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Reliability Evaluation of Distribution System with Multiple Micro-Sources

***Abstract**. A new minimal path model of reliability evaluation of distribution system with multiple micro-sources is presented to analyze the effect of different type micro-source to the distribution system reliability in which the control mode of micro-source, the network configuration, operation and control characteristics of microgrid are fully considered. The results of the RBTS bus 6 verify the validity of the model and show the remarkable different effect of different type micro-source and its control mode to the reliability of distribution system.*

***Streszczenie.** Analizowano niezawodność sieci z dołączonymi mikro-źródłami. Rozważono konfiguracje sieci oraz charakterystyki sterowania. (**Ocena niezawodności sieci zasilającej z wieloma mikro-źródłami**)*

Keywords: multiple micro-sources, distribution system, minimal path, **reliability evaluation**
Słowa kluczowe: sieć zasilająca, mikro-źródła, niezawodność.

Introduction

In recent years, the increasing depletion of conventional energy, and the more and more pressure from environment promote the widespread use of distributed generation (DG) [1-4]. DG brings positive impact on the reliability of the distribution system and its customers, which has been proven [5].

However, with the increase of DG penetration, multi-machine control becomes increasingly difficult, power quality problems become increasingly serious, and the economy of distributed generation technology is more and more difficult to reflect [6]. DGs have been not suitable to access to bulk grid directly.

In this situation, modern power electronic technology and control theory are introduced to form microgrid concept, which is based on distributed generation technologies, combined with batteries, supercapacitors and other energy storage devices [6,7]. In microgrid, micro-sources are connected to large grid by power electronic technology, they no longer directly face the impact of the grid failure, the operation mode change or load change [8-10].

However, the micro-sources in microgrid such as photovoltaic, wind power, fuel cells, geothermal power, tidal and wave power, small hydropower, etc., have a lot of differences in their power generation technologies and control methods, coupled with the two microgrid operation mode: grid connected mode and island operation mode [10], making the micro-source and microgrid control methods become more complicated and diverse.

At present, there are a large number of achievements in micro-source and microgrid control method [10]. Under the influences of micro-source control, microgrid control and energy storage control technology, the micro-source within microgrid has high reliability. The micro-source power output characteristics have been not obvious to large grid and customers, replaced by the micro-source control mode and microgrid control strategy.

To achieve fast, flexible and changing operation mode, microgrid is equipped with a large number of power electronic based static switches. In this paper, a minimal path model of reliability evaluation of distribution system with multiple micro-sources (DSM) is discussed to analyze the effect of different type micro-source to the distribution system reliability, in which micro-source control mode, DSM network configuration, microgrid operation and control characteristics are fully considered.

Micro-source type and its control mode

Micro-Source Type

Generally, the micro-sources in microgrid are made of renewable energy, such as solar energy, wind, biomass, geothermal, tidal and wave energy, water, etc. However, there are some micro-sources converted from conventional energy, such as micro gas turbine. In addition, the energy storage system has become an essential micro-source in microgrid for its many advantages, such as providing short-term supply for the energy buffer, improving power quality, optimizing microgrid operation and improving the economic efficiency or other indicators of microgrid.

Majority of micro-sources, such as micro-gas turbine, photovoltaic, fuel cells, etc., can not be connected to the AC power grid directly, except through power electronic conversion device. To achieve the interconnection, the micro-source inverter control method should meet the following conditions:

1) To ensure the "plug and play" simplicity for each micro-source;

2) To ensure the smooth transfer between the two operation modes: grid connected mode and island operation mode;

3) To ensure the independent control of active power, reactive power of micro-source;

4) To ensure fast response to load dynamic change.

To meet the requirements above and take full account of the different characteristics of various micro-sources, the existing micro-source control strategies generally include the following [10]:

1) PQ control method;

2) V/f control method;

3) droop control method.

Among them, the droop control method will not be considered in this paper, for it has difficulty in adjusting without difference.

PQ Control Method

The micro-source under PQ control mode injects specified active and reactive power into microgrid, independent of loads fluctuations or other micro-source output changes [10].

