PLANNING OF FLEXIBLE POWER SOURCES IN POWER DISTRIBUTION SYSTEMS WITH HIGH PENETRATION OF DISPERSED GENERATION

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ABSTRACT

With the wide application of dispersed generations (DG), power distribution systems are transferring from passive to active. Acting as important composition of DG, wind turbine (WT) and photovoltaic (PV) are developing quickly in these years for their clean and renewable. In high penetration scenarios, as the power outputs of WT and PV are uncontrollable, the volatility and inter-mittency of WT and PV power make the net load curve a "duck curve", and the flexibility and ramping needs become significant, which may threaten the security and reliability of power system operation. Thus, to allocate enough flexible power sources are essential. Based on the definition of power system flexibility, the characteristics of power system flexibility and flexible sources are first analyzed. Then, a quantitative evaluation model of power system flexibility, which appears in a probability form, is proposed and solved using Monte Carlo simulation method. After that, on the basis of flexibility improvement, the siting and sizing problems of flexible sources are discussed. Finally, case studies are made on the IEEE 33-bus test system to verify the validity of the model and method proposed, and several conclusions are obtained.

INTRODUCTION

Conventionally, power distribution systems do not have power sources. Step-down substations from the higher voltage level are regarded as their power sources. In recent years, a large number of dispersed generations (DG) are accessed to power distribution systems, which changes power distribution systems from passive to active. Wind turbine (WT) and photovoltaic (PV) are regarded as the most potential DG to be developed in large scale[1]. However, due to the instant changing of natural conditions, the output power of WT and PV are uncertain. The uncertainty must be balanced by other power sources to guarantee the real-time balance between power supply and demand. Thus, the penetration rate of DG is limited. Research found that the maximum penetration rate of DG is about 30% under present conditions.

To further increase the penetration rate of DG, efforts should be made from two aspects. One is to upgrade present power distribution networks, both from power source and from power network, to adapt the larger uncertainty of DG. The other is to enhance the control of present power distribution networks, such as demand side response, network reconfiguration, etc. The former is called "network solutions", while the later is called "non-network solutions". In this paper, the upgrade of power source is discussed.

As it is mentioned above, due to the uncertainty of DG, the power distribution network should have enough response ability to balance the uncertainty. Such response ability is called as "flexibility".

This paper first introduces the definition and character-ristics of power system flexibility. Then, a flexibility evaluation index is proposed and verified on the siting and sizing problems of flexible sources.

HIGH PENETRATION SCENARIOS OF DG

To develop renewable energy in a large scale has been the consensus of all countries to reduce greenhouse gas emission and control air pollution. In this process, DG will be the main form. However, the power outputs of such DGs are uncertain, which has been a new challenge of modern power systems.

Although DG outputs are uncertain, theirs distribution rule can be mathematical described from statistics. The most common used rules are that wind speed obeys Weibull distribution, and light intensity obeys Beta distribution in a long time scale, while they both obeys normal distribution in a short time scale.

For the uncontrollable of DG outputs, the net load curve[2], which is the difference between load curve and DG output curve, replaces the initial load curve, and becomes the analysis object in high penetration scenarios. Figure 1 is the load, wind, solar profiles of California in April 2020, forecasted by California independent system operator (CAISO).

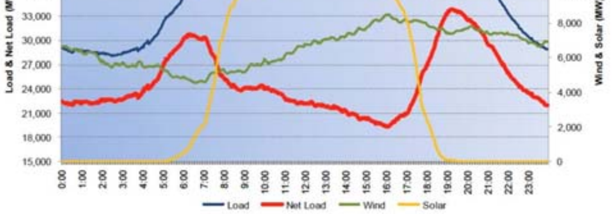

Figure 1: Load, wind, solar profiles of California in April 2020, forecasted by CAISO

In this figure, compared with the initial load curve (blue curve), the net load curve (red curve), which is called as a "duck curve", appears more changeable. It means that the flexibility and ramping needs are more significant both in rate and duration.

POWER SYSTEM FLEXIBILITY

Definition of power system flexibility

The definitions of power system flexibility are not the same from different organizations.

North American Electric Reliable Corporation (NERC) defined power system flexibility as the ability to satisfy the change of power loads using system resources. Power system flexibility mainly reflects in system operation[3].

