

ANTI-FAULT ABILITY EVALUATION OF DISTRIBUTION SYSTEMS

Liu Jian, *Senior member, IEEE* Cheng Hongli Xu Jingqiu
Xi'an University of Science & Technology
Xi'an, 710054, Shaanxi, China
edliu@bylink.com.cn chhl@xust.edu.cn jingqiux@sohu.com

Abstract: A family of parameters to evaluate the anti-fault ability of distribution networks is put forward. The total anti-fault ability is defined as the product of the anti-fault parameter of the network structure and the anti-fault parameter restricted by the limitation of electrical devices. Faults are assumed on each feeder, each bus, each substation and each transmission line, respectively. In each case, a novel approach with the index of minimum load shielding is adopted to restore the load as much as possible. A load balancing method is also discussed. The shielded load due to the network structure and the limitation of the electrical devices are analyzed, respectively. A distribution network anti-fault ability table is used to show the influence range and extend of the various types of faults. A load shielding table ordering the influence extent in turn and a feeder-fault related table showing in which cases a certain feeder section will be shielded due to network structure or security considerations are also presented. An example is given showing that the evaluation of anti-fault ability is helpful for distribution network planning and emergency adjustments.

Keywords: *distribution networks, reliability, security, power system planning, anti-fault ability, evaluation, load shielding managements*

1 INTRODUCTION

Reliability indices are commonly used to evaluate the robust performance of distribution plans and designs [1]. However, it just takes into consideration of the network topology in calculation of reliability except for checking whether an overload occurs after the network reconfiguration. Moreover, reliability indexes are defined to deal with small disturbances such as faults on a feeder section. But, it takes little effect upon the reliability indexes in case of some serious faults, such as faults on HV transmission lines, main substations and buses, due to the quite small probability of such faults.

Rethinking of the large scope blackout of interconnected North America power grid, we realize that although the possibility of disastrous accidents is very small, the harmful effects are very serious [2]. Therefore, it is necessary to emphasize the evaluation of the anti-fault ability of distribution networks in case of disastrous accidents in order to find out the weak parts and to take effective measures in time.

Static security analysis of transmission networks is coped with in the reference [3]. It gives warning to some supposing faults, such as over-load of some electrical equipment, which affects safe operation to power network. Furthermore, it is able to evaluate the safe level so as to find out weak parts in the system

operations. Reference [4] investigates the security analysis of distribution networks.

But the anti-fault ability of distribution networks are not perfectly described since the limitation of electrical apparatus is not considered in [1] while limitation of network structure not taken into consideration in [4].

We put forward a family of parameters to evaluate the anti-fault ability of distribution networks considering both limitations.

2 ANTI-FAULT ABILITY PARAMETERS

2.1 Structural anti-fault ratio (H)

Structural anti-fault ratio of distribution networks (H) is defined as:

$$H = L_{\alpha} / L_T \quad (1)$$

Where, L_T is the total load affected by the fault. L_{α} is the total load can be restored from the viewpoint of the network structure (i.e., not considering the limitation of electrical apparatus) at the emergency state.

ΔL_H was defined as the load to be shielded at the emergency state duo to the limitation of network structure.

$$\Delta L_H = L_T - L_{\alpha} \quad (2)$$

2.2 Safe anti-fault ratio (R)

Safe anti-fault ratio of distribution networks (R) is defined as:

$$R = L_{\beta} / L_{\alpha} \quad (3)$$

Where L_{β} is the total load can be safely supplied considering the limitation of electrical apparatus.

ΔL_R is defined as the load to be shielded for safe operation of the distribution network. It is the load being lost at the emergency state duo to the limitation of electrical apparatus.

$$\Delta L_R = L_{\alpha} - L_{\beta} \quad (4)$$

2.3 Total anti-fault ability (K)

The total anti-fault ability (K) is defined as

$$K = HR \quad (5)$$

ΔL_K is defined as the total load to be shielded at the emergency state, i.e.,

$$\Delta L_K = L_H - L_R \quad (6)$$

K and ΔL_K indicate the ratio of the load can be restored to the load being affected by the fault and the load to be shielded considering both limitations of electrical apparatus and the network structure, respectively.

2.4 Static security indices (S)

Static security index (S) of the i -th apparatus is defined as

$$S_i = I_i / I_{R,i} \quad (7)$$

Where I_i and $I_{R,i}$ are the existing current and the rated current (i.e., the limitation) of the i -th apparatus, respectively.

