Establishment of key grid-connected performance index system for integrated PV-ES system

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Abstract. In order to further promote integrated optimization operation of distributed new energy/energy storage/active load, this paper studies the integrated photovoltaic-energy storage (PV-ES) system which is connected with the distribution network, and analyzes typical structure and configuration selection for integrated PV-ES generation system. By combining practical grid-connected characteristics requirements and technology standard specification of photovoltaic generation system, this paper takes full account of energy storage system, and then proposes several new grid-connected performance indexes such as paralleled current sharing characteristic, parallel response consistency, adjusting characteristic, virtual moment of inertia characteristic, on-grid/off-grid switch characteristic, and so on. A comprehensive and feasible grid-connected performance index system is then established to support grid-connected performance testing on integrated PV-ES system.

1. Introduction

In recent years, solar energy and wind energy as the representative for new energy have been increasingly developed and applied all over the world. Because grid-connected power generation system of new energy with intermittent and random has great impact on stable operation of power grid, new energy power generation system with energy storage devices has attracted more and more attention, whose development and scale of production have been gradually expanded. While the corresponding testing method and testing standard for their grid-connected performance are relatively lagging, which has become a barrier to new energy and energy storage integrated power generation system for industrial production and scale application.

The existing technologies on inverter unit for grid-connected new energy are relative mature, such as maximum power point tracking (MPPT) efficiency, power quality, low voltage ride through and so on. In Southern California of United States, Edison power company proposed improvement suggestions about performance of photovoltaic (PV) inverter from the point of view of high penetration adapting to PV power generation system through analysis on the test data of three-phase 480 V AC commercial photovoltaic inverters [1]. NTUA laboratory gave performance test methods of PV inverters for current...
test standard of PV inverters by testing their characteristics under different operating conditions in Greece and Cyprus [2]. Dutch Energy Research Association gave test results and overall evaluation of six commercial photovoltaic inverters whose capacity was up to 5 kW in terms of energy conversion efficiency, power point tracking efficiency, power quality and electromagnetic compatibility and so on [3]. In order to meet the needs of the development of new energy and power system, IEC 61727-2004 [4], IEEE 1373-1999 [5] and IEEE 1547-2003 [6] were published one after another. These technical standards are proposed mainly from the system level based on the new energy power generation system, while the test standards and evaluation system based on both the new energy power generation and energy storage system (ESS) have not been completed.

To promote coordination development between solar power and power grid, the State Grid Corporation of China had unveiled the “State Grid Corporation Technical Regulations of PV Power Plants Connection to the Grid (Trial)” in July 2009, and had formally released Q-GDW 617-2011 [7] and Q-GDW 618-2011 [8] successively in 2011, which made clear requirements of technical indexes and test regulations about response characteristic, anti-islanding protection characteristic, power output characteristic, power quality indexes as well as other general performance of middle and small scale grid-connected PV power stations, and made detailed technical regulations of all aspects about grid-connected characteristic of ESS in distribution network, whose voltage is 35 kV and below, in 2010 [9]. After that, Electric Power Research Institute of China (CEPRI) had developed a test platform of grid-connected photovoltaic inverters [10], and analyzed power quality of photovoltaic power generation system in terms of test conditions, test methods and test results [11]. Meanwhile, CEPRI went on studying and simulating by means of two test methods on the PV inverter low voltage ride through [12], and analyzed the basic structure and operation mode of PV inverter [13]. Tianjin Electric Power Research Institute of China inspected performance of grid-connected inverter equipments through the construction of test platform of grid-connected inverters and improved related test standards [14]. State Grid Electric Power Research Institute of China (SGEPRI) had developed mobile test platform of small PV power plant, which can test grid-connected performance and power station’s general performance of grid-connected PV power station, whose rated capacity does not exceed 200 kW and grid-connected voltage level is 380 V [15].