International Energy Agency (IEA) defined that a power system is flexible if it can – within economic boundaries – respond rapidly to large fluctuations in demand and supply, both scheduled and unforeseen variations and events, ramping down production when demand decreases, and upwards when it increases[4].

Besides, definition and discussion on power system flexibility can be found in other references[5].

Obviously, the definition from IEA is more suitable for power distribution systems with high penetration of DG.

Description of power system flexibility

Broadly speaking, flexibility is an intrinsic of power system; it has directions; and it must be evaluated at a determined time scale. All power system equipments or control methods that can response the uncertainty of DG output can be regarded as flexibility resources.

There are three main characteristics of power system flexibility.

1) Flexibility is an intrinsic of power system. Power systems are born with flexibility as the designed power source capacity is always larger than the peak load.
2) Power system flexibility has its directions. The ramping down ability (when DG output increase or power load decrease) corresponds to downward flexibility, while the ramping upwards ability (when DG output decrease or power load increase) corresponds to upward flexibility.
3) As the response speed of variety flexibility resource is different, power system flexibility must be evaluated at a determined time scale.

Usually, {1min, 10mins, 15mins, 60mins} are chosen as the time scales that evaluate power system flexibility. The reason is that 1min and 10mins are the time scale that chosen to limit the maximum active power fluctuation of wind farm under normal operating conditions in China National Standard GB/T 19963-2011 (see Table 1), while 15mins is usually the shortest time scale for wind forecasting, and 60mins is the time scale for short-term dispatching of power systems. Of course, the time scale can be changed if necessary.

Table 1: Maximum active power change permission of wind farms under normal circumstances

Installed Capacity / MW	Maximum Active Power Change Permission in 10mins / MW	Maximum Active Power Change Permission in 1min / MW
<30	10	3
30~150	Installed Capacity/3	Installed Capacity/10
>150	50	15

Obviously, the lack of ramping down ability can be balanced by the curtailment of DG outputs, which is a problem of economy. On the contrary, the lack of ramping up ability can only be balanced by load shedding, which is problem of security and reliability. To avoid such situations, enough flexible sources are essential.

Flexible sources in power system

Flexibility resources in power system mainly include:

1) Slow-response flexible power source, such as thermal power plant, hydropower plant, etc;
2) Fast-response flexible power source, such as gas turbine, energy storage system, etc;
3) Demand side management, such as demand response, interruptible load (IL), etc;
4) Regional interconnected power grid;
5) Flexible AC transmission system (FACTS).

Among the flexibility resources in power system mentioned above, the 2nd kind flexibility resource is the main method to improve the flexibility of power distribution networks from the power source side. With the continuous increase of DG penetration, such flexible power sources are essential. However, the species and capacity are difficult to choose. The planning scheme should satisfy the system's flexibility requirements in variety time scales with a best economy.

Below is a very brief assessment of several flexible power sources, which means they may change with technology development. For example, with the continuous decreasing of battery energy storage cost, its duration may be much longer than present.

Table 2: Assessment of several flexible power sources

Type	Capacity	Ramping	Duration	Life
Gas turbine	medium	medium	longest	medium
Battery storage	smallest	fastest	shortest	shortest
Pumped-storage	largest	slowest	medium	longest

FLEXIBILITY EVALUATION

Mathematical model

From the analysis above, once the time scale of flexibility evaluation is determined, the flexibility evaluation index (*FEI*) of a power distribution system can be defined as the probability that flexibility resources satisfy the flexibility requirements. Taking the upward flexibility as an example, the index can be described as follows.

$$FEI_{\Delta t}^{U} = \Pr\left\{P_t^{sp} - \Delta P_{\Delta t} + R_t^{U} \cdot \Delta t \geq P_{t+\Delta t}^{dm}\right\}$$

Where $FEI_{\Delta t}^{U}$ refers to the upward *FEI* under time scale Δt ; P_t^{sp} refers to the power supply in the t moment; $\Delta P_{\Delta t}$ refers to the power decrease of DG in the next Δt period; R_t^{U} refers to the upward ramping ability of the system in the t moment; $P_{t+\Delta t}^{dm}$ refers to the power demand in the $t+\Delta t$ moment.

