Article

Control Technique of Generation Transfer for Microgrid

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Abstract: When a microgrid is grid-tied to a distribution system, it can provide surplus power generation to the distribution system, if any abnormality or interruption occurs in the distribution system, the microgrid can operate in standalone mode to isolate the impact of the abnormality or interruption. However, if the microgrid can not collect enough information from the distribution system, it may cause the failure of generation transferring of distribution feeders, or even further influence the stability of the distribution system. In this paper, a strategy for the resilient control of a microgrid is proposed. It can solve the above-mentioned problem, reduce the duration of the outage of loads. This strategy is experimented in the microgrid in the Institute of Nuclear Energy Research (INER), the reliability is also analyzed to evaluate the unavailability of the microgrid in INER, and it is verified that the proposed strategy can reduce the duration of the outage of loads, and hence the reliability of a microgrid can be upgraded.

Keywords: Microgrid; Distribution System; Generation Transfer; Reliability

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1. Introduction

For the power system, an electrical grid with the resilient recovery function [1-5], is meant to be that when the failures caused by serious natural disasters occur, it will recovery to normal power feeding state fast and automatically, and let the public facilities and important loadings operate in normal mode. It is estimated that the financial loss caused by the disasters caused by windstorms in the United State of America is about 35 to 55 billion USD per year, the outage cases caused by the natural disasters comprise about 78% of that of annual cases, and the percentage keeps rising. Therefore, the goals for the future power system development must include reliability and resilience. To establish a resilient electrical grid, many smart electrical meters, relays and Automatic Transfer Switches (ATS) should be attached. By means of the failure locating, isolation and recovery and automatic power distribution techniques, the reliability indices of the system such as System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI) [6] can be increased efficiently.

In Taiwan Power Company (TPC), the Distribution Automatic System (DAS) utilizes the latest technologies and automation techniques [7], integrate the distribution system, communication system and the computer system into a complete, automatic monitoring system. With Supervisory Control And Data Acquisition (SCADA), the automation of the substation, bus and users is achieved, and keeping the safety of the system, decreasing the power loss in the bus, and increasing the quality of the power usage from the loads are set as the targets. DAS is mainly constructed by Feeder Dispatch and Control Center (FDCC), Remote Terminal Unit (RTU), Feeder Terminal Unit (FTU), Automatic Line Switches (ALS) and the optical fiber system. The automation of the distribution bus is primarily based on SCADA, and automatic Fault Detection Isolation and Recovery (FDIR), but it is only applied to the accidents at the main bus. When an accident at the distribution bus occurs, the system will detect the occurrence of the accident by the information collected by it, then locate he accident to automatically open the switches at the upstream and

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downstream parts of the accident for the isolation of the accident. After that, the power of the sound area in the upstream part will be restored, then the solution to the load transferring of distribution feeders will be proposed as the reference for the coordinators to reduce the area and time of outage significantly, and upgrade the quality reliability of power feeding, and the safety of work. Now INER has accomplished of the feeder dispatching technique, and is able to be controlled by FDCC to perform generation, grid-disconnection and grid-connection. To further improve the reliability of the power feeding, the papers about the resilient recovery for the dispatching microgrid were referred [8-13], the double-source high voltage feeding system was designed. This paper describes how this system operates with smart switches and feeding bus breakers, and the automation program for the high voltage monitoring platform with fast resilient recovery, for the microgrid's self-recovery and generation transferring, which reduces the outage time of loads and decrease SAIDI, SAIFI, and further upgrades the reliability indices of power feeding from migrogrids.

2. Method of Generation Transferring With Distributed Generators

When the failure of the distribution system occurs, the coordinators of FDCC will respond based on the feeding information, and confirm the failure type, then isolate and restore. Human error will enlarge the range of the failure in the distribution system, and make the duration of the outage longer. Therefore, to reduce the time of the outage, the reliability can be upgraded by load transferring. However, for the safety concern, in reality the restoring procedure of DAS still determined by the coordinators of FDCC, they manually transfer the loads, this makes the time of the outage remains several minutes. Furthermore, under the condition of many renewable energy generators and distributed generators connected to the distribution system, if these distributed generators can not collect the operating information of the distribution system fast and correctly, and adjust the strategy of power control properly, the failure during the restoration or even the crisis of the operation safety of the distribution system could happen when performing load transferring of distribution feeders. Therefore, during the load transferring of distribution feeders, the related information should be provided for the distributed generators in order to reduce the duration of outage. Figure 1 shows the load transferring of distribution feeders of secondary substation A and B, and SW1~3 are the switches. Take SW1 on and SW2~3 closed as the initial state, when a failure at feeder B in the secondary substation B occurs, the relay detects the failure, then SW2 will be open state, and the failure is isolated and eliminated by DAS by opening SW3. Therefore, the loads between the switches closest the failure point are interrupted. After the confirmation of the open state of the switches closest, the coordinators of FDCC close SW1 to perform the load transferring of distribution feeders. Then the interrupted loads are restored.

