Fuzzy comprehensive evaluation for grid-connected performance of integrated distributed PV-ES systems

Z H Lv1,3, Q Li1, R W Huang2, H M Liu2 and D Liu1

1Jiangsu Electric Power Research Institute, Nanjing 211103, China
2College of Energy and Electrical Engineering, Hohai University, Nanjing 211100, China
E-mail: 517480859@qq.com

Abstract. Based on the discussion about topology structure of integrated distributed photovoltaic (PV) power generation system and energy storage (ES) in single or mixed type, this paper focuses on analyzing grid-connected performance of integrated distributed photovoltaic and energy storage (PV-ES) systems, and proposes a comprehensive evaluation index system. Then a multi-level fuzzy comprehensive evaluation method based on grey correlation degree is proposed, and the calculations for weight matrix and fuzzy matrix are presented step by step. Finally, a distributed integrated PV-ES power generation system connected to a 380 V low voltage distribution network is taken as the example, and some suggestions are made based on the evaluation results.

1. Introduction
Photovoltaic (PV) power generation, one of the widespread new energy generations, offers great convenience to remote areas or rural areas, where extension of power grid is infeasible or uneconomic. At the same time, with natural unpredictability and randomness, PV vastly accesses to the grid brings greater challenges for safe, reliable and efficient operation of the power grid. Energy storage (ES) technologies can improve instability of PV generation output, whose principle is to restrain fluctuation of voltage and frequency in grid-connected operation mode through rapid active and reactive control, so that the output power of new generations remains stable within a certain range of time [1][2]. Energy storage technologies can be divided into mechanical energy storage, electromagnetic energy storage and chemical energy storage [3][4]. At present, there are more and more extensive and in-depth researches on ES technologies all over the world.

The random fluctuation of distributed PV generation output distributes on wide-area time scale from millisecond to hour, it is hard to meet the demand of multiple time scale power restrain of distributed energy for single energy storage technology [5]. The battery energy storage is used to restrain fluctuation of PV in [6], which results in too large charging current of battery, polarization and abscission of active material in the electrode. If combination of energy storage technologies about super capacitor and battery with strong complementary in performance, that is to take advantage of large rated power of super...
capacitor and large rated capacity of battery ES, and optimize charging and discharging strategy of them to extends their life, then the total life-cycle costs would be decreased obviously.

Study on evaluation for grid-connected performance of PV is rather mature. Many aspects of the impacts on load characteristics, power grid scheduling, voltage and reactive power, those come from the large-scale PV power accessed to the grid, was analyzed in [7]. Voltage offset and power flow change with different capacity PV generation connected to the grid were studied in [8][9]. The impacts of grid-connected PV systems in large-scale and high-voltage on security and stability of power grid was analyzed in [10].

Although these well-done studies have certain guiding significance for the evaluation of the grid-connected performance of integrated PV-ES systems, it does not consider all the impacts of PV-ES systems, distributed power and new energy generation systems, and the testing standard and evaluation system of PV with ES have not been established.

This paper gives two typical topologies of distributed integrated PV-ES systems, and proposes a more comprehensive performance index evaluation system combining with current ES technologies. Grey correlation is introduced to form a multi-level fuzzy comprehensive evaluation model together with the ambiguity function theory [11], which combines both advantages of grey correlation and fuzzy comprehensive evaluation.

2. Analysis on typical topologies of distributed integrated PV-ES systems

The integrated PV-ES system is usually composed of the PV array, ES device, DC/DC converter and loads. ES is mainly divided into four categories: electrochemical energy, physical energy, electromagnetic energy and phase-change energy. The typical technical parameters of them are listed in Table 1. According to the table, battery is not suitable for high power and frequent charging/discharging due to its big energy density, small power density, short cycle life, low charge/discharge efficiency and sensitive to the charge/discharge process. Super capacitor is not suitable for large-capacity situation due to its lower energy density, which is 30% of the battery, but it can be applied to frequent charge and discharge cycle due to their high power density, long cycle life and high charge/discharge efficiency. The two ES technologies have strong complementarities. Lots of literatures state that the hybrid energy storage system can make use of the complementary characteristics of battery and super capacitor, so as to improve power output capability, reduce losses, increase charge and discharge times, and extend the life of the battery.