Solution algorithm

Mento Carlo simulation method is used to calculate the *FEI*. The calculation steps are as follows.

1) Initialization: basic system data, siting and sizing of WT, PV and flexible sources; set simulation times N_{max}, set n=0 and s=0;
2) Generate a random scenario, in which the active change of each WT or PV obeys normal distribution, as well as the national standard;
3) Use optimal power flow calculation tool to judge whether the flexibility need can be satisfied? If yes, s=s+1; if no, continue;
4) Does the simulation end? If yes, $FEI = s$ / N_{max} and end; if no, return to the 2nd step;

In step 3), optimal power flow calculation is used to judge whether the power flow can converge, considering both the ramping need from DGs and ramping ability from flexible sources.

The calculation flow chart is as follows.

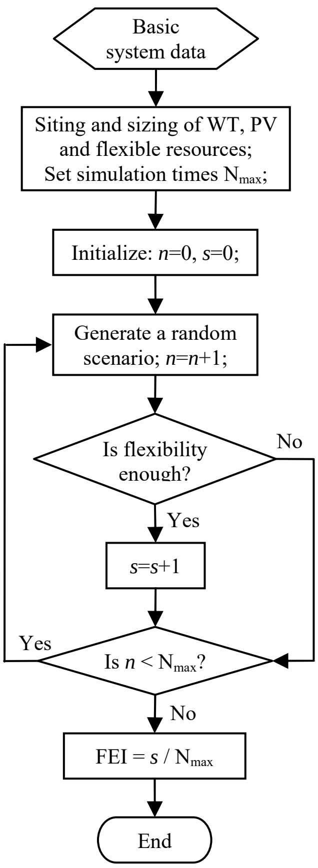

Figure 2: Calculation flow chart of the flexibility evaluation index

FLEXIBILITY IMPROVEMENT

Using the evaluation index proposed above, both the upward and the downward flexibility of the system can be evaluated under different time scales. Then, according to the evaluation results, the species and capacity of flexible power sources planning can be defined using an optimization model. The objective function of the model is as follows.

$$\min \quad \sum_{i=1}^{n} z_i \cdot P_{Gi}^{N} \cdot C_i \cdot k_i$$

Where n refers to the species of flexible power resource; z_i is the decision variable, z_i=1 for build and z_i=0 for not build; P_{Gi}^{N} refers to the installed capacity of the i^{th} species of flexible power resource; C_i refers to the cost of a unit capacity; k_i is the conversion factor, which mainly decided by the operation life and maintenance cost of the equipment.

And the constraints include both the *FEI* expectation constraint and other conventional constraints, where the *FEI* expectation constraint is that the system *FEI* is not less than a given value FEI_{exp}.

$$FEI_{\Delta t}^{U} = \Pr\left\{P_t^{sp} - \Delta P_{\Delta t} + R_t^{U} \cdot \Delta t \geq P_{t+\Delta t}^{dm}\right\} \geq FEI_{exp}$$

Obviously, this is not a simple single objective optimization model. Details of the model and its solution algorithm will be discussed in other paper.

CASE STUDY

Case study is made on the IEEE 33-bus distribution test system. The diagram of the system is shown in Figure 3. Total load of the system is (20+j9.8) MVA, and the load distribution is shown in Table 3.

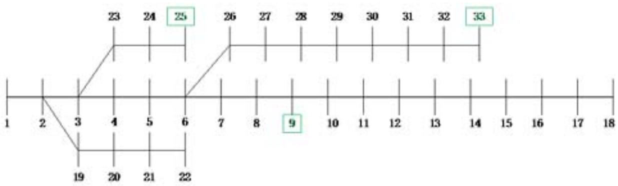

Figure 3: Diagram of IEEE 33-bus test system

Table 3: Bus load distribution

Bus No.	Load / MVA	Bus No.	Load / MVA	Bus No.	Load / MVA
1	0.63+j0.42	12	0.31+j0.18	23	0.47+j0.26
2	0.52+j0.31	13	0.31+j0.18	24	2.19+j1.04
3	0.47+j0.21	14	0.62+j0.42	25	2.19+j1.04
4	0.63+j0.42	15	0.31+j0.05	26	0.31+j0.13
5	0.31+j0.16	16	0.31+j0.10	27	0.31+j0.13
6	0.31+j0.10	17	0.31+j0.10	28	0.31+j0.10
7	1.04+j0.52	18	0.47+j0.21	29	0.63+j0.37
8	1.04+j0.52	19	0.47+j0.21	30	1.04+j0.52
9	0.31+j0.10	20	0.47+j0.21	31	0.78+j0.37
10	0.31+j0.10	21	0.47+j0.21	32	1.10+0.52
11	0.23+j0.16	22	0.47+j0.21	33	0.31+j0.21