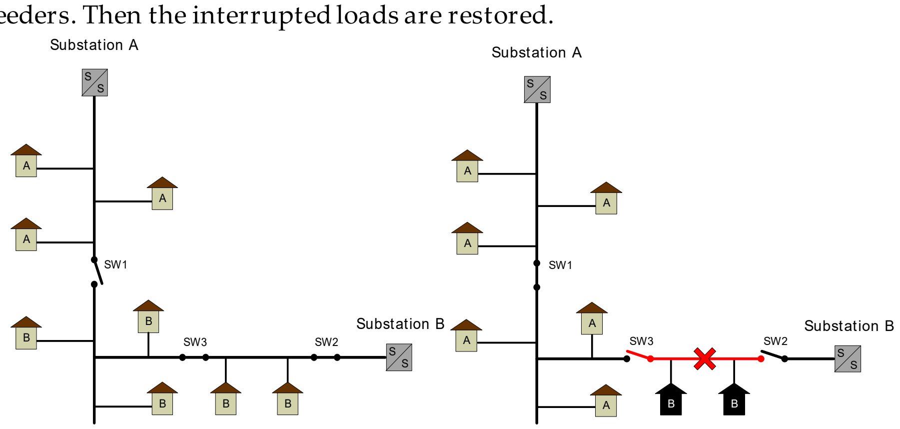

Figure 1. Illustration of load transferring of distribution feeder at feeder A and B of secondary substations.

If there are distributed generators such as renewable energy generators, microgrids, or steam/electricity co-generation plants, as shown in Figure 2, when the failure at feeder occurs, SW2 and SW3 open to isolate the failure, the distributed generators keep in autonomous voltage control mode, which enables keep generating under islanding mode. At this moment, DAS makes SW1 closed for generation transferring of distribution feeders, this makes two power sources grid-connected, and leads to trip at feeder or distributed generators due to nonsynchronous connection between power sources, finally causes the failure of generation transferring of distribution feeders. Besides, even if the distributed generators are equipped with islanding mode detection, able to be grid-disconnected from distribution system, when the distribution system is already load transferred to by another normal feeder, the renewable energy generators will not be grid-connected to the system within 5 minutes from the start of outage for the safety consideration. And the renewable energy generators will not be able to adjust the strategy of voltage control properly according to the operation information of the distribution system, this will affect the stability of power feeding and safety of power usage. To ensure the safety of the distribution system, a solution to the fast generation transferring of distribution feeders is proposed in this paper. In this solution, a switch is attached at the grid-connecting point of the feeder and renewable energy generators, microgrids, steam/electricity co-generation plants, or other distributed generators. When there is an abnormality at the feeder, the switch mentioned above opens automatically to make the isolate failure point, and after the loads are transferred to another feeder, the distributed generators will be grid-connected to another feeder and adjust the control mode of the distributed generators, by utilizing the dispatching method of mutual communication and the synchronizing grid-connect relays. This solution can make the distribution system with microgrid restored fast, and upgrade the utilization ratio of the distributed generators.

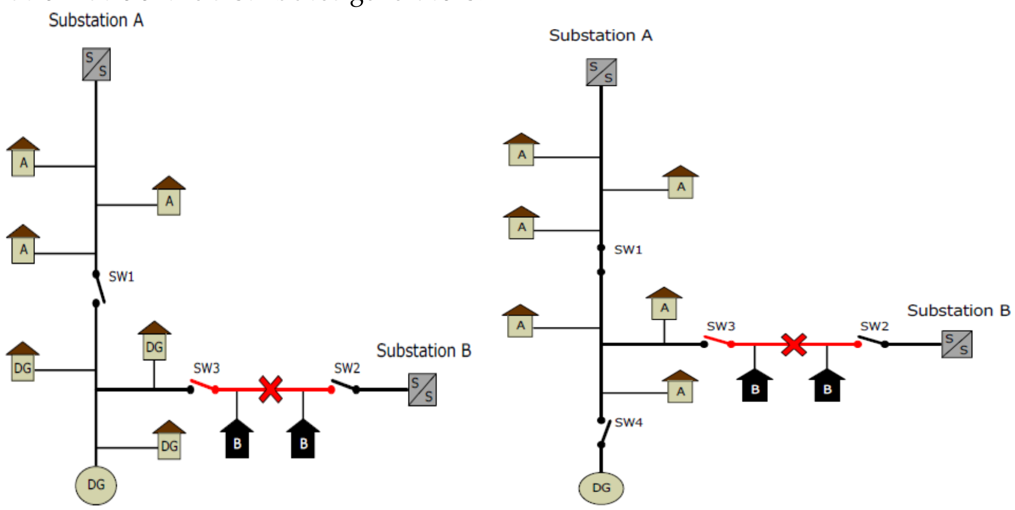

Figure 2. Illustration of generation transferring of distribution feeder at feeder A and B of secondary substations, distributed generators included.

3. Analysis of The Reliability of Power System [5]

To evaluate the reliability, the previous outage data, which mean the outage data of a distribution system within certain duration, such as a year, half a year or a quarter. The basis of the outage data includes the degree of outage, amount of the affected households, root cause of outage, and the range of outage. To analyze and evaluate the reliability of a system, usually the different indices are referred. From the users' point of view, the reliability indices means the absolute, determinable, and significant values, the reliability indices account for the continuity of power feeding. Because the distribution system connect the power generators to users, the expression of reliability indices are related to users. According to the statistics of Electric Power Research Institute (EPRI), the reliability indices related to users that power companies adopt most include SAIFI and SAIDI, here's a brief introduction:

1. System average interruption frequency index (SAIFI)

$$\text{SAIFI} = \frac{Times\ \ of\ \ Outage}{Amount\ \ of\ \ Fed\ \ Households} = \frac{\Sigma\lambda_i N_i}{\Sigma N_i} \tag{1}$$

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which represents the average outage times per user in one year, where λ_i is the failure rate at load *i*, whereas N_i is the amount of households fed at load *i*.