We defined the security level according to S as

$$S = \begin{cases} 1.2 \sim \infty; & \text{extremely unsafe} \\ 1.0 \sim 1.2; & \text{unsafe} \\ 0.9 \sim 1.0; & \text{with risk} \\ 0.7 \sim 0.9; & \text{safe} \\ 0.0 \sim 0.7; & \text{very safe} \end{cases} \quad (8)$$

2.5 Significance of the proposed parameters

Evaluation of anti-fault ability parameters is helpful to find out the weak parts of distribution networks and to take effective measures in time.

The larger K is, the higher anti-fault ability of a distribution network is. A larger H indicates that the structure of the distribution network is better. A larger R indicates that the capacity of electrical apparatus of the distribution network is more sufficient.

On the other hand, the anti-accident ability of a distribution network is weak in case of K being too small. We need to improve the network structure while H is too small. The capacities of some electrical apparatus need to be expanded if R is too small and the unsafe apparatus before load shielding (i.e., with a rather large S value) is the one should be expanded. Especially, the apparatus with the largest value of S is the weakest part of the distribution network.

3 ANALYSIS OF ANTI-FAULT ABILITY PARAMETERS OF DISTRIBUTION NETWORKS

3.1 Flow chat of anti-fault ability analysis

The procedure of anti-fault ability analysis for a distribution network consists of four parts, i.e., anti-fault ability analysis assuming faults on feeder sections, buses, substations and HV transmission lines.

Flow chat of anti-fault ability analysis assuming faults on each feeder section is shown in Figure 1. After a fault is set on a certain feeder section, the fault section is isolated^[5] while the load of the affected healthy sections are transferred to the other connected feeders as much as possible by closing the corresponding loop switches without considering whether overload would occur. Meanwhile, structural anti-fault ratio (H) and the load to be shielded due to the limitation of network structure ΔL_H can be calculated. Then, a load balancing approach is implemented to avoid overload to the most extent. Static security index (S) of each electrical apparatus is calculated, respectively. Once there are unsafe apparatus (i.e., S larger than 1.0), some load should be shielded until all of the apparatus are safe. Therefore, safe anti-fault ratio (R) and the load to be shielded due to the limitation of electrical apparatus ΔL_R can be calculated. Consequently the total anti-fault

ability (K) and the total load to be shielded (ΔL_K) in case of the assumed fault can be worked out. The network reconfiguration scheme and the shielded load can also be listed. Then, the fault being set on other feeder sections, the similar procedure is carried out respectively, till all of the feeder sections are treated.

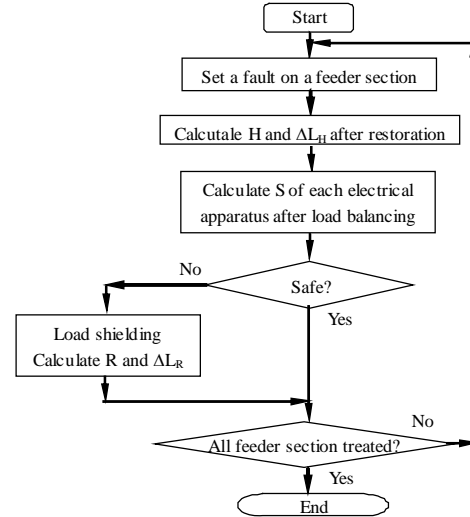


Figure 1: Flow chat of anti-fault ability analysis with faults assumed on each feeder section

The procedures of anti-fault ability analysis assuming faults on buses, substations and HV transmission lines are similar to anti-fault ability analysis assuming faults on feeder sections and will not be detailed in the paper.

3.2 Load balancing approach

Generally, tracing in the direction opposite to the power flow from a certain loop-switch TS_i , we can find two feeders with the corresponding source points (i.e., switches in the main substations). We define the two feeders as a feeder-couple of the loop-switch TS_i . The source point undergoing a larger current is called the hot source point (HSP) while the other one called the cold source point (CSP). The load balance ratio of the i -th feeder-couple (LBC_i) is defined as

$$LBC_i = I_{HSP} / I_{CSP} \quad (9)$$

Where I_{HSP} and I_{CSP} are currents though the hot source point (HSP) and the cold source point (CSP), respectively.

