IOP Conf. Series: Earth and Environmental Science **133** (2018) 012010 doi:10.1088/1755-1315/133/1/012010

Comprehensive evaluation of impacts of distributed generation integration in distribution network

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Abstract. All Distributed generation (DG) as the supplement to renewable energy centralized utilization, is becoming the focus of development direction of renewable energy utilization. With the increasing proportion of DG in distribution network, the network power structure, power flow distribution, operation plans and protection are affected to some extent. According to the main impacts of DG, a comprehensive evaluation model of distributed network with DG is proposed in this paper. A comprehensive evaluation index system including 7 aspects, along with their corresponding index calculation method is established for quantitative analysis. The indices under different access capacity of DG in distribution network are calculated based on the IEEE RBTS-Bus 6 system and the evaluation result is calculated by analytic hierarchy process (AHP). The proposed model and method are verified effective and validity through case study.

1. Introduction

On the situation that centralized development of renewable energy tends to saturate, distributed generation (DG) as an effective supplement is developed rapidly because of its low pollution, high energy efficiency and flexibility. By 2015, DG installed capacity in China has reached 45.33 GW. The DG capacity is expected to be 195 GW and the output account for 22% of the total production in 2020. Among varieties of DGs, there are several common use categories: wind turbine (WT), cell fuels, photovoltaic arrays (PV), micro gas turbine, small hydropower, etc. Because of DG connected to the network in a large scale, the economy, power quality, safety, and reliability of the distributed network are affected. In order to obtain more rational planning and better operation management that the distributed network needs under the effect of DG, it is essential to establish a scientific and systematic comprehensive evaluation Index system.

The previous evaluation method is mainly to evaluate single index. Considering the coordination coefficient among each index, a comprehensive evaluation index system is proposed in [1]. A reliability calculation method with consideration of the correlation between wind speed and load is proposed in [2]. In [3], the fuzzy AHP method, combined with the advantages of AHP and fuzzy evaluation method is applied to the distribution network comprehensive Assessment. The effect of DG on reliability, power quality, environment, economy of distributed network is taken into consideration in [4], and then an evaluation index system of DG affecting the network is established. The effects of DG different access modes on system reliability are studied in [5-6], In [5] DG's optimal access capacity and access point are studied from the aspects of inverse power constraint, voltage elevation and short-circuit current, and interval algorithm is used in [6] to compute the reliability Index of system before and after DG incorporation. Considering the output characteristics of wind power and PV system, the influence of DG on power flow distribution is studied in [7], and the variation performance of flow distribution is obtained by simulation. Compared with the previous work, the recent evaluation method has been improved greatly, and the evaluation index is more and more abundant, which increases the soft index of distribution network operation and management level, service, economy and so on.

In order to enrich the evaluation index system of distribution network, based on previous work, the effect of DG on power flow, power quality, line loss rate, reliability and operation management are synthetically considered in this paper and a comprehensive evaluation index system containing DGs is proposed, thus to provide scientific guidance to the planning and construction of the active distribution network and to strengthen the operation and management of distribution network.

2. Construction of comprehensive evaluation index system

2.1. Comprehensive evaluation index system

DG has attracted much importance due to their economy, flexibility, high efficiency and environmental friendliness. As more and more DGs are connected to the distribution network, the influences of the access of DG on distribution network are becoming more and more serious.