2. System average interruption duration index (SAIDI)

$$\text{SAIDI} = \frac{Summary\ of\ The\ Duration\ of\ Outage}{Amount\ of\ Fed\ Households} = \frac{\sum U_i N_i}{\sum N_i} \quad (2)$$

which represents the average duration of outage per user in one year, where U_i is the duration of outage at load *i*.

The reliability is analyzed based on the probability and statistics of the failures of unit in the system, then the reliability indices are derived. Although the theory of reliability in distribution systems is already developed very well, there are still different methods for evaluation and analysis. In general, most practical methods can analyze the previous reliability of the systems in existence, such as Network Method, Monte Carlo Simulation Method, or State-Space-Method. However, in reality, the methods of planning and analyzing the structure of a distribution system are restricted. A quantitative reliability analysis includes evaluating the solutions to designing a distribution system, various structures for power feeding with different locations of loads, the cost of outage, etc. A distribution system consists of many units of power equipment, the failures in any unit could cause the interruption of power feeding. First, the equivalent reliability indices of series and shunt connections of the equipment are derived. If the system consists of many units in series connection, a failure in any unit causes the malfunction of system, and the reliability indices of the system are shown below:

$$\lambda_S = \sum_i \lambda_i \quad (3)$$

$$U_S = \sum_i \lambda_i \gamma_i \quad (4)$$

$$\gamma_S = \frac{U_S}{\lambda_S} = \frac{\sum_i \lambda_i \gamma_i}{\sum_i \lambda_i} \quad (5)$$

where λ is the average failure rate (f/yr), γ is average downtime or repair time (hours), U is the duration of unavailability (hours/yr). If the system consists of many units in shunt connection, every failure in any unit is independent, and the reliability indices of the system are shown below:

$$\lambda_P = \frac{\lambda_1 \lambda_2 (\gamma_1 + \gamma_2)}{1 + \lambda_1 \gamma_1 + \lambda_2 \gamma_2} \quad (6)$$

when the values of $\lambda_i \gamma_i$ are much smaller than 1, λ_P can be simplified as

$$\lambda_P = \lambda_1 \lambda_2 (\gamma_1 + \gamma_2) \quad (7)$$

$$\gamma_P = \frac{\gamma_1 \gamma_2}{\gamma_1 + \gamma_2} \quad (8)$$

$$U_P = f_P \gamma_P \cong \lambda_P \gamma_P = \lambda_1 \lambda_2 \gamma_1 \gamma_2 \quad (9)$$

Network simplification method is the most direct skill for reliability calculation. It utilize the units in series and shunt connection which were mentioned above based on the topology of the system. It is a very simple method, and it can solve the problem very fast with great precision, however, for large scale networks, the calculation becomes more complicated. In IEEE Std 399-1997, an evaluation method of reliability, called Failure Modes and Effects Analysis (FMEA) is proposed, it is a useful tool to quantitatively evaluate and design reliability. When there's outage in a distribution system, FMEA is based on the reliability indices of the unit of the distribution system and the structure of the system, it lists the combinations of units that cause the interruption

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according to the reliability indices (λ_S, γ_S, U_S) of each unit of the system, and the reliability indices such as SAIFI can be calculated for decision reference. FMEA can be applied to the design of a distribution system, including the reliability data, basic evaluation of the reliability of a power system, economic evaluation of reliability, the cost of outage of users. When power distribution engineers have many different planning programs, FMEA can show the obvious change and influence between the reliability and cost, which are good for choosing the proper designing or improvement solution of the distribution system. Procedures of FMEA include:

1. Define all reliability indices of the units, including average failure rate λ and average duration of outage γ.
2. Calculate the effect on the system in case of every failure mode of the units.
3. Sum up the effect of each failure mode, and derive indices of load of the system: λ_S, γ_S, U_S.
4. Calculate system reliability indices such as SAIDI, SAIFI by the indices of load.

