Uncertainty Analysis in the Power Grid Operation with Renewable Energy Generations

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Abstract. The renewable energy sources such as wind power and solar energy are widely interconnected to the current power network. The proportion of the renewable resources to the entire energy sources in the power grid is increasing. Since wind power and solar energy are intermittent, which have more uncertain factors, power grid operation is being impacted by generation of the renewable energy sources. Especially in the area of power balance and dispatch. Severe power imbalance, which causes the huge frequency deviation, will lead to the stability of power system. Therefore, it is very important to deal with the uncertainties of renewable energy. The existing deterministic approaches are not sufficient to deal with the uncertain factors. This paper analyzes the effect of renewable energy uncertainties in power grid operation based on the fuzzy theory and probabilistic methods. The steady-state security analysis is taken as an example to handle renewable energy uncertainty in power grid operation.

1. Introduction
At present, the global fossil energy is increasingly exhausted. Renewable energy is from natural resources such as sunlight, wind, tides, water and geothermal heat, which are clean and renewable. Therefore, developing renewable energy is an important approach to solve energy crisis and environmental pollution. The grid connected generation of renewable energy such as wind and solar energy not only reduces the fuel cost of power generation, but also plays an important role in environmental protection. Thus, the renewable energy generations such as wind power and solar energy are widely used in many countries in the world \([1-2]\). Some countries have issued preferential policies to develop new energy. In this case, the proportion of the renewable energy installed in the power system is rapidly increasing. For example, China’s wind power developing is quickly increasing in the recent years, and now is number one in the world. China invests heavily in wind power in recent years. Figure 1 shows the investment scale of China’s wind power from 2013 to 2019. The capacity of China’s new installed wind power is rapidly increasing. It is increased every year, and reached 220GW in 2019. Figure 2 shows the capacity of China’s new installed wind power from 2013 to 2019 \([3]\).

However, the renewable energy sources such as solar energy and wind power are intermittent, which have more uncertain factors. These uncertainties will add difficult to accurately predict the output of wind power and solar energy \([4-8]\). Consequently, power system power balance and grid operation are impacted by the uncertainties of the renewable energy sources. Severe power imbalance, which causes the huge frequency deviation, will lead to the stability of power system. The improper power dispatch may impact the economy and security of power grid operation. It is necessary and also extremely important to analyze and deal with the uncertain factors in renewable energy. The existing deterministic approaches are not sufficient to deal with this kind of uncertainty. Various methods have been proposed
to solve the uncertainties of renewable energy in the areas of wind power or solar energy forecasting, wind power dispatch, and integrated energy system operation [9-21].

![Figure 1](image1.png)

**Figure 1.** The investment scale of China’s wind power during 2013 – 2019

![Figure 2](image2.png)

**Figure 2.** The capacity of China’s new installed wind power during 2013 – 2019

The major idea in uncertainty analysis is adoption of the subjective probabilities. The corresponding method has been developed in recent years, and there are many significant advances in all kinds of areas. Certainly, probabilistic methods are also used to solve power system operation problems with uncertainty, which can overcome the disadvantages of deterministic criteria. Probabilistic power flow (PPF) is an example to solve power flow problem using probabilistic approach. It gives the whole picture of all probable values of output results such as power flows and bus voltages, which considering the load uncertainty and generation unit unavailability [22-24]. However, it should be noted that the purpose of introducing probabilistic methods into system operation is to add one more dimension to enhance system operation rather than replacing the traditional deterministic approaches. There is no conflict between deterministic and probabilistic methods since these two kinds of approaches are applied at different situations and/or scenarios in power system operation. This paper analyzes the effect of renewable energy uncertainties in power grid operation based on the fuzzy theory and probabilistic methods. The proper approaches to handle renewable energy uncertainty in power grid operation are recommended.

2. Uncertainty analysis of renewable energy

The fundamental element of power grid operation is power balance, that is, total generations must meet the requirements of load demands in the system. Otherwise, there will be a problem of power system stability. With the development of power grid, a large amount of generation sources is connected to power grid. Especially, some new generation sources such as wind power and solar energy are very different with the traditional generations based on fossil energy. Although these new energies are environmentally-friendly and no pollution, they are volatility, intermittent and stochastic, which have characteristic of uncertainty.

Figure 3 shows the output sequence of measured wind power in one day in a wind farm. It can be observed from Figure 3 that the wind power fluctuates during 24 hours. The wind power output is controlled by the amount of wind. The wind power can be zero if there is no wind in some time. Due to the uncertain factors, connecting the renewable energy to grid brings big challenge to power system operation.
operation. This is because power balance must be met at any time \( t \) and all generators will operate within their capacity limits, that is,
\[
\sum P_{i,t} = P_{L,t} + D_t, \quad i \in G_T, G_{gas}, G_H, G_w
\]
\[
P_{G_{min},t} \leq P_{G_{i},t} \leq P_{G_{max},t} \quad i \in G_T, G_{gas}, G_H, G_w
\]

where
- \( P_{G_{i},t} \): outputted real power for generator \( i \) at time \( t \);
- \( G_T, G_{gas}, G_H, G_w \): thermal, gas, hydro and wind power generator unit, respectively;
- \( P_{G_{min},t} \): the lower limit of real power of generator \( i \);
- \( P_{G_{max},t} \): the upper limit of real power of generator \( i \);
- \( P_{L,t} \): the system real power losses at time \( t \);
- \( D_t \): the total load demand at time \( t \).