Photovoltaic cells, wind power and other renewable energy power, affected by natural conditions largely, are intermittent and non-dispatching. System voltage and frequency have little influence on their power outputs. Ideally these micro-sources should maintain the maximum power output, in order to achieve the maximization of cost-effective; Micro gas turbine and fuel cell are difficult to respond quickly to the rapid loads changes because of their larger output time constant [10], so they all use PQ control method generally.

PQ control method is generally used in grid connected mode, to make full use of the economic benefits of micro-source.

V/f Control Method

V/f control method can maintain the voltage and frequency of micro-source at a constant value, by setting their reference values and detecting their real-time values at the inverter output ports by PI regulator.

V/f control method is generally used in island operation mode to maintain the voltage and frequency of micro-source at their rated value and provide the basis for other micro-source voltage and frequency control.

The micro-sources in V/f control mode must have sufficient power density, energy density and a smaller time constant. Fuel cells or micro-gas turbine with energy storage device are set in V/f control mode generally.

Structure, Operation and Control Feature

Microgrid Structure

Microgrid has a flexible structure, in accordance with the different needs by different electricity customers, but it generally includes micro-sources, energy storage devices, management system, loads, as well as several feeders, and the entire network is radial [6-8]. Microgrid has "plug and play" simplicity for each micro-source. Loads are connected to different feeders in microgrid respectively according to their importance degree and power quality requirements, in order to achieve load classification and hierarchical control. A typical microgrid from CERTS is shown in Fig. 1.

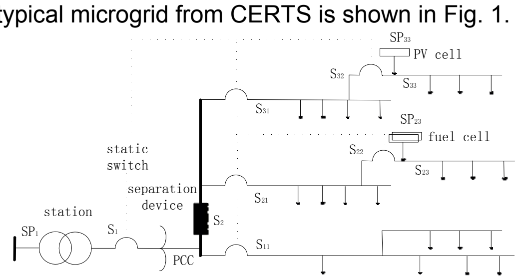

Fig. 1 A typical microgrid from CERTS

Connection Feature to the Distribution System

The connection standard is only for the point of common coupling (PCC) of microgrid and distribution network, not for any specific micro-source in microgrid. The performance of microgrid to distribution network is evaluated as a whole unit by coordinating a group of micro-sources, storage devices and loads with similar geographical locations. Microgrid is a "grid-friendly" single controlled set. It can slip smoothly into the distribution system operation to exchange energy with distribution system and run independently when distribution network failure occurs [8].

Microgrid can be regarded as a simple scheduled load for power systems and a customizable power for customers [8]. The distribution network structure will undergo a fundamental change after microgrid access, from a radiation network into a complex system composed of several radial microgrids, with DGs and loads distributed in network. It is called double-radiation with multiple-power structure in this paper.

Intentional Islanding of Microgrid

Some customers in distribution system may be supplied by DGs only, then the DGs and these customers together is called the power island of distribution system, island for short [9,10]. There are two kinds of islands: intentional island and non-intentional island. The only difference is that the former is man-made in advance in accordance with the strategy to determine the splitting points while the latter is random.

Microgrid generally has mature intentional islanding technology, including the intentional islanding principles and load shedding scheme. Better intentional islanding plan and reasonably island range, combined with automatic restore technology, can achieve seamless transition between the grid connected mode and the island operation mode.

Microgrid Control

Microgrid has two typical operation modes: the grid connected mode and the island operation mode, and it has different control method in different operation mode:

1) The master-slave control method

This method sets a micro-source as main power supply which can control other micro-sources power output by communication according to microgrid actual operation to achieve power balance and meet the requirements of microgrid voltage and frequency. The method is mainly used in the island operation mode. Main micro-source generally uses V/f control method, while other micro-sources use PQ control method.

2) The point to point control method

In this method, all micro-sources generate active and reactive power output independently in accordance with their established control modes without communication, if there is failure in one micro-source or the system needs to access new micro-sources, the remaining micro-sources are not affected. In this method, all micro-sources use PQ control method generally.