4. Design of Resilient Restoring For Microgrid

This section focuses on the high voltage distribution system of the microgrid in INER. This system was connected to a feeder from TPC (called OQ38) in ordinary, and also connected to two other feeders from TPC called Jia-An substation and Song-Shu substation as spare feeding in double loop feeding type at 69kV. Then the spare feeding is stepped down at Zhong-Er substation (69kV/11.4kV, 10MVA) and called feeder 4E-1 afterward. There is an inter-lock between feeder OQ38 and 4E-1 to avoid connecting at the same time, as shown in Figure 3. Furthermore, the distributed generators and energy storage system can self-feed in case of power loss of exterior feedings, and keep stand alone operation. In this paper, the generation transferring by distributed generators was applied to design a resilient restoring system in a migrogrid. At the double loop feeding OQ38 and 4E-1, and ATS is set as an interlock switch of the high voltage distribution system. A logic program of generation transferring by 2 feeders for the interlock switch in the high voltage monitoring platform in microgrid is designed. This program can make breaker at feeder OQ38 open by failure detecting of the overvoltage and overcurrent relays in case of failures at feeder OQ38. And the smart switch which connects the distribution system and microgrid is opened consequently, to further enure the isolation of the feeder with failure from the microgrid. The failure signal is sent to the high voltage monitoring platform in microgrid and FDCC of TPC for fast failure analysis, as shown in Figure 4. Next, the logic program of the distribution can determine if the interlock switch nearby needs to be switched or not, and transfer the microgrid to the normal feeder. This makes the distributed generators of the microgrid can feed power effectively, and realizes automation of power distribution. This self-recovery function can reduce the outage time of users, and upgrade the reliability of the microgrid.

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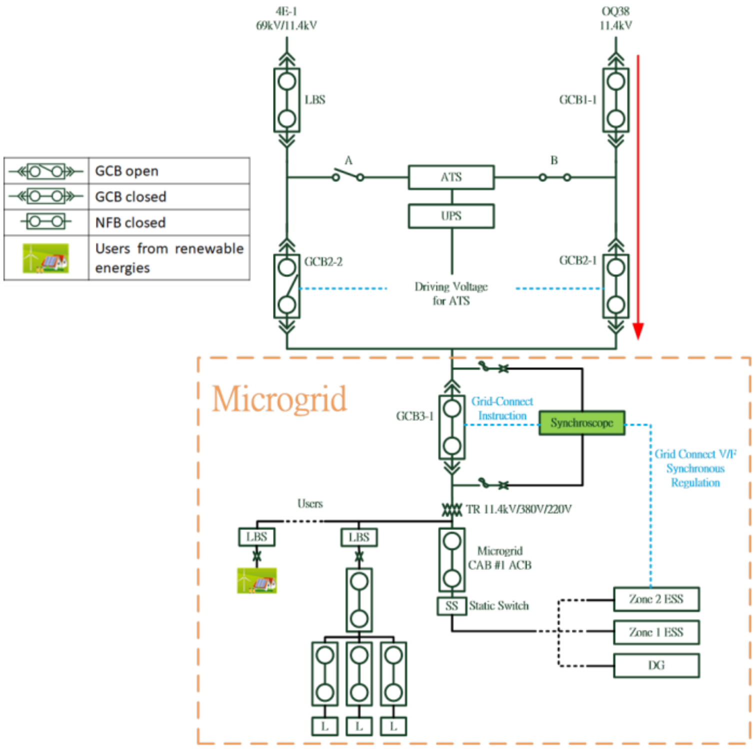

Figure 3. Power feeding loops of OQ38 and 4E-1.

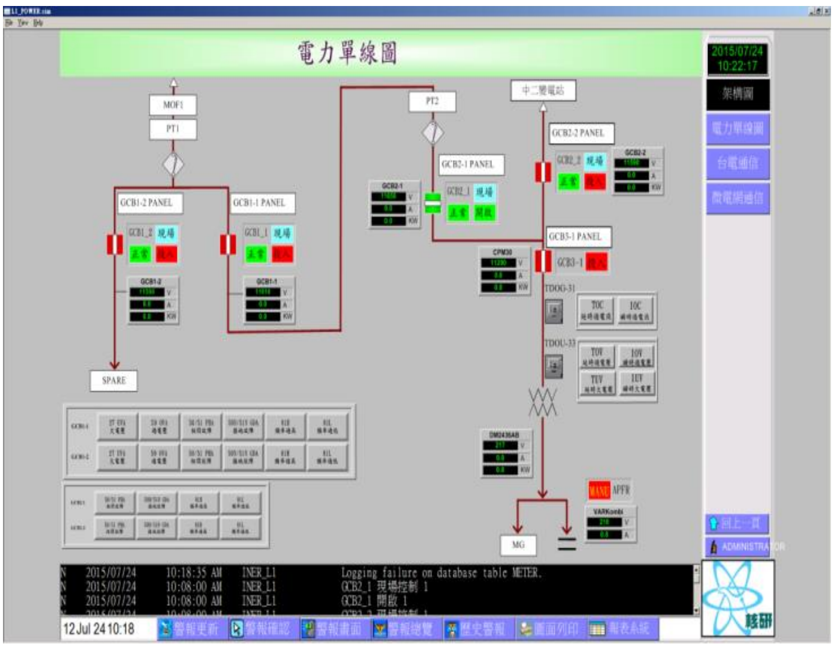

Figure 4. High voltage monitoring platform of the microgrid.

In the newly designed structure of ATS control power feeding, the power feeding of ATS and its UPS is from the potential transformers (PT) of 4E-1 and OQ38 in order to make sure ATS has a stable power feeding. Currently, ATS has an independent PT which can detect the voltage, and power feeding of it can be set as local or remote. In local mode, feeder 4E-1 or OQ38 can be set as the main power feeding. In remote mode, the logic program in the high voltage monitoring platform is designed for power dispatching. Figure 5 shows the designed logic flow chart, the mechanism and steps are as follows:

1. Choose the mode of ATS. Set ATS as remote mode or connected to feeder OQ38 or 4E-1. If ATS is set connected to feeder OQ38 or 4E-1, then skip to step 3.