Different from wind power, photovoltaic and other new energy, the integrated distributed photovoltaic and energy storage (PV-ES) system is weakly connected with the distribution network, and its grid-connected performance is relevant lower. On the basis of grid-connected characteristic of current photovoltaic generation system, ESS and active load is bound to affect the dynamic grid-connected characteristic of the whole system. The following issue is how to detect grid-connected performance of distributed PV-ES.

The existing grid-connected performance indexes on distributed generation, PV station and energy storage system cover a lot of aspects, such as in-grid principle, electric power quality, power control, voltage regulation, frequency characteristics, safety and reliability, relay protection, communication, electricity measurement and grid-connected detection, etc. Several novel indexes suitable for distributed integrated PV-ES system are proposed in this paper, such as “paralleled current sharing characteristic”, “parallel response consistency”, “adjusting characteristic”, “virtual moment of inertia characteristic”, “on-grid/off-grid switch characteristic”, and so on. These novel indexes will effectively develop the grid-connected performance indexes of the PV-ES system, and have important significance for the scientific evaluation of the grid-connected characteristics of the integrated PV-ES system.

2. Configuration determination of integrated PV-ES system
In order to improve conversion efficiency of PV-ES and voltage stability of the DC buses, and optimize charging and discharging control of energy storage, four typical topological structures of integrated
distributed PV-ES system, shown in Figure 1, are comparatively analyzed, and their main advantages and disadvantages are assembled in Table 1.

![Figure 1. (a)](image1)

![Figure 1. (b)](image2)

![Figure 1. (c)](image3)

![Figure 1. (d)](image4)

**Figure 1.** Four typical configurations of PV-ES

**Table 1.** Comparatively analysis of four typical configurations of PV-ES

| Configuration Types                  | (a)  | (b)  | (c)  | (d)  |
|--------------------------------------|------|------|------|------|
| PV Utilization Ratio                 | high | lower| high | high |
| PV Grid-Connected Efficiency         | high | low  | high | lower|
| ES Charging Efficiency               | high | high | high | low  |
| ES Discharging Efficiency            | low  | high | high | lower|
| Complexity                           | low  | low  | high | low  |
| Controllability                      | high | low  | high | high |
| Whether to Recommend                 | yes  | no   | no   | yes  |

A typical demonstration pilot in China selected type (b), it contains 250 kVA voltage-source inverters, 150 kVA inverter with dual-mode and 150 kW charging controller. This configuration has the following advantages:

- The maximum charging efficiency of PV-ES is up to 98.5%;
- The maximum discharging efficiency of energy storage is up to 95.7%;
It has the technologies of centralized parallel operation control, mode smooth switching and protection. But this topology has the following problems:

- In order to control voltage of battery, charging control of battery and MPPT control of PV will not be taken into account under some certain conditions, which results in a waste of photovoltaic energy;
- Energy management systems (EMS) cannot dispatch and control directly the energy storage devices, which increases the coupling degree of system and causes the system to more difficulty realize optimization on efficiency of PV and economic operation of energy storage.

It can be seen in table 1 that four topologies have their own advantages and disadvantages in terms of the utilization ratio of PV, charging/discharging efficiency of PV-ES, system complexity and controllability. There is a big disadvantage on efficiency of PV in type (b), and EMS cannot dispatch and control directly the energy storage devices, which decreases the coupling degree of system, it is difficult to realize the aim about economical operation control of energy storage; type (c) has the highest utilization ratio of PV and charging/discharging efficiency of PV-ES, but it is difficult to form standardized products and the operation condition is complex. By contrast, there are only some disadvantages in type (a) and (d) in terms of discharging efficiency of energy storage, but utilization ratio of PV and controllability of system is higher. Therefore, the comprehensive performances of type (a) and (d) are better.

3. The key performance indexes on the integrated PV-ES system

Grid-connected performance and output power quality of PV generation system are the key factors for scale application. Grid-connected performance indexes on the integrated PV-ES system remain the same with the basic requirements of the traditional PV generation system after it accesses ESS. Meanwhile, new problems about grid-connected characteristic are also proposed.