Network Space Topography

Physics Simplified Model

The effects of switches in the electric distribution network reliability assessment process are very different because of the absolutely contrary calculation direction. In the DSM downstream reliability calculation process, the switch is similar to the common equipment, their equivalent reliability parameters are shown as follows:

(1) $$\lambda_e = \lambda_i + \lambda_{si}$$

(2) $$U_e = \lambda_i r_i + \lambda_{si} r_{si}$$

(3) $$r_e = U_e / \lambda_e$$

Where: λ_i, r_i, U_i -failure rate, average outage duration, average annual outage time of device i; λ_{si}, r_{si}, U_{si} -failure rate, average outage duration, average annual outage time of device i.

Switch is only the amendment to the reliability parameters of equipment in the upstream reliability calculation procedure. The equations are as follows:

(4) $$\lambda_e = \left(1 - p_i\right) \lambda_i$$

(5) $$U_e = \left(1 - p_i\right) \lambda_i \cdot r_{\min\{r_i, r_d\}}$$

(6) $$r_e = U_e / \lambda_e$$

Where: r_d-switching time of sectionlizer, p_i-switch reliable operation probability, $r_{\min\{r_i, r_d\}}$ -the minor of r_i and r_d.

Fig. 2 is a typical radial feeder. According to (1)-(3), in downstream reliability calculation course, there are:

(7) $$\begin{aligned}\lambda_e &= \lambda_{s_i} + \left(\lambda_{e_i} + \lambda_{e_{i+1}} + \cdots + \lambda_{e_n}\right) + \lambda_{s_{i+1}} \\ &= \lambda_{s_i} + \lambda_{s_{i+1}} + \sum_{j=i}^{n} \lambda_{e_j}\end{aligned}$$

(8) $$\begin{aligned}U_e &= \lambda_{s_i} r_{s_i} + \begin{pmatrix}\lambda_{e_i} r_{e_i} + \lambda_{e_{i+1}} r_{e_{i+1}} + \\ \cdots + \lambda_{e_n} r_{e_n}\end{pmatrix} + \lambda_{s_{i+1}} r_{s_{i+1}} \\ &= U_{s_i} + U_{s_{i+1}} + \sum_{j=i}^{n} \lambda_{e_j} r_{e_j}\end{aligned}$$

(9) $$r_e = U_e / \lambda_e$$

Fig.2. A typical radial feeder (*SP* is power, *S* is switch, *e* is device, *c* is customer.).

According to (4)-(6), in upstream reliability calculation course, there are:

(10) $$\begin{aligned}\lambda_e &= \left(1-p_{s_i}\right)\left(\lambda_{e_i}+\lambda_{e_{i+1}}+\cdots+\lambda_{e_n}\right)+\lambda_{s_{i+1}} \\ &= \lambda_{s_{i+1}}+\left(1-p_{s_i}\right)\sum_{j=i}^{n}\lambda_{e_j}\end{aligned}$$

(11) $$\begin{aligned}U_e &= \left(1-p_{s_i}\right)\begin{pmatrix}\lambda_{e_i}r_{e_i}+\lambda_{e_{i+1}}r_{e_{i+1}}+ \\ \cdots+\lambda_{e_n}r_{e_n}\end{pmatrix}+\lambda_{s_{i+1}}r_{s_{i+1}} \\ &= U_{s_{i+1}}+\left(1-p_{s_i}\right)\sum_{j=i}^{n}\lambda_{e_j}r_{e_j}\end{aligned}$$

(12) $$r_e = U_e / \lambda_e$$

Where: λ_e, r_e, U_e -the equivalent failure rate, the equivalent average outage duration, the equivalent average annual outage time.

According to (7)-(12), there is a definition as follows:

Definition 1: The region between adjacent switches is called zone, the equipments included in the same zone are similar in reliability logic, having the parallel relationship in reliability calculation, denoted by *Z*.

Network Space Topography

Definition 2: The topography of electric distribution network is made based on the concept of zone. In the topography, the zones are recognized as nodes (*v* represents the node, *V* represents the node set) while the switches are edges (*e* on behalf of the edge, *E* the edge set), known as DSM network space topology, denoted by *G* (see Fig. 3), because of the apparent difference from the physical simplified network.