Significantly, the access of DG source changed the power supply structure of the distribution network, thus changing the power flow distribution, voltage distribution and so on. The small scale of distributed power supply and short construction period can reduce the construction cost of power grid. We can measure the economical efficiency of distributed power supply by the slow construction efficiency of the distribution network [8]. The single - power radiation network of distribution system is transformed into a variety of distributed power weak ring networks because of the access of distributed generation. The line loss rate is a comprehensive technical economic indicator that reflects the planning, design, technical equipment and economic operation level of power grid. The power loss of the grid depends on the power flow distribution of the distribution system. The access of distributed power supply makes the flow direction of each branch in the distribution network no longer one-way flow, so the access of distributed power supply will inevitably affect the power grid loss [9]. The line loss rate is related to the number of DGs, the capacity of the access point and the distribution of load. When the access capacity of the DG is greater than the load capacity of the system, the power grid loss will increase. Due to the randomness and instability of the output power of DG, the parallel operation of DG can cause voltage fluctuation, voltage flicker and harmonic pollution, etc., thus affecting the power quality of the power grid [10]. In order to ensure the good power supply quality, it is necessary to integrate power quality into the comprehensive evaluation index system. When the system fails, the parallel operation of the DG will provide short-circuit current to the fault point. Different access modes and access capacity of DG have different effects on short-circuit current. The power supply reliability of the distribution network reflects the operating characteristics, the equipment structure, the running state and the power department's ability to manage the system and equipment of the distribution network [11-12]. As power supplies to power users in power outage, DGs can greatly reduce the user's annual power failure time. However, when analyzing the influence of DG on power supply reliability, the formation of isolated island and the randomness of DG output power should be taken into account. The radiant structure of the power supply of the distribution network has been fundamentally changed with the access of DG, reducing the sensitivity, speed, reliability and selectivity of relay protection, or causing the mal-operation and no-operation of protective devices [13-14]. The access of many kinds of distributed generation has a great influence on economic cost, voltage quality and safety of distribution network. Therefore, it is necessary to properly plan and improve the operation management level of the distribution network. In order to meet the above standards, a scientific and systematic comprehensive evaluation index system is urgently needed.

Therefore, it is necessary to quantify the several impacts of these DGs and make a comprehensive evaluation of the distribution network [15-16]. The economic and technical indexes of the influences of DG integration on the distribution networks are studied and analyzed in this paper. In this paper, the active power unit cost index is used to indicate the degree of delaying the investment of new equipment due to the access of DG; the grid loss index of distribution networks is used to show the economy of distribution network with DG; voltage pass rate index, total harmonic distortion rate index and power supply reliability index are used to represent the service quality of the distribution network with the integration of DG; the short-circuit capacity index and degree of influence of relay protection index are used to indicate the safety of the distribution network operation. A set of index system with seven indexes, which are active power unit cost, grid loss, voltage pass rate, total harmonic distortion rate, power supply reliability, short-circuit capacity and relay protection, is formed in the following figure.

2.2. Calculation methods of indexes

After introducing the integrated evaluation index system of distributed power access distribution network, next we will introduce the quantitative methods of each index in detail. Because the calculation methods of each index of the distribution networks with DG are different from that of the traditional distribution networks.

2.2.1. Active power unit cost

The cost of active power unit $C^{IRP}{}_{i,p}$ can be used to express the efficiency of power grid. If $C^{IRP}{}_{i,p}$ is negative, that indicates that the power of the transmission line of the node and the transformer is decreased, which reduces the use intensity of the existing equipment, thus delaying the investment of the power grid company in the new equipment. The calculation method of active power unit cost index ($C^{IRP}{}_{i,p}$) is as follows.

$$C_{i,p}^{IRP} = \frac{C_{i,p}}{\nabla p} \tag{1}$$

Where, $C_{i,p}$ is the cost of active power fluctuation of node i; Δp is the active power fluctuation value of node *i*.

2.2.2. Grid loss

The access of DGs can reduce the grid loss of distribution network. Because of the active power and reactive power provided by the distributed power source at the load point, the power of the flow on the line is reduced directly. The calculation method of grid loss (P_{loss}) s as follows [17-18].

$$P_{loss} = \sum R_i \frac{P_i^2 + Q_i^2}{U_i^2} \tag{2}$$

Where, P_{loss} is the total active loss of all branch roads; R_i is the resistance on the branch circuit i; P_i、Q_i and U_i respectively indicates active power, reactive power and the voltage amplitude of front-end node of branch ***i*.**

2.2.3. Voltage pass rate

Inappropriate access location and access capacity of DG may worse the voltage distribution of distribution networks. For instance, if DG is installed at the end node of the line, the voltage of the end node may exceed the normal range. According to distributed power supply different access mode, DGs can be divided into generator-based DG and converter-based DG. Different types of DG have different effects on power quality. The wind power generation is limited by the natural environment. The generation state of wind turbine is random, and the integration operating of wind generation can cause voltage instability and voltage fluctuation. In order to indicate the influence of the voltage distribution of the distribution networks with the access of DG, voltage pass rate (v_p) is calculated as follows.

$$v_{qr} = \frac{N_p}{N} \tag{3}$$

Where, N_p is the number of nodes with qualified voltage; N is the total number of nodes of distribution network.