3.1. Grid-connected performance indexes of traditional PV system

Existing grid-connected performance evaluation indexes of PV system mainly contain principles of accessing system, power quality, power control, voltage regulation, related characteristic of voltage, current and frequency, security, relay protection and security automatic equipment, communication and information, energy metering and grid-connected detection and so on. Among them,

- **Power quality indexes**: voltage deviation, frequency deviation, voltage fluctuation and flicker, unbalance of three-phase voltage, harmonic, DC component, and electromagnetic compatibility, and so on;
- **Power control and voltage regulation indexes**: active power control, voltage/reactive power regulation, and start-stop, and so on;
- **Characteristic of voltage, current and frequency indexes**: voltage response, frequency response, over-current response, and maximum permissible short-circuit current, and so on;
- **Relay protection and security automatic equipment indexes**: element protection, system protection, anti-island protection, fault information, recovery grid-connected protection, and so on.

The indexes of power quality are selected as example in this paper.

(1) Voltage Deviation

According to the GB/T 12325-2008 “Power Quality Power Supply Voltage Deviation” [16], below 20 kV three-phase voltage deviation is ±7% of nominal voltage, and 35 kV and above voltage deviation does not exceed ±10% of nominal voltage.

(2) Frequency Deviation
According to the GB/T 15945-2008 “Power Quality Power System Frequency Deviation” [17], normal frequency deviation is ±0.2 Hz, and especially, frequency deviation is ±0.5 Hz when the system capacity is small.

(3) Voltage Fluctuation and Flicker

According to the GB/T 12326-2008 “Power Quality Voltage Fluctuation and Flicker” [18], voltage fluctuation, denoted by $d$, is the difference between the adjacent two extreme voltages in the curve $V_u(t)$, the square root value of voltage, which is expressed as a percentage of system voltage in table 2.

### Table 2. Voltage fluctuation limit

| $r$ (times/h) | $d$% | LV<sup>a</sup> or MV<sup>b</sup> | HV<sup>c</sup> |
|---------------|------|-------------------------------|---------------|
| $r \leq 1$    | 4    | 3                             |               |
| $1 \leq r \leq 10$ | 3       | 2.5                           |               |
| $10 < r \leq 100$ | 2        | 1.5                           |               |
| $100 < r \leq 1000$ | 1.25    | 1                             |               |

According to the GB/T 156-2007, grades of nominal voltage $U_N$ are divided as follows:

- **a** Low Voltage (LV): $U_N \leq 1$ kV
- **b** Medium Voltage (MV): $1$ kV < $U_N \leq 35$ kV
- **c** High Voltage (HV): $35$ kV < $U_N \leq 220$ kV

(4) Unbalance of Three-Phase Voltage

According to the GB/T 15543-2008 “Power Quality Three-Phase Voltage Unbalance” [19], at the common connection point between PV-ES and power grid, unbalance of negative sequence voltage does not exceed 2% and especially, it does not exceed 4% if time is short.

(5) Harmonic Current

According to the GB/T 14549-1993 “Power Quality Public Power Grid Harmonic” [20], the limit of the Total Harmonic Distortion (THD) of current is THD $\leq 5\%$ and the limits of odd harmonic and even harmonic current ratio are shown in table 3.