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2. If the is set as remote mode, either feeder OQ38 or 4E-1 will be set as the main power, and the other one will be set as the spare power.
3. Detect the normality of the main power. If it is normal, then make ATS stay the same, and keep detecting this loop. If it is abnormal, then detect the normality of spare power. If it is normal, then make ATS switch, if it is abnormal, then make ATS stay the same.
4. Detect the normality of the main power. If it is normal, then make ATS switch, and power feeding is switched to main power, and go back to step 3. If it is abnormal, then make ATS stay the same, and keep the spare power as the power feeding.
5. Detect the normality of spare power. If it is normal and the main power is normal, then make ATS switch and go back to step 3. If the main power is still abnormal, then make ATS stay the same, and keep detecting this loop.
6. Detect the normality of spare power. If it is abnormal and the main power is normal, then make ATS switch, and go back to step 3. If the main power is normal, then make ATS stay the same, and keep detecting this loop.

Figure 6 shows the test result of the practical feeder transferring by the high voltage distribution system. When the power from OQ38 is down, the power feeding can be automatically switched to power from 4E-1 within 1 minute, and switched back to power from OQ38 when it is repaired.

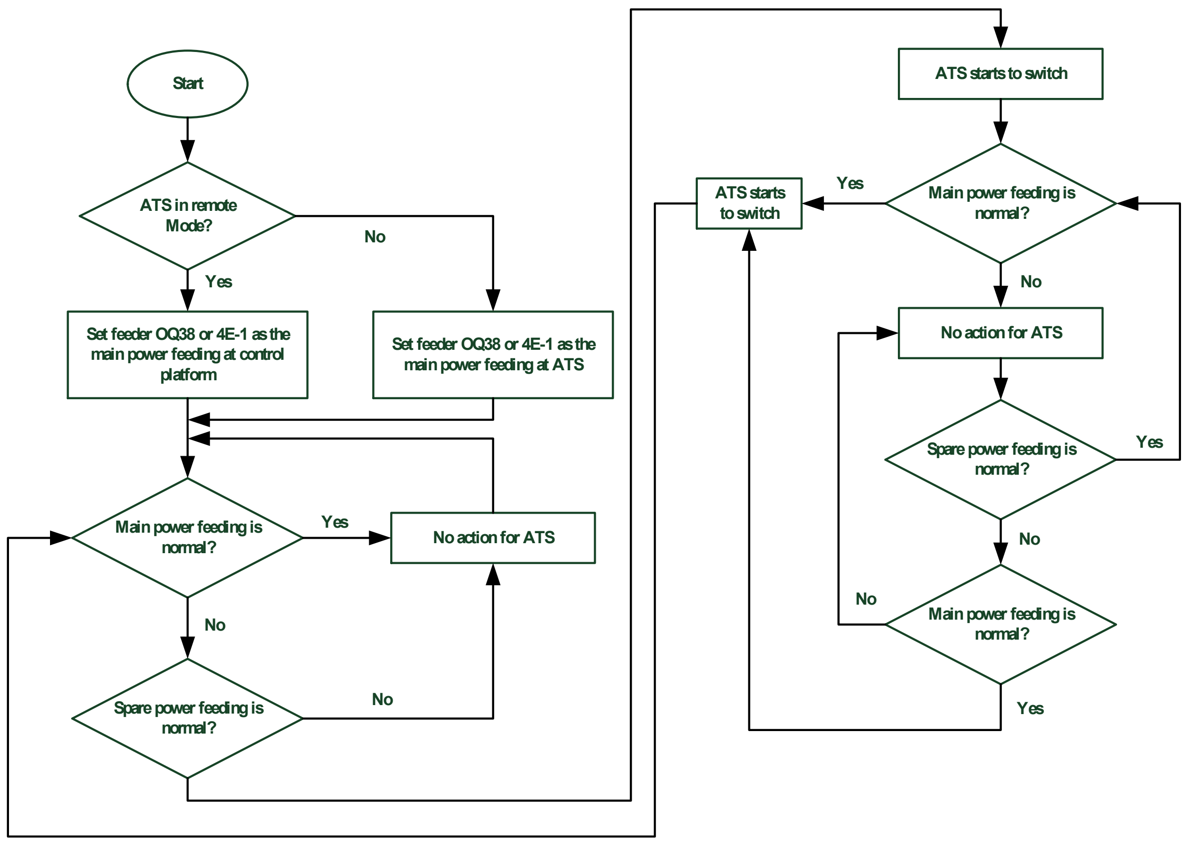

Figure 5. Flow chart of the control logic of the resilient restoring.

