A NOVEL FLISR RELIABILITY ASSESSMENT METHOD IN FEEDER AUTOMATION

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Fault location, isolation and service restoration (FLISR) in the feeder automation (FA) is usually used to improve the power supply reliability and provide outage management. The FLISR failure mechanism was analyzed based on the programmed sequences and intervals of the feeder terminal units (FTUs), master station of distribution automation system (MS-DAS) and the communication channel. Zero-failure reliability demonstration test was used to evaluate the FLISR reliability. Different from traditional evaluation in the pass/fail verification, normalized FLISR reliability assessed value was identified according to several FLISR test result scenarios, which include normal operation, isolation area expansion, whole system failure and fault area expansion scenarios. The final FLISR reliability was evaluated based on the statistical assessed value data of each test samples. The case study helps to prove the effectiveness of the proposed FLISR reliability assessment method. The research results could be used to evaluate the FLISR practical value in the field.

Keywords: Failure mechanism; FLISR; feeder automation, reliability assessment, feeder terminal unit.

1. Introduction

Fault location, isolation and service restoration (FLISR) in feeder automation (FA) is widely used in the modern urban and rural power distribution networks recently [1]. It is usually used to improve the power supply reliability and reduce the power outages loss in the electrical power distribution network (EPDN) [2].

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Existing methods proposed to evaluate the EPDN reliability are generally based on direct analytical techniques or Monte Carlo simulation [3-5]. The reliability of the distribution system with FA is determined by the traditional primary power distribution equipment and the installed automation equipment. Since the system reliability increases with the addition of the more automated switches and the corresponding FLISR function, the breadth-first-search techniques, event-tree methodology or other measures are used to consider complicated isolation and restoration procedures in EPDN reliability evaluation [6-7]. The analysis results show that FLISR can eliminate the need to perform switching operations manually and could have a significant effect on the system reliability [8].

A switch encountering failure may increase the system failure rate and result in deteriorating system reliability [9]. But FLISR failure is not considered in existing EPDN reliability evaluation methods. FLISR reliability evaluation method is important to the EPDN reliability assessment. FLISR is realized based on the distribution remote terminal units (DRTUs), which are also known as feeder terminal unit (FTU). FTUs are used to monitor and remote/local control the corresponding switches [10]. FLISR can be categorized into two groups based on the coordinated control of the FTUs, include FLISR with centralized intelligent control mode and FLISR with local reclosing control mode [11,12]. FLISR reliability with different control modes should be evaluated before it is put into production. Several FLISR test beds have been proposed and developed in laboratory environments to verify FLISR functions [13]. These platforms can only simulate limited types of faults and cannot be used in the field. An injection methodology is proposed to test the master station of distribution automation system (MS-DAS) based on a research and on-site test system in the field [14]. The FLISR with configuration and settings of the FTUs can be tested and validated. At the meantime, the action sequence of the FLISR was also tested based on the simulation platform or portable testing devices [15]. These proposed platforms are focused on the FLISR test tools implement. But the FLISR reliability assessment method is not discussed in these papers. Moreover, the number of test samples or the reliability assessment value should be given for the FLISR with different control modes. In this paper, the failure mechanisms of the FLISR with different control modes are analyzed during the fault handling process at first. Secondly, the FLISR reliability assessment method is proposed and illustrated according to the FLISR test results. The case study shows that the FLISR reliability evaluation can be carried out based on our proposed method efficiently.

2. FLISR failure mechanism analysis in feeder automation

2.1 Failure mechanisms of the FLISR with local reclosing control mode

In the local reclosing control mode, FLISR was realized by the coordinated control of the distributed voltage-time type feeder terminal units (VT-FTUs). Each sectionalizing switch was controlled by the corresponding VT-FTU with two setting time parameters, including X time length and Y time length. If the distribution line section located before the switch was energized, the corresponding VT-FTU would send the close signal to the switch after X time length. The switch would be kept on the open status by the corresponding VT-FTU if the distribution line lost electricity within Y time length after the switch was closed.