### Table 3. Limits of harmonic current ratio

| Harmonic Number | Limits of Ratio (%) |
|-----------------|---------------------|
| **Odd Harmonic** |                     |
| $3^{th}$ - $9^{th}$ | 4.0                  |
| $11^{th}$ - $15^{th}$ | 2.0              |
| $17^{th}$ - $21^{th}$ | 1.5              |
| $23^{th}$ - $33^{th}$ | 0.6                |
| above $35^{th}$ | 0.3                |
| **Even Harmonic** |                     |
| $2^{th}$ - $10^{th}$ | 1.0                 |
| $12^{th}$ - $16^{th}$ | 0.5              |
| $18^{th}$ - $22^{th}$ | 0.375          |
| $24^{th}$ - $34^{th}$ | 0.15            |
| above $36^{th}$ | 0.075             |

(6) DC Current Component

According to Q/GDW 617-2011 [7], Q/GDW 564-2011 [9] and Q/GDW 480-2010 [21], for converter type distributed power resources such as PV and ESS, the DC current feeding into the grid should not be more than 0.5% of its AC current value.
3.2. The novel grid-connected performance indexes

Addition of ESS has greatly improved the power quality issues, such as harmonic, voltage deviation, voltage fluctuations and flicker and so on. Several new indexes are proposed for grid-connected performance of the integrated PV-ES system.

3.2.1. Paralleled current sharing characteristic

Paralleled current sharing characteristic refers to automatic balance and sharing of currents withstood by all the distributed power branches. In order to improve reliability of the system, do not add any additional control of external current sharing as far as possible. When the input of voltage or load current changes, voltage should be kept stable, transient response of current sharing is good. Numerically, paralleled current sharing $PCS$ is as reciprocal of unbalance $S$.

$$PCS = S^{-1} = \left| \frac{I_k}{I_{k\text{max}}} - \frac{I_{PCC}}{\sum_k I_{k\text{max}}} \right|^{-1} \times 100\%$$  \hspace{1cm} (1)

where, $k=1,\ldots,K$, $k$ and $K$ are the number of the distributed power supply branch and the total number of its branch respectively, $I_{PCC}$ is current of public connection point, $I_k$ and $I_{k\text{max}}$ are the current and its maximum value of the $k^{th}$ distributed power supply branch respectively.

3.2.2. Parallel response consistency

Parallel response consistency $PRC$ of distributed PV-ES integration device refers to when other technical parameters are same, response deviation of each parallel branch should be kept within a certain small range under the same excitation. Its value can be expressed as the reciprocal of response deviation $\delta$ of each branch.

$$PRC = \delta^{-1} = \left( \sum_{k=1}^{K} R_k = \frac{\sum_{k=1}^{K} R_k}{N} \right)^{-1}$$  \hspace{1cm} (2)

where, $R_k$ is response of the $k^{th}$ distributed power supply branch when excitation of public connection point is given.

3.2.3. Adjusting characteristic

When active or reactive power of PV-ES integration device is above 20% total rated output, the device should be able to achieve continuous smooth regulation of active or reactive power, and participate in controlling active or reactive power of the system. The differential coefficient of active power $k_p$ and the differential coefficient of reactive power $k_q$ are as follows.

$$k_p = \frac{\Delta f}{\Delta P} \times 100\%$$  \hspace{1cm} (3)

$$k_q = \frac{U_0 - U_R}{U_N} \times 100\%$$  \hspace{1cm} (4)

where, $\Delta f$ is the variation of frequency of power grid, $\Delta P$ is the variation of active power of distributed power supply, $U_0$ is the terminal voltage of the distributed power supply without any load, $U_R$ is the terminal voltage when reactive current was rated, $U_N$ is rated terminal voltage of the distributed power supply.

3.2.4 Virtual Moment of Inertia Characteristic

In order to improve the stability of total power grid, the control strategy of energy storage converter is designed to simulate the droop characteristic of the synchronous generator and the moment of inertia of the generator rotor based on virtual synchronous machine technology, which produces the virtual inertia to participate in grid frequency regulation, so as to realize the steady support of the grid voltage and frequency.
Once the system frequency deviated from the rated value due to the system power supply or load demand changes, the integrated PV-ES system changes the power output following the frequency modulation auxiliary power value. The output variation of PV and ESS will result in the frequency regulation ability of the integrated PV-ES system, that’s virtual inertia response capability. The virtual inertia index is noted as \( H_{PV,ES} \), which is kept as a constant in converter control system, and it can be described as

\[
H_{PV,ES} = \frac{\Delta P_{pv} + \Delta P_{ES}}{\Delta f}
\]  

(5)

where, \( \Delta f \) is the frequency deviation, \( \Delta P_{pv} \) and \( \Delta P_{ES} \) are the corresponding output change of PV and ESS respectively. If the MPPT strategy is adopted in PV’s converter, \( \Delta P_{pv} \) was kept zero, the total virtual moment of inertia is only decided by the response performance of ESS’s converter.