Table 1. Typical technical parameters of different energy storage technologies

| ES Types              | Energy Density /kWh·m⁻³ | Power Density /kW·m⁻³ | Conversion Efficiency % | Smallest Unit Capacity /kWh | Cycle Life Year /a |
|-----------------------|--------------------------|-----------------------|-------------------------|-----------------------------|-------------------|
| Superconducting Magnetic ES | 178                      | 1000.0                | 96                      | 500                         | 30                |
| Super Capacitor       | 53                       | 176700                | 94                      | 1.0                         | 30                |
| Flywheel ES           | 424                      | 1766.8                | 90                      | 4.0                         | 30                |
| Lead-acid Battery     | 7.07                     | 106                   | 92                      | 0.5                         | 8                 |
| Lithium Battery       | 212                      | 212                   | 88                      | 5.0                         | 7                 |
| Acid Battery          | 243.7                    | 550.0                 | 88                      | 5.0                         | 7                 |

Two kinds of typical topologies of integrated PV-ES system including single ES and hybrid ES technologies are analyzed here, and the topologies are show in Figure 1.

(1) Single Integrated PV-ES System

Typical integrated PV-ES system is composed of PV array, battery, bidirectional DC-DC converters, DC-AC converter, photovoltaic power control system and ES control system and so on. The DC-DC
converter followed by PV array is a boost converter and its main function is to take Maximum Power Point Tracking (MPPT) control of PV output power and keep voltage of DC bus stable.

(2) Hybrid Integrated PV-ES System

Compared with single integrated PV-ES system, hybrid integrated PV-ES system has other type ES units apart from battery. Among which the more representative one is composed of battery and super capacitor (SC). PV power control system mainly controls output voltage to maximize output power. Hybrid energy storage control system regulates active power output of PV power station, and regulates two bi-directional DC-DC transform devices for distribution of active power between battery and SC, then achieves the optimal solution of charging and discharging process.

3. Grid-connected performance index system of distributed integrated PV-ES systems

Grid-connected performance, especially output power quality, is the key to scale application of solar PV generation system. Existing grid-connected performance evaluation indexes of PV power system mainly include: principles accessing the system, power quality, power control, voltage regulation, characteristics of voltage, current and frequency, security, relaying protection and safety automatic equipments, communication and information, energy metering and grid-connected detection and so on. Among them,

- Indexes of power quality mainly includes: harmonics, voltage deviation, voltage fluctuation and flicker, unbalanced three-phase voltage, electromagnetic compatibility, etc.
- Indexes of power control and voltage regulation mainly includes: active power control, voltage/reactive power regulation, starting and stopping, etc.
- Indexes of characteristics of voltage, current and frequency mainly includes: voltage response, frequency response, overflow response, maximum permissible short-circuit current, etc.
- Indexes of relaying protection and safety automatic equipment mainly includes: component protection, system protection, anti-islanding protection, fault information, grid-connected recovery, etc.

Addition of ESS has greatly improved power quality, such as harmonic, voltage deviation, voltage fluctuation and flicker and so on. Based on the above grid-connected performance indexes, a novel grid-connected performance indexes of integrated PV-ES system is proposed, as shown in table 2.

| First Grade Index        | Second Grade Index                  |
|--------------------------|-------------------------------------|
| S1: Power Characteristic | S11: Active Power Output            |
|                          | S12: Power Factor                   |
|                          | S13: Active Power Control           |
|                          | S14: Reactive Power Control         |

Figure 1. Topology of integrated PV-ES system

Table 2. Grid-connected performance index system of the integrated PV-ES system
4. Grid-connected performance comprehensive evaluation

Comprehensive evaluation is a multi-disciplinary technology. The performance factors of distributed PV-ES system are more and miscellaneous, and it is hard to determine existing interaction between different factors and the index values quantitatively. This paper proposes a comprehensive evaluation method based on grey correlation degree and fuzzy evaluation theory. The grey correlation degree is applied in fuzzy comprehensive evaluation to achieve weights of indexes about distributed grid-connected PV-ES, which effectively overcomes the respective defects, and enjoys the advantages of both at the same time.

4.1. Method and process of comprehensive evaluation

Fuzzy evaluation is a method that gives the possibility of a certain specific comment according to some special criteria. Considering factors about grid-connected performance of distributed PV-ES system, this paper quantifies the original qualitative evaluation for some important factors based on their importance degrees.