2.2.4. Total harmonic distortion rate

Similarly, photovoltaic power generation, the micro gas turbine power generation is connected to the power grid through the inverter. The opening and closing of the converter switch circuit will result in the harmonic component of the switching frequency to be injected into the distribution network, and the harmonic distortion will occur in the voltage waveform. In this paper, the total harmonic distortion rate index (THD_u) is chosen to quantitative the impact degree of harmonic distortion, and the calculation method is as follows.

$$THDu = \frac{\sqrt{\sum_{h=2}^{H_{\max}} {U_h}^2}}{U_1} \times 100\% \tag{4}$$

Where U_h is the RMS of the n_{th} harmonic voltage, U_1 is the RMS of fundamental voltage. H_{max} is the highest harmonics considered.

2.2.5. Power supply reliability

The power supply reliability calculation of distribution network with the access of DG is different from that of traditional distribution network. Due to the uncertainty and randomness of DG output power, the power supply reliability calculation method of distribution network with DG is complicated. In previous studies, the output power of DG is generally considered as constant value to calculate the power supply reliability. This method simplifies the computation process, but results in less accurate calculation of power supply reliability. In this paper, the output power of DG and load power adopt the time correlation model. The strategies used in the calculation are as follows. First, the output power of DG and load power at the moment of failure are calculated according to the time correlation model. Second, the power supply reliability calculation of distribution network with DG is carried out by considering the island operation mode of DG. The fault frequency and failure time of the load point are calculated by simulating the failure of components in the distribution network. The average service availability index (ASAI) is adopted in this paper. The calculation method of ASAI is as follows [19-20].

$$ASAI = 1 - \frac{\sum_{i \in R} U_i N_i}{\sum_{i \in R} 8760 N_i} \tag{5}$$

Where, U_i is the annual average duration of power failure of load point i; N_i is the number of users of the load point *i*.

2.2.6. Short-circuit capacity

The integration operating method of DG will provide short-circuit current to the fault point. When the access capacity of the DG reaches a certain degree, it may make the relay protection of the distribution network unable to make the correct action. The short-circuit capacity index S_c is selected to measure the security of distribution network with DG in this paper, and the calculation formula is as follows [21-22].

$$S_c = \sqrt{3} U I_f \tag{6}$$

Where, U is the bus voltage; I_f is the largest short circuit current.

2.2.7. Relay protection

The previous studies of the influence of DG access on relay protection of distribution network are studied and analyzed, and we find that the influences on the protection of fuse are mainly about two aspects. On the one hand, because of the three section current protection based on the circuit breaker of the traditional distribution network, the access of DG may destroy the coordination relationship of the setting value and setting time of protective elements. On the other hand, the reverse short-circuit current can cause the failure of the fuse, leading to the loss of reliability of relay protection [23-25].

In this paper, a three grade quantization model of relay protection is adopted [26]. When there is no DG access to distribution network, p_i=100. If the access of DG does no affect the normal operation of relay protection, p_i=90. If the access of DG affects the sensitivity of protection, but does not affect the correctness of the protection, p_i=75. Finally, if the access of DG leads to the mal-protection or refusal of protection, p_i=60.

3. Comprehensive evaluation method

3.1. Calculation method of index weight

Analytic hierarchy Process (AHP) is an effective method for quantitative analysis of non quantitative events and for objective analysis of subjective judgment. The basic idea of AHP is to decompose complex problems by establishing clear hierarchy structure. The calculations of indices which can describe the influence of DG on the distribution network are illustrated in section 2 and the weights of each index need to be determined in the comprehensive evaluation. The indices can not be compared directly because of the different factors such as dimension, quantity level and evaluation standard. The utility analysis method is adopted to obscure each index into a unified dimensionless index for comparison.