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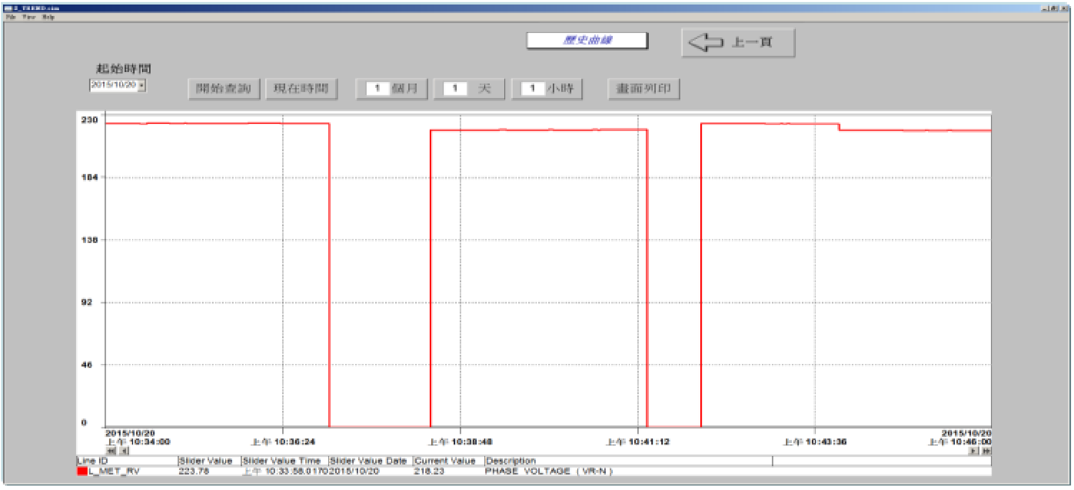

Figure 6. Test result of the feeder transferring by the distribution of the microgrid.

5. Reliability Analysis of The Power Feeding of A Microgrid

In this section, the reliability is analyzed under the regarding the microgrid of INER, which is fed by feeder OQ38 which is connected to TPC Rui-Yuan substation, and feeder 4E-1. In this section, 3 cases are discussed. In case 1, a loop from OQ38 is connected to the interlock switch of the high voltage distributor with an 800 meters 3C#1 cable. In case 2, there are two loops of cable. As for case 3, two additional power feedings of 69kV from TPC Jia-An and Song-Shu substations are connected through feeder 4E-1 to the microgrid. First, the reliability indices of each unit of the system should be determined. These reliability indices are based on the statistics of the using experience in the past few years. Then the equivalent reliability indices of series and shunt connection are used to calculate the reliability of power feeding of the main bus in the microgrid. Suppose that for the bus below 11.4kV, the average failure rate is 0.132 f/yr-kM, the outage time is 240 minutes per event, for the bus of 69kV, the average failure rate is 0.001 f/yr-kM, the outage time is 60 minutes per event, for the transformer, the average failure rate is 0.036 f/yr, the outage time is 210 minutes per event, for the distributed generators (DG) and energy storage system (ESS) related equipment (wind towers, photovoltaic modules, batteries, DC/AC converters, and transformers, etc.), the average failure rate is 1 f/yr, the outage time is 60 minutes per event. Besides, there are some restrictions in the analysis:

1. The units of the distribution system have only two states (on and off).
2. The reliability of protecting equipment (switches, breakers and fuses, etc.), DG, and ESS is 100%.
3. The microgrid consists of DG, ESS and loads can keep steady operating.

5.1. Case 1: Single-Loop Structure with Feeder OQ38

The system structure of case 1 is the shown in Figure 7, and table 1 shows the failure-related parameters of each unit. The reliability indices of bus B4 are evaluated. L1, L2, L3 are buses of 3.5kM, 0.8kM, and 0.1kM, respectively. T1 is the main transformer, D1 is the combination of DG and ESS. L1, L2, L3, and T1 are in series connection and simplified in Figure 8, then the block 1 and block 2 in Figure 8 are considered in shunt connection, and the reliability indices are calculated, which are listed in Table 2. After the analysis, the average failure rate is 3.50×10^{-4}(f/yr), the average repair time is 0.7988 hour, the time of unavailability is 2.79×10^{-4}(hours/yr).

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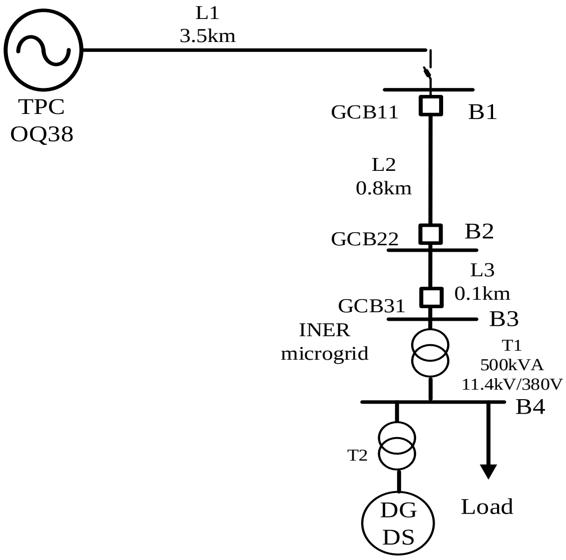

Figure 7. Structure of the microgrid in case 1.

Table 1. Failure-related parameters of each unit.