The largest LBC among all of the feeder-couples in an interconnected distribution network is defined as

$$LBD = \text{Max}\{LBC_i : i = 1 \sim N\} \quad (10)$$

Where N is the number of feeder-couples in the interconnected distribution network.

A heuristic approach to find out the topology with the most balancing load is shown in Figure 2.

In Figure 2, ET_0 , ET , ET' and ET'' are arrays of switch states of the initial topology, most balancing topology, temporary topology and quasi-balancing topology, respectively. LBD_0 , LBD and LBD' are the index of distribution network load balance of the initial topology, most balancing topology and temporary topology, respectively.

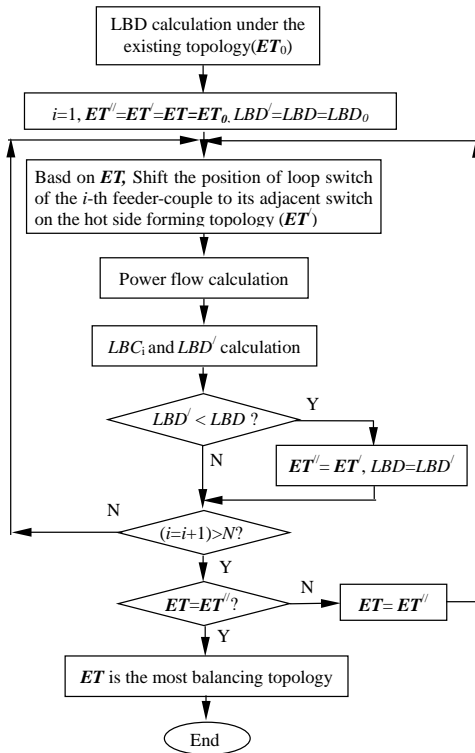


Figure 2: Flow chat of load balancing approach

In fact, the load balancing approach is a greedy procedure. ET is set as the initial topology in the beginning. Based on ET , each loop-switch is moved to its corresponding hot source point (HSP) for one step with calculation of LDB , respectively. The topology with the most decrement of LDB is selected to be the new ET . Such procedure is executed repeatedly until ET not changed.

3.3 Load shielding approach

As for a feeder, m load shielding regions can be obtained by tripping, m load shielding regions can be obtained by tripping, m switches. If the corresponding m regions are not overlapping, the tripping operations of the m switches are defined as independent tripping operation (ITO). Otherwise they are called as dependent tripping operation (DTO).

If there are unsafe apparatus under the most balancing topology, a load shielding approach should be carried out.

Load shielding schemes are based on the switches installed on the feeder. The procedure of load shielding approach under the most balancing topology is as the following steps:

- i) Establish a family of sets $F^{(k)}$ representing the load shielding schemes with k switches need to trip. Let $k=1$.
- ii) Find out the total load to be shielded by power flow calculation under the most balancing topology (ΔL_{Σ}).
- iii) Trip each switch independently to calculate the corresponding shielded load, respectively, forming a set of $F^{(k)}$.

- iv) Execute the scheme in $F^{(k)}$ and calculate the corresponding shielded load, respectively. Find the scheme with the minimum load shielded (ΔL_k) in $F^{(k)}$ and label the scheme as $F_{\min}(k)$. $F_{\min}(k)$ is the minimum load shielded scheme with k switches need to trip.
- v) Eliminate the scheme with shielded load larger than ΔL_k in $F^{(k)}$ and $F^{(l)}$. Add each switch in $F^{(l)}$ to each scheme in $F^{(k)}$ respectively and eliminate the dependent tripping operation (DTO) in the results forming a set of $F^{(k+1)}$.
- vi) Exist if $F^{(k+1)}$ is an empty set $\{\phi\}$. Otherwise let $k=k+1$ and go back to step iv).
- vii) Find the scheme (F_{opt}) with the minimum shielded load (ΔL_{opt}) among $F_{\min}(i)$ s, where $i=1$ to k .

4 ILLUSTRATIVE EXAMPLE

An actual distribution network to explain the proposed anti-fault ability evaluation method is shown in Figure 3.