The improved grey correlation method is introduced here to calculate the weights of indexes. The weight experience judgment values from experts is considered as the original data to carry on pure further numerical calculation, and it makes full use of sub-index information of experts experience judgment, which causes the weight coefficients impartially. The whole evaluation process is divided into two steps, the first step is to obtain the fuzzy matrix $T$, and then to obtain the weight matrix $A$, finally the fuzzy comprehensive evaluation result $S$ is obtained by fuzzy matrix $T$ multiplying weight matrix $A$. The comprehensive evaluation process is shown in Figure 2.
4.2. Calculation of weight matrix $A$

(1) Suppose that $m$ experts make experience judgment for $n$ evaluation index weights, and to form data columns as follows:

$$X = [X_1, X_2, \ldots, X_n]^T = \begin{bmatrix} x_1(1) & x_1(2) & \cdots & x_1(m) \\ x_2(1) & x_2(2) & \cdots & x_2(m) \\ \vdots & \vdots & \ddots & \vdots \\ x_n(1) & x_n(2) & \cdots & x_n(m) \end{bmatrix}$$  \hspace{1cm} (1)

(2) Select the biggest weight from $X$ as the reference one $X_0$.

$$X_0 = [x_0(1), x_0(2), \ldots, x_0(m)]$$  \hspace{1cm} (2)

(3) Calculate the distance between each row weight index $X_i, i=1, \ldots, n$, and the reference one $X_0$.

$$D_{0i} = \sum_{k=1}^{m} [x_i(k) - x_0(k)]^2$$  \hspace{1cm} (3)

(4) Calculate the weight of each index $\omega_i$.

$$\omega_i = \frac{1}{1 + D_{0i}}$$  \hspace{1cm} (4)

(5) Calculate the normalization weight of each index $\omega'_i$, and $A = [\omega'_1, \omega'_2, \ldots, \omega'_n]^T$.

$$\omega'_i = \frac{\omega_i}{\sum_{i=1}^{n} \omega_i}$$  \hspace{1cm} (5)
4.3. Calculation of fuzzy matrix $T$ and comprehensive evaluation result $S$

(1) Determine each index factor set $U$;
(2) Determine the evaluation grade $P$, $P$=$\{\text{Excellent, Good, Average, Barely Passed, Unqualified}\}$ = $\{\text{E, G, A, P, U}\}$;
(3) Determine the membership degree of every grade evaluation index quantitatively, and to form fuzzy matrix $T_{uu}$;
(4) Calculate the evaluation value $S$ as follows,

$$S = T \cdot A = [s_1, s_2, s_3, s_4, s_5]$$

The value $S$ is the indexes in single layer. If there is more than one level in the index system, it should be calculated from the base level to the top level one by one, and the evaluation results of all grade indexes can be obtained.

5. Analysis of example

An integrated PV-ES system accessed to 380 V low voltage distribution network is selected as the simulation case to analyze grid-connected performance.

5.1. Calculation of weight matrix $A$

According to the statistics with experience judgment given by 23 experts, the weight of each index by improved grey correlation degree is achieved level by level according to equation (1) to (5), the indexes in first level include: power characteristic, power quality, response characteristic, security and protection, and system characteristic, shown in table 3.

| First level index | Weights | Second level index | Weights |
|-------------------|---------|--------------------|---------|
| S1                | 0.275   | S11                | 0.348   |
|                   |         | S12                | 0.278   |
|                   |         | S13                | 0.237   |
|                   |         | S14                | 0.137   |
| S2                | 0.247   | S21                | 0.18    |
|                   |         | S22                | 0.18    |
|                   |         | S23                | 0.171   |
|                   |         | S24                | 0.157   |
|                   |         | S25                | 0.15    |
|                   |         | S26                | 0.162   |
| S3                | 0.194   | S31                | 0.132   |
|                   |         | S32                | 0.125   |
|                   |         | S33                | 0.128   |
|                   |         | S34                | 0.109   |
|                   |         | S35                | 0.108   |
|                   |         | S36                | 0.109   |
|                   |         | S37                | 0.105   |
|                   |         | S38                | 0.185   |
| S4                | 0.143   | S41                | 0.18    |
|                   |         | S42                | 0.18    |
|                   |         | S43                | 0.171   |
|                   |         | S44                | 0.159   |
|                   |         | S45                | 0.149   |
|                   |         | S46                | 0.161   |
5.2. Calculation of Fuzzy Evaluation

According to industry standards, measuring calculation data and experts evaluation statistics, the assessment grades \{E, G, A, P, U\} can be determined. Here a single example, the membership statistic results of power quality are shown in table 4.