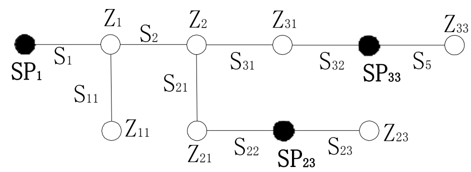

Fig.3 Network space topography of Fig.1 (*SP* is power, *S* is switch, *Z* is zone.).

Particularly, if there is no zone between two switches, a virtual zone will be made, and similarly, a virtual switch will be made between two zones if there is nothing.

Definition 3: The zone including load point is called load point zone. But the power point is not in any zone due to its special characteristic in the calculation process of reliability parameters.

Minimal Path Model

Definition of Minimal path [11]

Definition 4: The edge set between load point zone and power point, is called the path of load point zone, denoted by *P*.

Definition 5: The combination of all paths between load point zone and power point is called the path sets of the load point zone.

Definition 6: Each edge corresponds to a real number, called the weight of edge, denoted by *W(e)*, and the graph *G* is called weighted network space topology.

Definition 7: If *P* is any path in the weighted network space topology *G*, $W(P)=\sum_{e\in E(P)}W(e)$ is known as the weight of path *P*.

Definition 8: The path with smallest weight is called the minimal path, denoted by P^*.

The path and the minimal path of zone Z_{31} to the power point SP1 are all S_1-S_2-S_{31}, while to the power point SP_{33} are all S_{32} in Fig. 3.

Parameter Information Description

There are only three kinds of components, namely, switch (edge), zone (hollow node) and power point (solid node) in DSM network space topology, whose parameter information can be described as follows:

Zone, which is the hollow node in the network space topology, has the parameters information:

zone name {node number, failure rate, average outage duration, average annual outage time}.

Power point, which is the solid node in the network space topology, has the parameters information:

node name {node number, capacity}.

Switch, which is the edge in the network space topology, has the parameters information:

switch name {edge number, the switching time}.

Process of Reliability Assessment

DSM minimal path searching can be done by depth-first search and breadth-first search method [12,13].

Reliability Parameters Calculation of Zones on the Minimal Path

Any zone on the minimal path of load point zone having failure equipment will lead power outage, and the outage duration time is due to the power point situation. The outage duration time is the sum of the operation time of sectionlizer and tie switch when there is backup power supply, or it will be repair time if there is only one power point. In both cases, the failure rates are identical. Set the reliability parameters of zone Z_i as failure rate λ_{Z_i}, average outage duration r_{Z_i}, and average annual outage time U_{Z_i}, then the contribution of zone Z_i to the equivalent reliability parameters of load point zone Z_j are as follows respectively:

(13) $$\lambda_{Z_j}^{Z_i} = \lambda_{Z_i}$$

(14) $$U_{Z_j}^{Z_i} = \lambda_{Z_i}\cdot r_{\left\{r_{Z_i},r_{sum}\right\}}$$

(15) $$r_{Z_j}^{Z_i} = U_{Z_j}^{Z_i} / \lambda_{Z_j}^{Z_i}$$

Where: r_{sum}-the sum of the operation time of sectionlizer and tie switch.

Reliability Parameters Conversion of Zones Not on the Minimal Path

If there are circuit breakers, fuses on feeder' first terminal, any zone not on the minimal path of load point zone having failure equipment has no impact on the load point.

If there are no circuit breakers, fuses on feeder's first terminal, then there are two situations as follows:

1) The switch able to isolate the failure of the non-minimal path zone is on the minimal path of the load point zone, then the power outage time is the time to repair equipment failures, the contribution of zone Z_i to the

equivalent reliability parameters of load point zone Z_j are as follows respectively:

$$\hat{\lambda}_{Z_j}^{Z_i} = \lambda_{Z_i} \quad (16)$$

$$\hat{U}_{Z_j}^{Z_i} = \lambda_{Z_i} \cdot r_{Z_i} \quad (17)$$

$$\hat{r}_{Z_j}^{Z_i} = \hat{U}_{Z_j}^{Z_i} \Big/ \hat{\lambda}_{Z_j}^{Z_i} \quad (18)$$

