Dynamic islanding strategy regarding sustainable on-load capacity of photovoltaic/energy-storage hybrid system in microgrid

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Abstract. To measure sustainable loading capacity of photovoltaic/energy-storage system, indexes for sustainable loading power margin and energy margin are defined. With this basis, a dynamic islanding strategy for distribution system with photovoltaic/energy-storage system is proposed. The reliability assessment algorithm of the distribution network is improved based on Monte Carlo Simulation, by considering the fluctuation of PV output and load demand. Finally, it conducts a reliability assessment for modified RBTS Bus6, and results of simulation show that the proposed strategy can ensure continuous and stable operation of important loads within Micro-Grid, and enhance the reliability of distribution network.

1. Introduction

In order to make distributed generation (DG) play a better role in its power supply, standard IEEE1547.4-2011 encourages conscious islanding operation. It is pointed out that planning islanding should take dynamic characteristics, switching strategy of micro-power supply and load into consideration [1].

Currently, there are lots of researches focuses on the division strategy of islanding within the microgrid globally. It is proposed an off-island planning based on DG capacity, location and network structure in [2, 3], but it is not always applicable in the microgrid with strong power output and load demand volatility. Wang Y considered importance of load in microgrid, classified islanding by pre-determined load reduction strategy under island mode [4]. It is proposed a multi-objective islanding optimization model for distribution network with potential power supply of microgrid in [5].

However, above literatures are based on a certain moment when distribution network fails, takes output power and load status of DG as a certain amount, with this benchmark to divide static island search, ignores the dynamic random changes in power supply and demand in the island operation. Their static islanding strategy is hard to guarantee sustainable and stable supply of important loads during the fault period. Therefore, the reliability assessment based on the expected operation status of islanding strategy needs to be discussed.

In this paper, it firstly proposes concept and evaluation index of sustainable on-load capacity of photovoltaic/energy-storage hybrid system. Secondly, dynamic islanding model of micro-grid is proposed with considering sustainable on-load capacity of photovoltaic/energy-storage hybrid system, which makes up the lack of static islanding. Finally, it conducts a reliability assessment for
distribution network with different islanding strategy under microgrid, by using reliability evaluation algorithm that takes account of the PV output and the load demand volatility.

2. Component model

2.1. Probabilistic Model of Load
In order to work out timing of PV output, this paper adopts the photovoltaic model of Reference [6], which can reflect characteristics of timing and randomness of PV output under different weather types in the target area.

2.2. Probabilistic Model of PV
Distribution network load has time-varying and randomness. Therefore, result of load forecasting is actually a random variable, and normal distribution is usually used to approximate reflect load uncertainty. In this paper, load stochastic model in Reference [7] is used.

2.3. Storage Energy Constraint Model
With considering charging and discharging efficiency of storage energy, the maximum output power of storage energy and the capacity limitation, the charging and discharging process should meet the constraints mentioned in Reference [8].

3. Sustainable on-load capacity of photovoltaic/energy-storage hybrid system

3.1. Photovoltaic reliable power output
The uncertainty of PV system output makes people only pay attention to their power value. In fact, PV system has some capacity value simultaneously. In this paper, concept of photovoltaic credible output is proposed. The credible output \( P_\alpha(t)|_{\Delta t} \) of photovoltaic in \( \Delta t \) period is the least output level that PV can reach with certain probability (confidence) \( \alpha \) in \( \Delta t \) period after time \( t \). For example, if \( \alpha = 90\% \), \( \Delta t = 15\text{min} \), so photovoltaic credible output power is \( P_{90\%}(t)|_{15\text{min}} \), which means the least PV output level can reach with 90% confidence in 15min is \( P_{90\%}(t)|_{15\text{min}} \).

![Figure 1. photovoltaic reliable power output under different confidential level](image)

During actual operation, a certain prediction error will be taken into consideration in the PV prediction to determine the PV's credible output. This paper uses above PV model, to get the PV credibility curve under different weather types through random sampling simulation method. Specific calculation steps are as follows:
(1) Establish a PV power generation timing model under different weather types.
(2) Generate Ne daily timing samples of PV output by sampling.
(3) Work out credible curve of PV power output by calculating Credible value for PV power output \( (P_{\alpha}(t)_{\Delta t}) \) in different times of the day under different weather types. The schematic diagram of the PV credible output under different confidence levels is shown in Figure 1, among them, the sampling interval on the curve is 15 minutes, therefore, \( P_{\alpha}(t)_{\Delta t} \) can be calculated by the following formula:

\[
P_{\alpha}(t)_{\Delta t} = \left\{ P_{\beta} \left\lfloor P_i \left( t + \Delta t \right) > P_{\beta} \right\rfloor \geq \alpha \right\}
\]

In the formula, \( P_i[-] \) indicates the probability value that the inequality constraint holds.