| Second Level Indexes | Measuring/Calculation Data | Industry Standards | Grade membership |
|----------------------|-----------------------------|--------------------|------------------|
| S21                  | 1.8                         | [0, 4.0]           | E: 0.5, G: 0.3, A: 0.2, P: 0, U: 0 |
| S22                  | 5%                          | [-7%, +7%]         | E: 0.2, G: 0.5, A: 0.3, P: 0, U: 0 |
| S23                  | 0.8%                        | [0, 1.3%]          | E: 0.3, G: 0.4, A: 0.2, P: 0.1, U: 0 |
| S24                  | 2.5                         | [0, 4]             | E: 0.2, G: 0.2, A: 0.3, P: 0.3, U: 0 |
| S25                  | 0.8                         | [0, 1]             | E: 0.1, G: 0.2, A: 0.3, P: 0.4, U: 0 |
| S26                  | 0.3%                        | [0, 0.5%]          | E: 0.2, G: 0.3, A: 0.3, P: 0, U: 0 |

\(^{a}\) the allowed distortion rate of harmonic current when the number of odd harmonic \( \leq 11\);

\(^{b}\) the limit of voltage fluctuation when the voltage variable frequency \( \leq 1\).

Then the fuzzy matrix of power quality is

\[
T_e = \begin{bmatrix}
0.5 & 0.2 & 0.3 & 0.2 & 0.1 & 0.2 \\
0.3 & 0.5 & 0.4 & 0.2 & 0.2 & 0.3 \\
0.2 & 0.3 & 0.2 & 0.3 & 0.3 & 0.3 \\
0 & 0 & 0.1 & 0.3 & 0.4 & 0.2 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

Combined with improved grey correlation analysis presented above, we can calculate the corresponding index weight and fuzzy evaluation:

\[
S_t = T_e \cdot A_s = \begin{bmatrix} 0.2561 \ 0.3224 \ 0.2649 \ 0.1566 \ 0 \end{bmatrix}^T
\]

According to the principle of the maximum membership, evaluation result of power quality characteristic about grid-connected performance of distributed integrated PV-ES generation system is good.

Similarly, fuzzy evaluation results of power characteristic, response characteristic, security and protection, system characteristic on distributed integrated PV-ES generation system are obtained as follows,

\[
S_1 = [0.3745 \ 0.4374 \ 0.1644 \ 0.0237 \ 0]^T
\]

\[
S_2 = [0.2237 \ 0.3089 \ 0.3227 \ 0.1457 \ 0]^T
\]

\[
S_3 = [0.6931 \ 0.2749 \ 0.0320 \ 0 \ 0]^T
\]

\[
S_4 = [0.3473 \ 0.3946 \ 0.2054 \ 0.0527 \ 0]^T
\]

Evaluation results of the second grade index are \{G, G, A, E, G\}. Similarly, the first level indexes are carried out as follows,

\[
S = T \cdot A = [0.3577 \ 0.3548 \ 0.2068 \ 0.0809 \ 0]^T
\]
According to the principle of the maximum membership, fuzzy comprehensive evaluation result about grid-connected characteristic of the distributed integrated PV-ES generation system is excellent, the comprehensive performance is nice and it is recommended.

In order to observe the effect of ES bringing to the grid-connected performance of integrated PV-ES systems, the capacity of ES is designed as half. The specific measurement data and membership degrees are as shown in Table 5.

| Second Level Indexes | Measuring/Calculation Data | Grade membership |
|----------------------|-----------------------------|-------------------|
|                      |                             | E    | G    | A    | P    | U    |
| S21                  | 3.2                         | 0    | 0.1  | 0.5  | 0.4  | 0    |
| S22                  | 6%                          | 0    | 0.1  | 0.4  | 0.5  | 0    |
| S23                  | 1.1%                        | 0    | 0    | 0.5  | 0.5  | 0    |
| S24                  | 3.2                         | 0    | 0.1  | 0.3  | 0.6  | 0    |
| S25                  | 0.85                        | 0    | 0.2  | 0.5  | 0.3  | 0    |
| S26                  | 0.4%                        | 0.1  | 0.1  | 0.4  | 0.4  | 0    |

The calculation process is similar to the previous. Due to the limitation of length, no more tautology will be here. The final evaluation result $S'$ is as follows:

$$S' = T' \cdot A' = \begin{bmatrix} 0.0162 & 0.0979 & 0.4344 & 0.4515 & 0 \end{bmatrix}^T$$

And the comprehensive evaluation result is Barely Passed, it shows that the configuration of ES is not optimal, and it should not be recommended.

### 6. Conclusion
As for the distributed integrated PV-ES generation system, the grid-connected performance evaluation index system was established, and the comprehensive assessment method based on fuzzy evaluation theory and grey correlation degree was proposed. The simulation results show that ES could greatly improve the grid-connected performances of distributed PV power generation system. How to determine the optimal configuration of hybrid ES and realize the control strategy of PV-ES system need to be further studied.

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