The fluctuation of wind power or solar energy will impact power balance (i.e. system frequency stability) as well as power system economic dispatch. The effect of renewable energy on grid operation is mainly manifested in the following aspects: 1) in-dispatchable. It causes imbalance power. 2) random. It increases difficult and uncertainty to grid operation. and 3) anti-peak regulation. It causes abandon of wind/solar/water since all generations can be over the load demands and thermal power units may reach their lower limits.

To solve the problem of instability in wind power generation, power electronic technology can be used to organize the integration of physical components and convert wind energy into electrical energy in the form of alternating current. Since the peak time of wind power output is not the same as peak load time in the power system, the battery or storage device can be used to store the wind power when it is redundancy in some time period. To enhance the accuracy in renewable energy forecasting, the prediction technology needs to establish a relationship model between the partial factors for the node system structure. It is necessary to combine the historical data of renewable energy sources and the machine learning based on big data to update the correlation model between weather, power generation, power consumption, and comprehensively aggregate the predicted data of node energy schedulability.

3. Analysis of grid operation with renewable energy
With the increasing penetration of renewable energy generations in power grid, the uncertainties of renewable energy must be highly addressed, since these uncertainties affect power grid operation. Thus, it is very important and urgent to investigate the uncertainties of renewable energy and to develop efficient and reliable methods to reflect them in power grid operation such as power flow, security assessment, economic dispatch in power systems. A general method to analyze uncertainty is based on the distribution of an input parameter through a model. It does not use a point value for a parameter. The
distributions mentioned above for the input parameters are able to be produced from a number of sources, e.g., experimental data, phenomenological models, or a combination of the experimental data and different models.

The probabilistic behavior of power systems has been recognized for a long time. Probabilistic system reliability evaluation methods have been well developed in the past decades. They are mainly used in probabilistic power system planning. Recently, probabilistic methods have been used to analyze the problems related to power system operation. This paper takes power flow security analysis as an example to analyze grid operation with uncertainty.

Power flow calculation is a basic analysis in power system operation. Generally, the input variables such as power output of generation sources, and load power of load demand (real and reactive load) are assumed known in power flow calculation. However, since the outputs of renewable energy sources are uncertain, which make power flow calculation have uncertain input variables. In this case, a probabilistic approach or a fuzzy approach can be adopted to solve this situation. Probabilistic power flow is mainly based on the mean and variance of uncertain variables. Fuzzy power flow (FPF) uses fuzzy number to deal with the uncertainty. In addition, a fuzzy-stochastic power flow (FSPF) may be a better method to conduct power flow calculation with uncertain input variables, since in the practical power systems, some load is fuzzy one in some case [25], and some load is stochastic [24], or some load is both fuzzy and stochastic.

Power flow calculation is a basis to study steady-state security analysis [26]. Steady-state is one of power grid operation states. The steady-state security is to make sure the system parameters such as frequency and voltage unchanged. However, it is very hard to reach this ideal state since the load demands and generator output power are dynamic varied. If the imbalance power causes a big frequency or voltage deviation, the system stability will be impacted (system may be collapsed in the worst case). Thus, it is very important to study steady-state security through using all kinds of means. Since a great amount of repeated power flow studies are needed in security analysis, as well as there exist load changes and uncertain power generation (i.e., solar energy and wind power with the uncertainty), the complexity of the security assessment problem and required computation burden will be increased greatly. To reduce the computation amount of the steady-state security assessment, the concept of “steady-state security regions” (SSSR) is proposed. One approach for SSR is to compute a ‘hyper-box’ to approximately express the steady-state security regions. Furthermore, an expanding method to obtain the hyper-box has been developed, which tends to the maximal region [27-29].

The expressions of power flow calculation can be written as follows.

\[ P_i = V_i \sum_{j=1}^{n} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \]  \hspace{1cm} (3)

\[ Q_i = V_i \sum_{j=1}^{n} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \]  \hspace{1cm} (4)

where

\( P_i \): active power injection connecting to bus \( i \);
\( Q_i \): reactive power injection connecting to bus \( i \);
\( V_i \): the bus voltage vector;
\( \theta_i \): the angle of voltage;
\( B_{ij} \): the susceptance of branch \( ij \).