Please note in the following, the credible output of PV at a certain moment all refers to the confidence output when \( \Delta t \) is 15mins, so that \( P_{\alpha}(t)_{15\text{min}} \) is abbreviated as \( P_{\alpha}(t) \).

3.2. Assessment Indicators

In order to evaluate the continuous power supply capability of load under distribution network with optical storage in the fault condition, this paper presents evaluation index of the sustainable load capacity of optical storage system. Among them, sustainable load capacity of optical storage system means: the capability that optical storage system can provide uninterrupted power supply to load on island within a certain period, which includes both sustainable power supply and energy supply, details are as follows:

(1) Continuous loading power margin \( (M_p) \): the load supply margin that optical storage system can achieve when power balance in isolated island can be met during the fault period, which is calculated as follows:

\[
M_p(t) = \min\left(1 - \frac{\sum_{i \in K}(1 + \beta)P_{Li}(\tau)}{\sum_{i \in K}(P_{ai}(\tau) + P_{dmax})}\right) \times 100\% \quad \tau \in [t, t_{end}]
\]

In which, \( P_{Li} \) is the predicted demand power of the \( i \)-th load, \( \beta \) is load forecast error, \( P_{ai} \) is the credible output in the \( i \)-th PV under the confidence \( \alpha \), \( P_{dmax} \) is the maximum discharge power of the \( i \)-th energy storage, and \( t_{end} \) is predicted fault end moment, while \( K \) is the range of micro-grid islanding.

(2) Continuously loading energy margin \( (M_u) \): the load supply margin that optical storage system can achieve when energy balance in isolated island can be satisfied during the fault period, the formula is as follows:

\[
\left\{ \begin{array}{l}
A(t) = E_{re} - \delta \int_{t}^{t_{end}} \sum_{i \in K}((1 + \beta)P_{Li}(\tau) - P_{ai}(\tau))d\tau \\
M_u(t) = \left( \frac{A(t)}{E_{min,i}} - 1 \right) \times 100\%, \quad \tau \in [t, t_{end}]
\end{array} \right.
\]

In which, \( A(t) \) is the remaining storage capacity after \([t, t_{end}]\) period under the loading range, \( E_{min,i} \) is the minimum allowable remaining capacity of the \( i \)-th energy storage, \( E_{re} \) is the sum of the initial capacity of each energy storage device, \( \delta \) is the charge-discharge efficiency.

\( M_p(t) \) and \( M_u(t) \) reflect the continuous loading capacity of island optical storage system in \([t, t_{end}]\) period from the perspective of power balance and energy adequacy respectively. The larger the value is, the larger the load increased margin brought by optical storage system will be, otherwise will be smaller.

3.3. Dynamic islanding strategy

To ensure the sustained and stable power supply to important users, this paper proposes a dynamic islanding strategy, which including the strategy of optimization and reconstruction on a long time scale and the strategy of load-shedding on a short time scale. The optimization and reconstruction strategy is to work out islanding partitioning model and optimize islanding partitioning plan with a certain time interval \( T_z \), while load-shedding strategy refers to priority to remove the less important
load in island real-time operation, if the active power imbalance exceeds a certain limit. The proposed strategy uses evaluation index of sustainable load capacity to assess current increased margin for optical storage system, and to incorporate more load into island under the condition that island can run stably and continuously. Its mathematics model is as below:

$$\text{max } L = \max \sum_{i=K} \lambda_i L_i$$

$$ s.t. \left\{ \begin{array}{l} M_p(t) \geq 0 \\ M_w(t) \geq 0 \\ \text{Meet the energy storage constraints mentioned in Section 2.3} \end{array} \right.$$ (4)

In which, if the value of $L_i$ is 1 or 0, it means whether the load point $i$ is included in the island operation plan load set $K$. $\lambda_i$ is load importance index, the greater the value is, the more important it is, the more priority to incorporated into $K$.

4. Distribution network Reliability Assessment Considering Load and Power Fluctuation

To cover the volatility and randomness of PV and load demand during islanding operation in the reliability assessment, this paper improves the reliability assessment algorithm based on Monte Carlo. The specific algorithm flow and method are based on the traditional reliability Evaluation method [4]. For island load operation, the reliability assessment should base on actual operation situation, now only presents assessment process of island operation load as follows:

(1) Island data initialization: setting predict fault repair time as $T$, confidence level of PV credible output as $\alpha$, then work out PV credible output curve and load forecast curve within $[t_{occ}, t_{end}]$ period, $t_{occ}$ is the moment when breakdown occur, $T=t_{end} - t_{occ}$. Setting dynamical division time interval as $T_p$. Set $n$ as1, $n$ means the $n^{th}$ dynamic partition island during breakdown period. $K_n$ is the $n^{th}$ island load set, initial $K_0$ is empty set.