Based on the 1-9 reciprocal scaling theory [27], AHP compares each index and constructs the judgment matrix E. If the consistency test formula satisfies the formula (7), the consistency of matrix E can be accepted.

$$\mathrm{CR} = \frac{\lambda_{\max} - N}{(N-1)\mathrm{RI}} < 0.1 \tag{7}$$

Where: is the maximum eigenvalue of matrix E; *N* is the number of evaluation objectives, RI presents the average random consistency index. Then, the weight coefficient of evaluation objective x is computed by (8):

$$w_x = \frac{\prod_{y=1}^{N} e_{xy}}{\sum_{x=1}^{N}\prod_{y=1}^{N} e_{xy}^{\frac{1}{N}}}, 0 < w_x < 0.1 \tag{8}$$

Where e_{xy} represents the relative important value of index S_X to S_Y, w_x represents the weight coefficient of index.

3.2. Fuzzy Comprehensive evaluation method

Because of the difference of dimension, evaluation standard and nature of each index, it is unreasonable to compare each index directly. In this paper, the utility transformation method is used to get the index function to obscure the indexes, and to eliminate the factors such as the dimension of each index and the evaluation standard, then indices can be compared with each other under an unified dimension.

By using the weight coefficient and the utility value of each index, the comprehensive evaluation score of the scheme can be obtained, and the calculation formula is

$$S = \frac{100\sum_{x=1}^{N} w_x U_x}{M} \tag{9}$$

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Where *S* represents the final score of a scheme; U_x represents the utility value of the index; set M=1; the minimum score of the scheme is 0, the maximum is 100.

4. Case Study

4.1. Case instruction

To verify the evaluation index and method proposed in this paper, the main feeder F4 of IEEE-RBTS BUS6 system is taken as an example to simulate different DGs integration. The system structure is shown in Figure1. The voltage base value of the test system is 10 KV, the convergence precision is 10-4, LGJ-150 conductor is used in the system, and there are 23 load points, 26 nodes, 30 lines, 14 breakers, 22 isolation switches and 13 fuses.

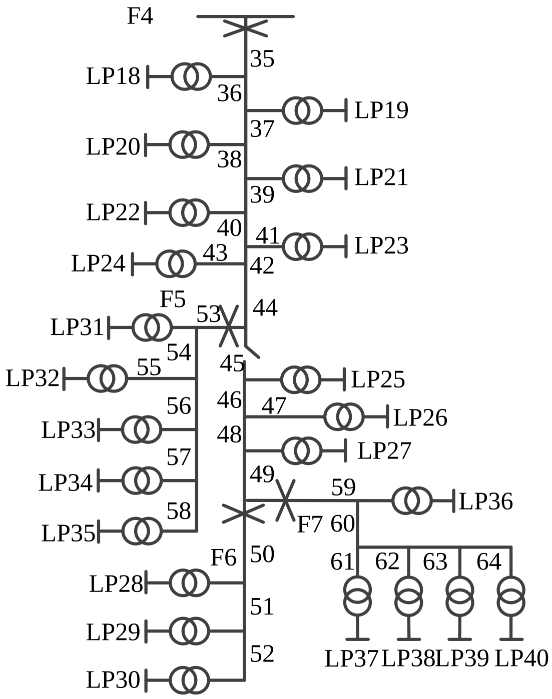

Figure 1. Test distribution network

Four scenarios of DG access plan are simulated in this paper. In Scenario 1, the access location and capacity of DGs are: LP30, 200kW; LP35, 200kW; LP40, 100kW. In Scenario 2, the access location and capacity of DGs are: LP22, 400kW; LP27, 400kW; LP30, 360kW; LP35, 360kW; LP40, 400kW. In Scenario 3, the access location and capacity of DGs are: LP22, 800kW; LP27, 900kW; LP30, 900kW; LP35, 900kW; LP40, 800kW. In Scenario 4, the access location and capacity of DGs are: LP22, 1000kW; LP25, 990kW; LP27, 1000kW; LP30, 990kW; LP35, 990kW; LP40, 1000kW.

Assuming that the system is completely reliable, the component failure rate data of the test system is shown in table.1 and the simulation results are shown in table.2.