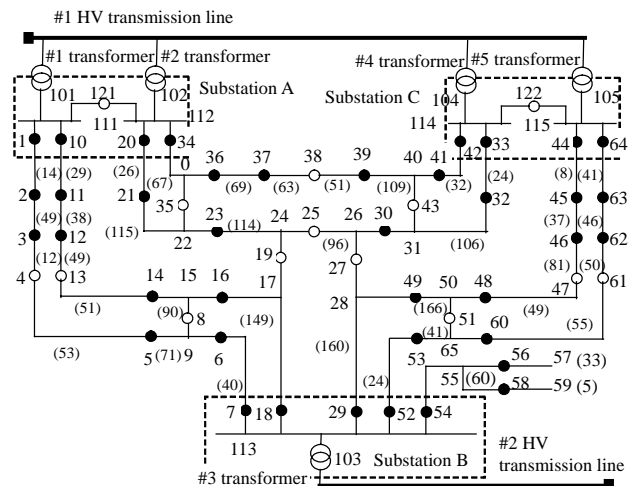


Figure 3: An actual distribution network to explain the proposed anti-fault ability evaluation method

The rated current of each main transformer (i.e., the nodes labeled by 101, 102, 103, 104 and 105) is 2000A. The capacity limitation of each bus (i.e., the nodes labeled by 111, 112, 113, 114 and 115) is also 2000A. The rated current of each feeder switch is 400A. The tapped load of each feeder section is shown as numbers in brackets (the numbers after decimal point is ignored to simplify the analysis). The circles in the figure represent the switches. The solid circles represent the closed switches (i.e., sectionalizing switches). The blank circles represent the tripped switches (i.e., loop switches). The number besides each switch is its coding number.

The anti-fault ability is evaluated by the proposed method described in paragraph two and three. The results are listed in Table 1.

A lot of information can be obtained from Table 1. Once a fault occurred on #2 HV transmission line or

substation B or Bus 113, the healthy regions won't be entirely restored due to the limitation of network structure. Besides, some load should be shielded as well due to the limitation of electrical apparatus. Once a fault occurred on feeder section 54-56-58, the healthy regions won't be entirely restored due to the limitation of network structure. Once a fault occurred on #1 HV transmission line or substation A or substation C or Bus 111, 112, 114 or 115, although all of the healthy regions would be able to be restored on the viewpoint of

network structure, some load should be shielded as well due to the limitation of electrical apparatus. As for faults occurred on the other parts, all of the healthy regions would be able to be restored on the viewpoint of either network structure or limitation of electrical apparatus. The load balancing schemes and the minimum load shielding schemes to guarantee safe operation and avoid large scope blackout are also listed in Table 1.

| Fault position | H | ΔL_H | Unsafe apparatus before load shielding | $S_i(\%)$ | R | ΔL_R | ΔL_K | $K(\%)$ | Network reconfiguration scheme | Shielded feeder sections |
|-------------------------|------|--------------|--|--|-------|--------------|--------------|---------|--|--|
| #1 HV transmission line | 1.0 | 0.0 | Switch 7 Switch 18 Switch 29 Switch 52 Switch 6 Switch 19 Switch 27 Switch 53 Feeder 7-6 Feeder 9-6 Feeder 17-18 Feeder 19-23 Feeder 27-29 Feeder 27-30 Feeder 52-53 Feeder 53-65 | 124 151 145 150 114 114 105 144 124 114 151 114 145 105 150 144 | 0.446 | 734 | 734 | 44.6 | Switches to trip: 1, 10, 20, 34, 42, 33, 44, 64, 11, 16, 21, 49, 32, 62 Switches to close: 13, 8, 61, 19, 27, 51 | 1-2 2-3 3-4 10-11 20-21 34-35-36 36-37 37-38 39-43-41 41-42 38-39 44-45 45-46 46-47 62-63 63-64 |
| #2 HV transmission line | 0.91 | 0.98 | Switch 10 Feeder 10-11 | 102 102 | 0.843 | 149 | 247 | 76.3 | Switches to trip: 7, 18, 29, 52, 54, 49, 16 Switches to close: 4, 13, 47, 61 | 16-18-19 54-56-58 56-57 58-59 |
| Substation C | 1.0 | 0.0 | Switch 29 Feeder 29-28 Switch 18 Feeder 18-19 | 125 125 101 101 | 0.624 | 256 | 256 | 62.4 | Switches to trip: 23, 16, 14, 5, 33, 42, 44, 64, 30 Switches to close: 25,38,61,19,8,13,4 | 44-45 45-46 46-47 |
| Substation A | 1.0 | 0.0 | Switch 18 Feeder 18-16 Switch 33 Feeder 33-32 Feeder 32-31 | 102 102 120 120 114 | 0.736 | 170 | 170 | 73.6 | Switches to trip: 1, 10, 20, 34, 49, 48, 60, 11, 23 Switches to close: 4, 13, 25, 38, 51, 47, 61 | 10-11 20-21 21-22-23 |
| Bus 115 | 1.0 | 0.0 | Switch 29 Feeder 29-28 | 125 125 | 0.521 | 126 | 126 | 52.1 | Switches to trip: 44, 64, 14, 5, 16 Switches to close: 61, 13, 4, 8 | 44-45 45-46 46-47 |
| Bus 111 | 1.0 | 0.0 | Switch 18 Feeder 18-16 | 102 102 | 0.848 | 29 | 29 | 84.8 | Switches to trip: 1, 10, 49, 48, 60, 11 Switches to close: 4, 13, 51, 47, 61 | 10-11 |
| Bus 112 | 1.0 | 0.0 | Switch 18 Feeder 18-16 | 101 101 | 0.943 | 26 | 26 | 94.3 | Switches to trip: 20, 34, 49, 16, 48, 14, 5, 60, 21; Switches to close: 19, 38, 51, 8, 47, 13, 4, 61 | 20-21 |
| Feeder section 54-56-58 | 0.0 | 38 | | | | | 38 | 0.0 | Switches to trip:54 | 56-57 58-59 |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |

Table 1: Distribution network anti-fault ability table

By ordering the contents in Table 1 in accordance with the amount of the healthy load must be shielded, the shielded load table is obtained as shown in Table 2.

| Fault position | ΔL_T (A) |
|-----------------------------------|------------------|
| #1 HV transmission line | 734 |
| Substation C | 256 |
| #2 HV transmission line | 247 |
| (or Substation B or Bus 113) | |
| Substation A | 170 |
| Bus 115 | 126 |
| Feeder section 54-56-58 | 38 |
| Bus 111 | 29 |
| Bus 112 | 26 |

Table 2: Shielded load table in case of various faults

It can be seen from Table 1 and Table 2 that faults on #1 HV transmission line may cause large scope blackout, faults on substation A or substation B or substation C or #2 HV transmission line or bus 113 or bus 115 may produce remarkable blackout, and that faults on feeder section 54-56-58 or bus 111 or bus 112 may also have serious influences on the distribution network.

According to Table 1, the feeder-fault related table can be formed as shown in Table.3 indicating the faults resulting in a healthy feeder section shielded. For instance, even if no faults occur on feeder section 44-45, 45-46 and 46-47, they have to be shielded in case of a fault occurs on #1 HV transmission line or substation C or Bus 115.

| Affected healthy feeder section | Related faults |
|---------------------------------|---|
| 44-45 | #1 HV transmission line Substation C Bus 115 |
| 45-46 | #1 HV transmission line Substation C Bus 115 |
| 46-47 | #1 HV transmission line Substation C Bus 115 |
| 10-11 | #1 HV transmission line Substation C Bus 111 |
| 20-21 | #1 HV transmission line Substation A Bus 112 |
| 56-57 | #2 HV transmission line Substation B Bus 113 Feeder section 54-56-58 |
| | |

Table 3: Feeder-fault related table

5 CONCLUSIONS

The approach of anti-fault ability evaluation is presented, which is a useful tool to find out key and weak parts in distribution networks. The total anti-fault ability (K) indicates the ability to restore affected healthy regions at the emergency state. K is defined as the product of the structural anti-fault ratio (H) and the safe anti-fault ratio (R). H indicates the ability to restore affected healthy regions from the viewpoint of network structure. R indicates the ability to restore affected healthy regions from the viewpoint of the limitation of the capacity of electrical apparatus.

Anti-fault ability evaluation is significant in expansion planning to improve the grid. It is also an important way to guarantee safe operation of distribution networks. Based on the proposed methods of load balancing and minimum load shielding plan, the operation scheme for fast restoration to avoid large scope blackout is also formed during anti-fault ability evaluation.

One of the advantages of anti-fault ability evaluation is that it may take both network structure and limitation of electrical apparatus into consideration.

The proposed approach was applied into the expansion planning and fast restoration of the distribution network in Xi'an city. The large scope and long time black out due to bus faults and transformer failure were avoided for two times since 2002.

The improvement of introducing uncertainty into the proposed approach is being investigated. Some results have shown that the improved approach is of remarkable promise on risk evaluation and economic planning.

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