(2) Islanding scheme Determination: According to the PV credible output curve and load forecasting curve, the islanding partition model is used to determine the islanding scheme load set $K_n$.

(3) Simulation operation: use PV and load model to work out PV output and load demand curve with considering stochastic fluctuation, and then simulate islanding operation under constraint according to islanding scheme load set $K_n$. If there is insufficient power supply, power balance will be satisfied by cutting load point with less importance, thereby to accumulate times and duration of power outage, and insufficient amount of power supply at each load point during the process, and then to update $K_n$.

Judge whether the time $nT_z$ is greater than or equal to the repair time $T$, if yes, then re-sampling the faulty component to continue this year's simulation, if not, then make $n=n+1$, $t=t_{occ}+nT_z$ and then return to step 2.

5. Case Study

5.1. Example parameters

This paper selects modified RBTS Bus6 F4 feeder system as the simulation example as shown in Figure 2. This article assumes that the order of importance of the loads in the microgrid is 8, 7, 6,...2 and 1, that is to say, the priority order of load access silos is LP19>LP11>LP20>LP12>LP21>LP13>LP22>LP23. Component reliability parameters refers to Reference [9]. The installation capacity of photovoltaic is 2MW, the rated capacity of energy storage is 2MW·h, the rated power of energy storage is 0.5MW.

The load data in references [10,11] are used as the annual demand forecast curve. The load forecasting curve is used as the average load. The load model described in Section 1.2 is used, where the variance of load fluctuations is taken as 8% of the load average at the corresponding time. The prediction error of the load demand forecast $\beta$ in the evaluation model of sustainable on-load capacity of photovoltaic energy-storage hybrid system is set to be $3\sigma$. 


PV Output Data are generated randomly according to the type of weather selected in section 1.1. The credible output curves under different weather types are obtained as described in Section 2.1 in this paper, where the confidence $\alpha = 95\%$.

This paper evaluates the reliability of the following three islanding strategies for microgrids.

- **Strategy 1**: Do not consider islanding in microgrids.
- **Strategy 2**: Consider the operation of islanding and use the islanding method of literature [4], that is, only use static power balance as the basis for dynamic islanding.
- **Strategy 3**: Consider islanding and use the dynamic islanding strategy regarding sustainable on-load capacity of photovoltaic energy-storage hybrid system, $T_s = 1\text{h}$.

Table 1. Reliability indices of distribution system

| Reliability indices | Strategy 1 | Strategy 2 | Strategy 3 |
|---------------------|------------|------------|------------|
| SAIFI               | 1.0382     | 0.9512     | 0.8541     |
| SAIDI               | 8.3296     | 7.4241     | 7.4238     |
| ASAI                | 0.99904    | 0.99915    | 0.99916    |
| EENS                | 56.5767    | 53.1402    | 54.4198    |
| SAIFI of microgrid  | 1.7897     | 1.4622     | 1.0961     |
| Energy depletion times | /     | 7856       | 0          |
| Number of secondary faults | /      | 41599      | 17         |

Table 1 shows the results of reliability evaluation of distribution system. The failure rate and the average power outage time of typical load point under three kinds of strategies are shown in Figure 3. Among them, LP9 and LP10 is non-island load while others are microgrid loads.

Below conclusions are from table 1 and figure 3:

(1) Strategy 3 has better reliability than Strategy 2. This is mainly because islanding strategy 2 based on static power balance does not take into account the uncertainty of the PV and load during the fault,
resulting in repeated resection and incorporation of load points and depletion of stored energy, which increases the failure rate of the microgrid load.

(2) As shown in Figure 3, Strategy 3 can reduce the failure rate and average power failure time of important loads to a greater extent. In the process of islanding, the number of energy storage exhaustion is 0 and the number of secondary faults also much lower than strategy 2.

![Figure 3. Index comparison of typical load point](image)

6. Conclusion

In this paper, it considers the uncertainty of PV output and load demand in the micro-grid, and proposes a dynamic islanding model based on the sustainable on-load capacity of photovoltaic energy-storage hybrid system. Simulation results show that the proposed strategy can take uncertainty of PV output and load into account during the breakdown period and ensure that the important loads in the microgrid will maintain stable power supply and improve overall power supply reliability of the system.

Acknowledgment

This work was supported by Natural Science Foundation of Guangdong Province, China (2017A030313304).

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