2) The switch able to isolate the failure of the non-minimal path zone is not on the minimal path of the load point zone, then the power outage time is the time to isolate equipment failures, the contribution of zone Z_i to the equivalent reliability parameters of load point zone Z_j are as follows respectively:

$$\hat{\lambda}_{Z_j}^{Z_i} = \lambda_{Z_i} \quad (19)$$

$$\hat{U}_{Z_j}^{Z_i} = \lambda_{Z_i} \cdot r_d \quad (20)$$

$$\hat{r}_{Z_j}^{Z_i} = \hat{U}_{Z_j}^{Z_i} \Big/ \hat{\lambda}_{Z_j}^{Z_i} \quad (21)$$

Load Point Reliability Parameters Calculation

Individual load point reliability parameters can be calculated as follows:

$$\lambda_{LP_j} = \lambda_{Z_j} + \sum_{i \in P^*} \lambda_{Z_j}^{Z_i} + \sum_{i \notin P^*} \hat{\lambda}_{Z_j}^{Z_i} \quad (22)$$

$$U_{LP_j} = U_{Z_j} + \sum_{i \in P^*} U_{Z_j}^{Z_i} + \sum_{i \notin P^*} \hat{U}_{Z_j}^{Z_i} \quad (23)$$

$$r_{LP_j} = U_{LP_j} \Big/ \lambda_{LP_j} \quad (24)$$

Flowchart of Reliability Calculating

The flowchart of reliability evaluation of distribution system with multiple micro-sources is presented in Fig. 4.

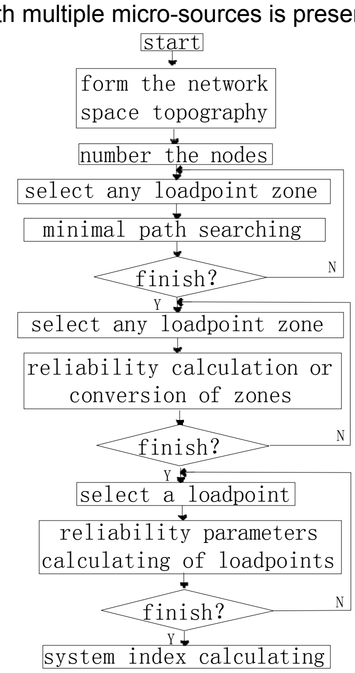

Fig. 4 Flow chart of reliability evaluation

Case Study

Case and Parameters

The modified RBTS BUS 6 has been studied as an example [14,15]. The single-line diagram is shown in Fig. 6. It is a typical complex rural/urban configuration with sub-feeders and it contains 30 sections, 23 load points, 23 fuses, 23 transformers, 18 sectionliaers, 4 circuit breakers and 1183 customers, where the sectionliaers operation time is 0.4 hours, the tie switch operation time is 1 hour. There are four DGs: DG_1 with 1MW on section 19, DG_2 with 1.5MW on section 22, DG_3 with 1MW on section 25, and DG_4 with 2MW on section 28. The whole F_5 is a microgrid, and the whole F_7 is a microgrid.

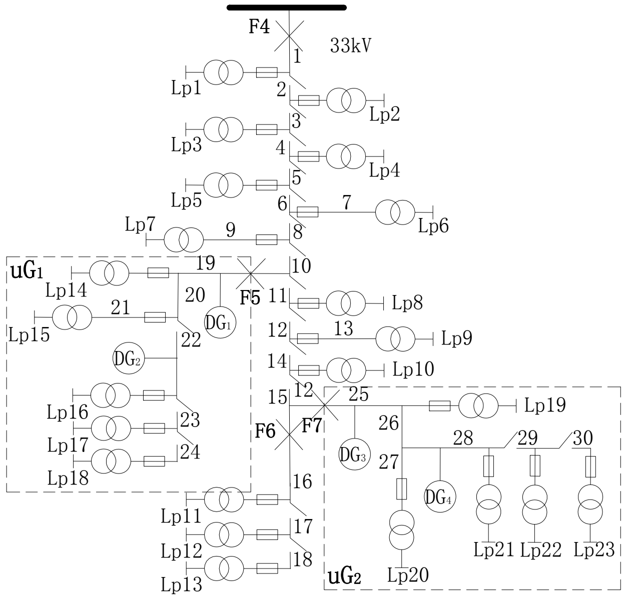

Fig. 5 Configuration of RBTS BUS 6 with multiple micro-sources

Calculation Results

This paper has calculated the reliability parameters in the following situations:

1) Without microgrid;

2) Set DG_1, DG_2, DG_3, DG_4 in PQ control mode;

3) Set DG_1, DG_2, DG_3, DG_4 in V/f control mode;

4) Set DG_1, DG_3 in PQ control mode, while DG_2, DG_4 in V/f control mode.

In case 2, microgrids will slip into island operation mode with a certain probability if there is failure out of microgrid, for lack of the micro-sources with V/f control method, while in Case 3 and Case 4, microgrids will be able to successfully slip into island operation mode.

Table 1-4 lists part load points reliability parameters, Table 5 shows the system reliability indices. It can be seen:

1) Load point reliability indices are improved significantly after microgrids access, namely, microgrid can improve distribution network reliability remarkably, but the extent are related with DG capacity and its control method;

2) In case 2, due to lack of the micro-sources in V/f control mode, the load within microgrid will be subject to the impact of the failure out of microgrid. Compared with the situation 3, 4, the load point failure rate within the microgrid is relatively high;

3) In case 3, all micro-sources are in V/f control mode, though stable islands operation can be achieved easily, it will cause the lack of active power output, so they have limited impact on other reliability parameters except the load point failure rate;

4) In case 3, the two microgrids can not only ensure the microgrid stable island operation, but also achieve a better control of power output for containing both PQ control and V/f control micro-sources, so the reliability parameters are better than other cases.

Table 1. Reliability indices of selected load points (case 1)

Load Point	Case 1		
	λ (f/yr)	r (hr)	U (hr/yr)
1	1.525	20.84066	31.782
11	1.76	10.68182	18.8
18	1.4	1.4	1.96
22	1.95	7.015385	13.68

Table 2. Reliability indices of selected load points (case 2)

Load Point	Case 2		
	λ (f/yr)	r (hr)	U (hr/yr)
1	1.29	3.111628	4.014
11	1.715	5.116035	8.774
18	0.9275	5.803235	5.3825
22	0.8025	5.456075	4.3785

Table 3. Reliability indices of selected load points (case 3)

Load Point	Case 3		
	λ (f/yr)	r (hr)	U (hr/yr)
1	1.29	3.111628	4.014
11	1.715	5.116035	8.774
18	0.44	10.68182	4.7
22	0.315	11.73333	3.696

Table 4. Reliability indices of selected load points (case 4)

Load Point	Case 4		
	λ (f/yr)	r (hr)	U (hr/yr)
1	1.29	0.520155	0.671
11	1.715	1.233819	2.116
18	0.44	1.4	0.616
22	0.315	0.955556	0.301

Table 5. Reliability indices of system

Case	1)	2)	3)	4)
SAIFI(int./cus.year)	1.570904	1.282272	1.152052	1.152052
SAIDI(hr./cus.year)	18.08159	5.183936	5.001628	1.036129
CAIDI(hr./cus.int)	11.51031	4.042775	4.341495	0.899377
ASAI	0.997936	0.999408	0.999429	0.999882

Conclusion

In this paper, DSM network space topology is made according to the different effects of switch in reliability calculation process, and a new concept of minimal path according to DSM characteristics is defined, a minimal path model of reliability assessment based on DSM network space topology is formed, in which various types of micro-source control features, and microgrid structure, control and operational features are considered. The calculation results show that microgrid has significant effect in improving the reliability of the distribution network, but the types of micro-source and their control modes have great impact on the reliability of distribution network.

Future research ideas and proposals:

1) The economy and stability elements should be considered;

2) The fast algorithm should be studied.

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