3.2.5 On-Grid/off-Grid Switch Characteristic

In normal in-grid operating mode, the distributed integrated PV-ES system connected into the grid in parallel. When some fault occurs in power grid or power quality is terrible, the distributed integrated PV-ES system is switched into isolating operating mode. After the fault restoration, the integrated PV-ES system would re-connect into the grid. In normal in-grid operating mode, the P/Q control strategy is selected to inject active power to grid. While in isolating operating mode, the U/f control strategy comes into operation to maintain an acceptable level of voltage and frequency for the distributed integrated PV-ES system. Some key parameters of the converter can be used to picture the On-Grid/off-Grid Switch Characteristic, such as rated input voltage of DC bus, rated input voltage of AC side, rated grid-connected frequency, efficiency of the whole machine, overload ratio, and so on.

3.3. Grid-connected performance index system

According to the above analysis, this paper puts forward two layers index system on grid-connected performance evaluation of the integrated PV-ES system. Among which, the upper layer contains power characteristic S1, power quality S2, response characteristic S3, security and protection S4 as well as system characteristic S5, the comprehensive index system is shown in table 4.

| Table 4. Grid-connected performance evaluation index system of the integrated PV-ES system |
|---------------------------------|---------------------------------|
| First Grade Index              | Second Grade Index              |
| S1: Power Characteristic       | S11: Active Power Output        |
|                                 | S12: Power Factor               |
|                                 | S13: Active Power Control       |
|                                 | S14: Reactive Power Control     |
| S2: Power Quality              | S21: Harmonics in Public Supply Networks |
|                                 | S22: Admissible Deviation of Supply Voltage |
|                                 | S23: Three Phase Voltage Unbalance Factor |
|                                 | S24: Voltage Fluctuation and Flicker |
|                                 | S25: Permissible Deviation of Frequency |
|                                 | S26: Temporary and Transient Overvoltage |
| S3: Response Characteristic    | S31: Voltage Response           |
|                                 | S32: Frequency Response         |
|                                 | S33: Over-current Response      |
|                                 | S34: Maximum Permissible Short Circuit Current |
The above index system is more comprehensive. Based on the index system, some methods can be used to go on stratified evaluation, such as Analytic Hierarchy Process (AHP) and fuzzy evaluation and so on. AHP is a decision-making methods combined with qualitative and quantitative analysis, and it takes elements decomposed into goals, guidelines, programs and other levels. The fuzzy comprehensive evaluation uses the fuzzy mathematics method based on certain criteria, gives the possibility of each item which is usually affected by multiple factors. In this paper, the possibility refers to the pros and cons of one index or overall performance of the distributed integrated PV-ES system. Therefore, real grid-connected performance of the integrated PV-ES power generation system can be evaluated comprehensively.

4. Conclusion
At present, the integrated PV-ES power generation system is very popular all over the world, but it still lacks grid-connected performance testing and evaluation criteria. By comparing and analyzing the existing schema of PV-ES system, this paper further carries on improving utilization ratio of PV, and charging and discharging efficiency of PV-ES and system configuration with reducing complexity of system. In the basis of existing grid-connected performance testing index of PV, several novel performance indexes are proposed to evaluate the integrated PV-ES power generation system, which effectively develops existing evaluation indexes, and finally a more comprehensive grid-connected performance index system on the integrated PV-ES power generation system has formed.

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