (Jabr and Pal, 2009)	$C_{\mathrm{DG}} = \sum_{i=1}^{n} P_{\mathrm{DG},i} + C_{\mathrm{L}}\left[P_{\mathrm{L(target)}} - P_{\mathrm{L(actual)}}\right]$	Type-I.	C_{L} : incentive penalty; $P_{\mathrm{DG},i}$: power output; $P_{\mathrm{L(target)}}$: target power loss; $P_{\mathrm{L(actual)}}$: actual power loss.	Small-scale power grid.	Consider the power loss of DN.	Only single-objective; Ignore labor cost, environmental influence and DR.
	Minimize cost and maximize the benefit (Porkar et al., 2011)	$C = \left(\frac{s}{h}\right) = C_{\mathrm{DG}} + C_{\mathrm{OM,DG}} + C_{\mathrm{SC}} + C_{\mathrm{OMSC}}$ $+C_{\mathrm{E}} + C_{\mathrm{loss}} + C_{\mathrm{ENS}}$ $TSB() = C_{\mathrm{DGsave}} + A \cdot \sum_{t=1}^{8760} \left[C_{\mathrm{Esave}}(t) + C_{\mathrm{losssave}}(t) C_{\mathrm{ENS}}(t)\right]$	All types.	C_{DG} : DG investment cost; C_{OMDG} : DG operation and maintenance cost; C_{SC} : synchronous condense (SC) cost; C_{OMSC} : SC operation and maintenance cost; C_{E}: cost of fuel cell; C_{loss} : energy loss cost; C_{ENS} : energy is not supplied cost.	Small-scale power grid.	Consider many uncertain parameters; Not only include cost but consider profit.	High complexity; Ignore the resident response; Ignor e labor cost, government subsidy, and environmental influence.
Technology index	Power loss	$S_{\mathrm{loss}} - S_{\mathrm{loss}}^{\mathrm{DG}} = (U_{\mathrm{G}} - U_{\mathrm{L}}) \cdot I_{\mathrm{DG}}$	Type-III reduces power loss most.	U_{G} : main grid voltage; U_{L}: load voltage; I_{DG} current through t DG.	Long distance and large-scale power grid.	Reduce power loss and improve system reliability.	Related to power factor, types and location of DGs; Only install type-IV on DN, the high penetration may cause greater power loss.
	Voltage profile	$U_{\mathrm{s}} = \sum_{i=1}^{K} \frac{\lvert U_i - U_{\mathrm{R}} \rvert}{U_{\mathrm{R}} \cdot K}$	Type-III improves voltage profile most.	U_{R} : reference voltage of electric power system; U_i: ith node voltage; K : number of nodes.	Long distance and large-scale power grid.	Primary substation voltage reduced; Voltage quality improved.	Shut down DGs during small-scale power grid.

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lead to the increase or decrease of power flow along the feeder line. The power flow of DN will change, and the power loss of DN will change accordingly. The power loss may increase or decrease, depending on various factors. Furthermore, in the large-scale grid, due to the long transmission distance, the installation of DGs with improper capacity at the end of the line will reduce the power loss. Generally, the power loss may be reduced by the penetration level of DGs. Meanwhile, note that the location of DGs installed on the DN must cause a different effect on the power loss. The equations of the power loss with DGs and without DGs are as follows:

$$S_{\mathrm{loss}} = S_{\mathrm{G}} - S_{\mathrm{L}} = (U_{\mathrm{G}} - U_{\mathrm{L}}) \cdot I_{\mathrm{link}} \tag{1}$$

$$S_{\mathrm{loss}}^{\mathrm{DG}} = S_{\mathrm{G}} - S_{\mathrm{L}} + S_{\mathrm{DG}} = (U_{\mathrm{G}} - U_{\mathrm{L}}) \cdot (I_{\mathrm{link}} - I_{\mathrm{DG}}) \tag{2}$$

where S_{G}, S_{L} and S_{DG} separately mean the power of the main grid, load, and DG; U_{G} and U_{L} denote the voltage of the main grid and load; I_{link} and I_{DG} are the current through the link and DG. The power loss reduced by DG is as follows:

$$S_{\mathrm{loss}} - S_{\mathrm{loss}}^{\mathrm{DG}} = (U_{\mathrm{G}} - U_{\mathrm{L}}) \cdot I_{\mathrm{DG}} \tag{3}$$

Furthermore, as concluded from the literature (Ufa et al., 2022), all types of DGs can reduce power loss. However, the power loss reduced by different types of DGs connected to DN is different. The installation type of type-III has the most obvious effect on the reduction of power loss. The types of DGs that reduce power loss are sorted in the order of type-III, type-I, type-II, and type-IV, respectively. When DGs can deliver both active and reactive power, which have the most obvious effect on power loss reduction. In addition, DGs type-III and type-II can generate reactive power (improve voltage profile), which also has a great impact on the reduced power loss. Finally, when there is only type-IV installed on the DN, the high penetration level of the DGs will cause greater power loss than that without DGs (Prakash and Lakshminarayana, 2018).

3.2 Voltage profile

The allowable deviation of the three-phase power supply voltage of 10 kV and below is ± 7% of the nominal voltage (Li et al., 2021), and the smaller the absolute value, the better. Therefore, the system voltage profile index is defined as the average value of the absolute value of the voltage profile of each node to represent the overall voltage deviation level of the system. The calculation formula is as follows:

$$U_{\mathrm{s}} = \sum\nolimits_{i=1}^{K} \frac{|U_i - U_{\mathrm{R}}|}{U_{\mathrm{R}} \cdot K} \tag{4}$$

where U_{R} means the reference voltage of the electric power system; U_i is the ith node voltage; K denotes the number of the node.

Similar to the power loss, the voltage profile is related to the power factor, location, capacity, and penetration level of DGs. However, for small-scale load systems, DG integration may lead to voltage overrun and other problems. Therefore, before the DGs have been connected to the power grid, a large number of experimental analyses should be conducted.

4 Discussion and conclusion

To research the comprehensive impact of DGs access on DN, this paper comprehensively evaluated and analyzed the economic indexes and technical indexes of DG, and summarized their advantages and disadvantages and applicable scenarios in Table 1. Besides, two valuable conclusions about the DGs evaluation index have been proposed, as follows:

a) Economic indexes are generally applicable to small-scale grids because the load fluctuation of residents with low load in small-scale grids will not be large. Large-scale grids, not only consider the benefits and investment costs of the power grid but also consider the demand side response. Meanwhile, in the large-scale power grid, the load fluctuation is high. The most significant to configuring DGs is to maintain the stability of the power grid, so minimizing the cost and maximizing the benefits are suitable for small-scale power grids.
b) Reasonable access to DGs will reduce the power loss and improve the voltage profile of the power grid, especially in the large-scale power grid. The power loss and voltage profile are related to the power factor and location penetration level of DGs. In small-scale power grids, it is better not to connect DGs under light load conditions, otherwise voltage quality may reduce.

Generally speaking, according to the scale of the power grid, it is very important to flexibly coordinate the grid-source and reasonably select the evaluation indexes to maintain the stability of the power grid and ensure the economy.

Author contributions

XY: writing the manuscript; XL: discussion of the economic index; XZ: discussion of the technology index; KL: editing; XF: discussion of the topic.

Funding

Grid-source coordination development-based power sources planning evaluation index system research (5214GH210011).

Conflict of interest

XY, XL, XZ, KL, XF was employed by Central China Branch of State Grid Corporation of China, Central Southern China Electric Power Design Institute Co., Ltd.

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