Table 1. Equipment reliability data

Equipment	Fault rate	Fault time/h
line	0.050/km a	4
transformer	0.015/a	200
breaker	0.002/a	4

Table 2. The Results of Different Indices

Index	Case 1	Case 2	Case 3	Case 4
Active power unit cost	4.48	4.14	3.98	3.91
Grid loss (MW)	0.79345	0.18695	0.16670	0.15880
Voltage pass rate	99.62%	99.98%	99.54%	99.24%
Total harmonic distortion rate	1.55%	1.62%	1.73%	1.82%
Power supply reliability	99.9465%	99.9787%	99.9811%	99.9816%
Short-circuit capacity	54.63	82.97	104.48	123.62
Relay protection	III	II	I	I

From the above table we can see that, the active power unit cost index and the grid loss index are getting lower as the access capacity of DGs increased. Thus, the integration of DGs improves the economic efficiency of distribution network. Because the randomness and instability of distributed power output power, with the increase of the access capacity of wind power and photovoltaic power generation, the influence of the output power of DGs on the voltage passing rate index of distribution network becomes bigger. So the voltage pass rate index presents a trend that increases first and decrease later. The opening and closing of the converter switch circuit of the converter-based DG will result in the switching frequency harmonic to be injected into the distribution network. Similarly, the total harmonic distortion rate index of distribution network with DG rises with the increase of the incorporation capacity of converter-based DGs.

Compared with scenario 1, the power supply reliability index of scenario 2 increases obviously. But the improvement degree of power supply reliability index of scenario 3 and scenario 4 is less obvious. When the power outrage occurs in the distribution system, DGs can operate in the isolated operation model, which ensures the reliability of the power supply for critical loads. So the power supply reliability of scenario 2, 3, 4 will increase. The reliability of distribution network is not only related to the access capacity of DG, but also to the components and network structure, so the increase of the index value of distribution network with higher access capacity is less obvious. The higher the access capacity of DG, the larger the short-circuit current and short-circuit capacity is provided. At the same time, the influence of relay protection on power distribution system is also increased. So measures to reduce the short-circuit capacity and the effect on relay protection should be adopted.

The score value of each index can be obtained by the calculation of nonlinear scoring function. The index weight calculated by AHP is as follows: 0.1160, 0.1465, 0.1081, 0.1081, 0.2193, 0.1563 and 0.1457. According to the index weights and scores, the comprehensive evaluation values of four scenarios are shown in table.3.

Table 3. Comprehensive evaluation values of different scenarios

Solution	Comprehensive Evaluation Value
Scenario 1	76.41
Scenario 2	87.23
Scenario 3	81.27
Scenario 4	79.38

From the comprehensive evaluation values of four scenarios, it can be seen that seven index values of distribution network with proper access capacity of DG are obviously improved. The comprehensive evaluation value of Scenario 2 is the highest, indicating that the comprehensive performance is the best. The access capacity of DGs of scenario 3 and scenario 4 is too large, which lead to serious impacts on the total harmonic distortion rate, short-circuit capacity and relay protection index of distribution network, so the improvement degree of comprehensive evaluation score is smaller than that of scenario 2.

5. Conclusion

(1) A comprehensive evaluation system fitting the practical demand of distribution network is proposed in this paper, which is based on the situation of various DGs integration, such as wind power and PV. The index system is composed of 7 indexes, active power unit cost, grid loss, voltage pass rate, total harmonic distortion rate, power supply reliability, short-circuit capacity and relay protection of distribution network. Through the calculation method of each index, a reasonable comprehensive score is obtained, and the result can be used as the basis of the network planning scheme.
(2) Different DGs integration to distribution network under proper access capacity can effectively improve the economic performance, voltage quality and safety index of distribution network, thus the comprehensive evaluation score of the distribution network can be improved. When the access capacity of DG is too high, some security and power quality problems will occur, such as ultra short circuit capacity, high harmonic distortion rate and large voltage fluctuation and so on.
(3) The comprehensive evaluation of future active power distribution network not only needs to consider the access of high penetration rate of DG, but also the new-type load, combined heat and power, and so on. It is necessary to reconsider the setting of the comprehensive evaluation index system and the calculation methods of the indexes, etc.

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