Three WTs are installed on bus 9, 25 and 33, respectively. Their installed capacity and maximum active power change permission are listed in Table 4.

In this case study, WTs are regarded as half output and their power factors are 0.95. Meanwhile, only their active power changes are considered.

Table 4: Siting, type, and sizing of the DGs

Bus No.	Type	Installed Capacity (MW)	Maximum Active Power Change Permission (MW)
9	WT	8	3
25	WT	12	3
33	WT	10	3

Assume that one flexible source with ramping ability 30%PG/min is installed on ten different bus with three different installed capacities (24MW, 26MW, 28MW, respectively). The *FEI*s calculated using the method mentioned above is shown in Table 5.

Table 5: *FEI* with different siting and sizing of a flexible source

Capacity / Location	24MW	26MW	28MW
bus 3	95.22%	98.38%	99.72%
bus 6	95.87%	98.76%	99.73%
bus 10	88.08%	93.83%	96.72%
bus 11	87.66%	92.37%	96.25%
bus 12	85.12%	90.61%	94.93%
bus 19	94.21%	97.97%	99.46%
bus 23	94.25%	98.06%	99.46%
bus 24	91.21%	95.74%	98.52%
bus 25	95.02%	98.41%	99.71%
bus 26	94.98%	97.87%	99.45%

To make the results clearer, results in Table 4 is described in Figure 4.

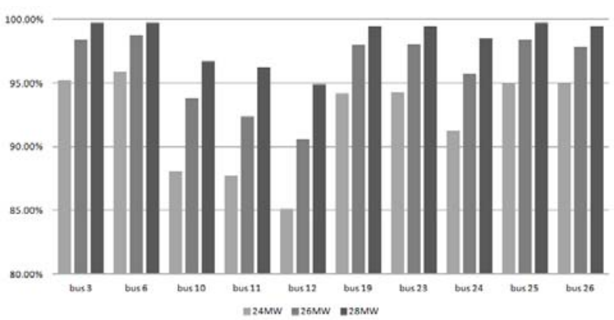

Figure 4: *FEI*s under different siting and sizing of a flexible source

From Table 4 and Figure 4, they show that also the installed capacity of the flexible source is much bigger than the net active load, even can support all the load, ramping need dissatisfactory still occurs at a certain probability. Because the maximum possible ramping need is 9MW/min, while the maximum ramping ability of the flexible source is 7.2MW/min for the 24MW generator, 7.8 MW/min for the 26MW generator, and 8.4 MW/min for the 28MW generator.

Meanwhile, *FEI* appears different when the flexible source is installed on different buses. Comparatively speaking, bus 3, 6, 23, 24, 25 and 26 seem better than other buses. Actually, bus 3, 23, 24 and 25 are buses those close to the WT bus 25, while bus 6 and 26 are buses those close to the WT buses both 9 and 33.

CONCLUSIONS

Flexibility is an intrinsic of power system. With the continuous increasing of DG penetration in power distribution networks, it is more and more brought into focus. A power system flexibility evaluation index based on probability is proposed, and according to the flexibility requirements in different time scales, the species and capacity in flexible power source planning can be defined with an optimal economy. And some conclusions are made as follows.

1) To reduce the system ramping dissatisfactory, the ramping ability of the flexible sources are more important than their installed capacities.
2) Different siting of the flexible sources may bring different flexibility benefits. A general suggestion is that flexible sources should be installed close to uncontrollable DGs such as WT or PV.

Further, as the *FEI* is an index defined using probability, the optimal planning of flexible sources is a problem needs further study.

Acknowledgments

We thank the financial supported from National Natural Science Foundation of China (51407117) and the “Yangfan Program” of Shanghai, China (14YF1410100).

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