Unit	λ (times/yr)	γ (hours)
L1	0.462	4.0
L2	0.1056	4.0
L3	0.0132	4.0
T1	0.036	3.5
D1	1.0	1.0

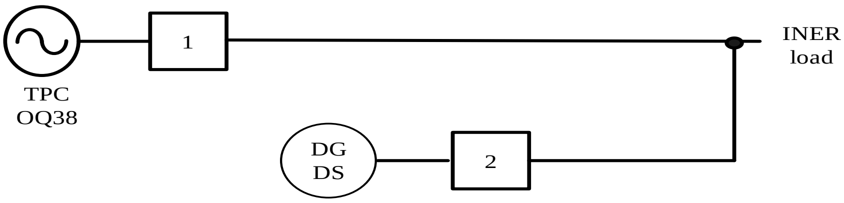

Figure 8. Simplified block diagram of the reliability analysis of the microgrid in case 1.

Table 2. Reliability indices of the loads of the microgrid in case 1.

Failure mode	λ (f/yr)	γ (hours)	U (hours/yr)
1//2	3.50×10^{-4}	0.7988	2.79×10^{-4}
Overall	3.50×10^{-4}	0.7988	2.79×10^{-4}

5.2. Case 2: Double-Loop Structure with Feeder OQ38

As shown in Figure 9, the double-loop structure is adopted between high voltage switch and the relay station, and the reliability indices of bus B4 are evaluated again. In the main bus of the microgrid, L3 and T1 in series connection can be simplified as shown in Figure 10. From Figure 10, the smallest subclasses of the reliability are part 1 and part 5 in shunt connection, part 2, part 3, and

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part 5 in series connection, part 4 and part 5 in series connection. These 3 subclasses are connected in series, and the overall values are calculated and shown in table 3. After the analysis, the average failure rate is 2.9×10^{-4}(f/yr), the average repair time is 0.798 hour, the time of unavailability is 2.31×10^{-4}(hours/yr). All failure-related indices are improved compare with case 1.

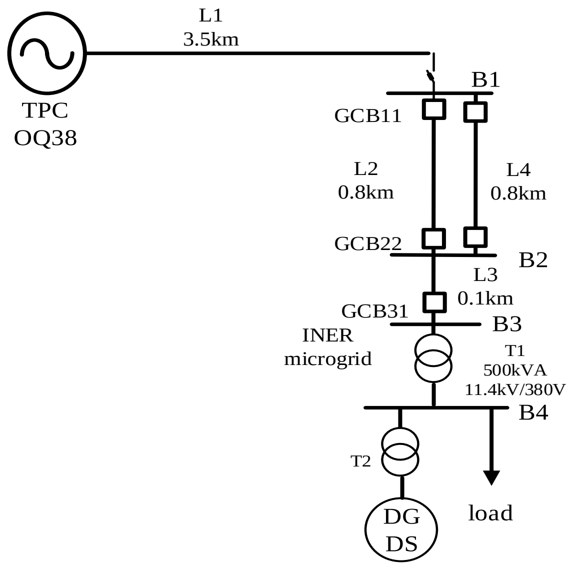

Figure 9. Structure of the microgrid in case 2.

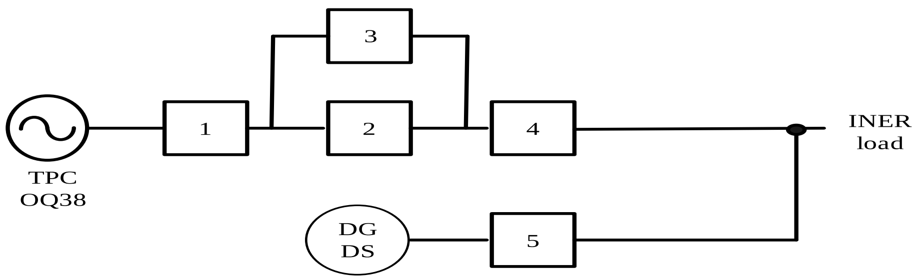

Figure 10. Simplified block diagram of the reliability analysis of the microgrid in case 2.

Table 3. Reliability indices of the loads of the microgid in case 2.

Failure mode	λ (f/yr)	γ (hours)	U (hours/yr)
1//5	2.64×10^{-4}	0.8	2.11×10^{-4}
2//3//5	3.49×10^{-9}	0.6667	2.33×10^{-9}
4//5	2.60×10^{-5}	0.7842	2.04×10^{-5}
Overall	2.90×10^{-4}	0.7980	2.31×10^{-4}

5.3. Case 3: Double-Loop Structure with Feeder OQ38 And 4E-1

As shown in Figure 11, additional power feedings from Jia-An substation and Song-Shu substation are connected, and the reliability indices of bus B4 are evaluated again. To analyze the reliability, L1 and L2 in series connection, L3 and T1 in series, L4 and T3 in series connection, are simplified in Figure 12. In Figure 12, the smallest subclasses of the reliability are part 1, part 3 and part 6 in shunt connection, part 1, part 3, part 4, and part 5 in shunt connection, part 2 and part 3 in

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shunt connection. Then the reliability indices of these 3 subclasses are calculated and listed in Table 4. After the analysis, the average failure rate is 2.61×10^{-5}(f/yr), the average repair time is 0.784 hour, the time of unavailability is 2.05×10^{-5}(hours/yr). Because of the shunt connect of feeder 4E-1, the reliability indices are improved compared with case 2.