The SSSR can be expressed by a set of power injections or generator outputs through solving the above-mentioned power flow equations (3) and (4) as well as network security constraints, that is

\[ R_p = \{ P \mid \exists \theta \in R, \text{and } (f_p(\theta) = P) \in R \} \]  \hspace{1cm} (5)

\[ R_Q = \{ I \mid \exists \mathcal{V} \in R, \text{and } (f_q(\mathcal{V}) = I) \in R \} \]  \hspace{1cm} (6)

where

\( R_p \): the real power steady-state security regions;
\( R_Q \): the reactive power steady-state security regions;
\( R \): the set of real and reactive security constraints;
\( f \): the set of power flows.
Since some variables in equations (3)-(6) are uncertainty, the existing deterministic methods and tools cannot be directly adopted to solve the above-mentioned power flow calculation and steady-state security analysis. The following steps will be used to solve this issue.

- A maximal SSSR (hyper-box) with uncertain unknown variables is formed by use of the lower and upper limits of each component in the grid. These limits are also called as security constraints of grid operation. They are generators capacity limits, transformer constraints and transmission line constraints.

- Fuzzy theory is used to handle the uncertain variables first. A LR type fuzzy number can be applied to express the uncertain variables. Generally, either a triangular or trapezoid LR fuzzy number is adopted.

- Optimization methods such as linear programming (LP) is applied to solve the model of the SSSR hyper-box. The optimization objective is to obtain the maximal steady-state security regions under the grid security constraints. Actually, the model of SSSR is nonlinear. It is needed to linearize the SSSR constraints and convert the nonlinear SSSR model into the linear model, so that we can use LP to solve it.

- The maximal SSSR with the adjustment ranges of a set of power injections or generator units is obtained. Obviously, the adjustment range of each generator unit must be within the limits of the unit capacity, that is

\[
(P_{G\text{M}}^i - P_{G\text{m}}^i) \leq (P_{G\text{max}}^i - P_{G\text{min}}^i) \tag{7}
\]

where
\[
P_{G\text{max}}^i: \text{the upper limit of the generator unit capacity};
\]
\[
P_{G\text{min}}^i: \text{the lower limit of the generator unit capacity};
\]
\[
P_{G\text{M}}^i: \text{the upper bound of the adjustment range of the unit } Gi;
\]
\[
P_{G\text{m}}^i: \text{the lower bound of the adjustment range of the unit } Gi.
\]

4. Example

IEEE 30 bus system is often adopted in power system analysis. Herein, we use it to compute the steady-state security regions of power system with renewable energy. The data of IEEE 30 bus system is taken from reference [30]. The system has 5 generators, 21 loads and 43 transmission branches (including transformers and transmission lines). The generators may be wind power units, which are connected on buses 2, 5, 8, 11 and 13, respectively. The capacity of each generator unit is listed in Table 1, where

\[
P_{G\text{max}}^i \text{ stands for the upper limit of the unit capacity, and } P_{G\text{min}}^i \text{ stands for the lower limit of the unit.}
\]

According to the steps of section 3, we form the steady-state security regions model by handling the uncertain variables and linearizing the security constraints. Through solving the linearized SSSR model using CPLEX Optimization tool, the results of steady-state security regions for IEEE 30 bus system are shown in Figure 4.

In Figure 4, each graph stands for the upper and lower limits of a unit capacity as well as the adjustable range (the maximal SSSR) of the unit. The top of red part and the top of crimson (or the bottom of yellow part) in the graph are corresponding to the upper and lower limit of the generator capacity, respectively. The green box is the calculated maximal SSSR for IEEE 30 bus system, where the top of green and bottom of green part (or top of yellow part) are corresponding to the upper and lower limit of the SSSR, respectively. The yellow part is within the capacity limits of the generator unit., but outside of the maximal SSSR. For units PG5 and PG11, there is no yellow part. It means that both the lower limits of unit capacity and its maximal SSSR are the same. For units PG8, PG11 and PG13, their maximal SSSRs reach the upper limits of unit capacities. Thus, the top of red part is the same as the top of green part for these units in the graph. Anyway, The SSSR adjustment range of each generator unit (green box) is always within the capacity limits of the generator unit.
Table 1. Generator Data of 30-bus system

| Generator units | PG2 | PG5 | PG8 | PG11 | PG13 |
|-----------------|-----|-----|-----|------|------|
| P_{Gimax} (MW)  | 80  | 50  | 35  | 30   | 40   |
| P_{Gimin} (MW)  | 20  | 15  | 10  | 10   | 10   |

5. Conclusion
The rapid development of renewable energy brings huge challenge to power system operation. This paper discussed the characteristics of the uncertainty of the renewable energy, which are volatility, intermittent and stochastic. It analyzed the impact of renewable energy on grid operation: 1) in-dispatchable, which causes imbalance power. 2) random, which increases difficult and uncertainty to grid operation. and 3) anti-peak regulation, which causes abandon of wind/solar/water. This paper took power flow security analysis as an example to analyze grid operation with uncertainty. The issue of steady-state security region of power grid operation is addressed based on fuzzy theory and linear programming method. IEEE 30 bus system is taken as example to demonstrate the results of steady-state security region.

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