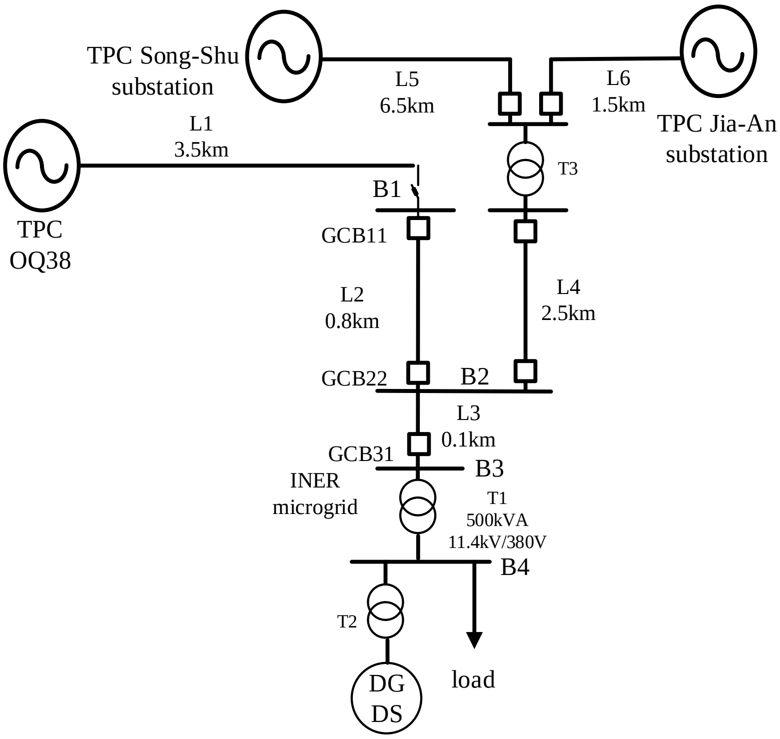

Figure 11. Structure of the microgrid in case 3.

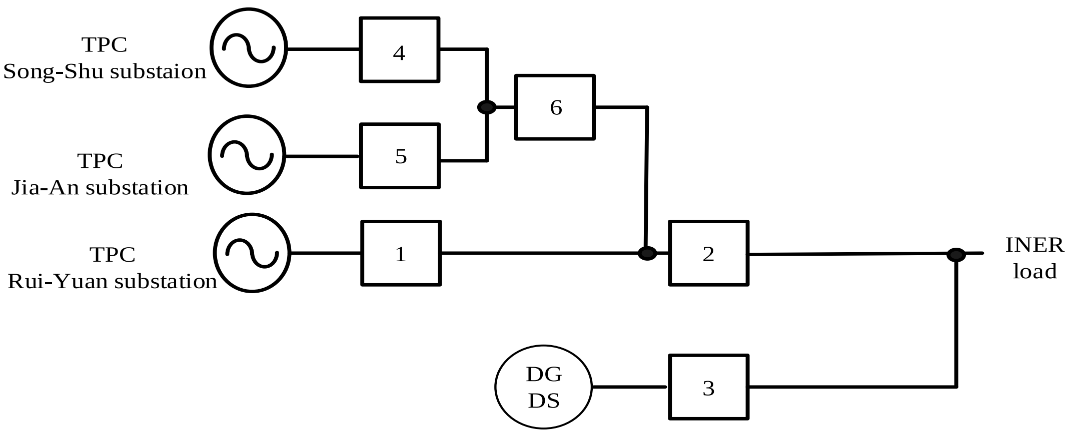

Figure 12. Simplified block diagram of the reliability analysis of the microgrid in case 3.

Table 4. Reliability indices of the loads of the microgid in case 3.

Failure mode	λ（f/yr）	γ（hours）	U（hours/yr）
1//3//6	6.43×10^{-8}	0.6653	4.28×10^{-8}
1//3//4//5	1.07×10^{-16}	0.3077	3.29×10^{-17}
2//3	2.60×10^{-5}	0.7842	2.04×10^{-5}
Overall	2.61×10^{-5}	0.7839	2.05×10^{-5}

6. Conclusion

The design of resilient control and the reliability analysis of a microgrid are proposed in this paper. By the smart switches and the automation program for distribution, the microgrid has self-recovery function and the outage time of users is reduced, then further achieve the goal of upgrading the reliability indices of the microgrid. In the case of the microgrid in INER, the ATS at double of feeder OQ38 and feeder 4E-1, is utilized as the control power of the interlock switch of the high voltage distribution system. The feeder transferring logic in the high voltage monitoring platform of the microgrid is designed. By this logic, if there is a failure at feeder OQ38, the smart switch which connects the distribution system and microgrid is opens consequently, to further make sure the isolation of the feeder with failure from the microgrid. The logic program can transfer the power feeding of the microgrid to the nearby normal feeder within 1 minute, this makes the distributed generators of the microgrid can feed power effectively. By the reliability analysis of this self-recovery function, the average outage time of a single loop of feeder OQ38 connected mirogrid is 2.79×10^{-4}(hours/yr), and that of double loops of feeder OQ38 and feeder 4E-1 connected microgrid is greatly reduced to 2.05×10^{-5} (hours/yr) . The outage duration of users is significantly reduced, and the reliability of the microgrid can be upgraded.

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