One simple ring main feeder is taken as an example and shown in Figure 1. There are two automatic reclosing devices (ARDs), n switches and the corresponding n FTUs. The $(m+1)^{th}$ switch is the tie switch with open status in the normal operation. There are m switches and the corresponding m FTUs between the ARD_1 and the tie switch, and n-m-1 switches and the corresponding FTUs between the ARD_2 and the tie switch.
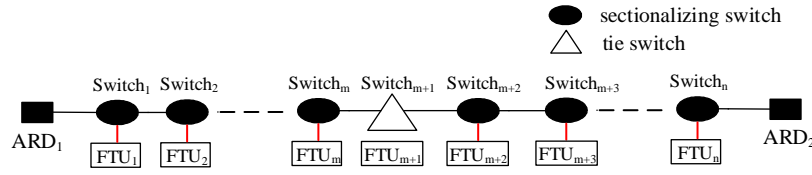

Fig. 1. The structure of one simple ring main feeder

The X time length of the ith FTU is represented by t_{xi}, and the Y time length of the ith FTU is represented by t_{iy}.

Assuming one permanent fault occurred on the section between the kth switch and $(k+1)^{th}$ switch at the time of t_0, and the number k is smaller than m.

The ARD_1 would trip the distribution line for the first time and then reclose the line at time t_{0y}, t_{0y} represents the reclosing time set in ARD. The ith FTU would send the close signal to the corresponding i^{th} switch at the time of t_{ci} given by,

$$t_{ci} = t_0 + t_{0y} + \sum_{p=1}^{i} t_{xp} \quad , i \le k \quad (1)$$

Once the kth switch closed under the control of the kth FTU at time $t_0 + t_{0y} + \sum_{p=1}^{k} t_{xp}$, the ARD_1 would trip the distribution line. Hence the kth switch would be kept in the open status according to the setting Y time length. And then

the ARD$_1$ would reclose the line at time $t_0 + 2t_{0y} + \sum_{p=1}^{k} t_{xp}$. The ith FTU would send

the close signal to the corresponding i^{th} switch for the second time at the time of t_{ci2} given by,

$$
\begin{cases}
t_{ci2} = t_0 + 2t_{0y} + \sum_{p=1}^{k} t_{xp} + \sum_{q=1}^{i} t_{xq} \,, & i < k \\
t_{ci2} = t_0 + t_{x(m+1)} + \sum_{p=i}^{m} t_{xp} \,, & k+1 < i < m+1
\end{cases}
\tag{2}
$$

where $t_{x(m+1)}$ represents the setting X time length in the tie switch numbered by $m+1$.

If all FTUs could control the corresponding switches according to the equations (1) and (2), the FLISR would be done after the $(k+2)^{\text{th}}$ switch was closed at time $t_0 + t_{x(m+1)} + \sum_{p=k+2}^{m} t_{xp}$. If any FTU did not act as the pre-set logic, the fault isolation area would be expanded.

2.2 Failure mechanisms of the FLISR with centralized intelligent control mode

In the FLISR with centralized intelligent control mode, the fault was located by the MS-DAS. Then the fault area would be isolated and the healthy area would restore the power supply service by the corresponding switches controlled by the FTUs.
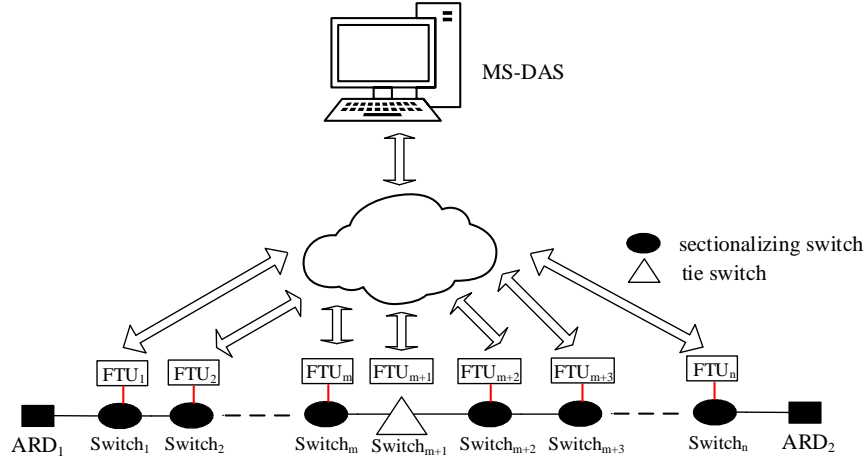

Fig. 2. The schematic diagram of FLISR with centralized intelligent control mode

The principle of the FLISR with centralized intelligent control mode is shown in Figure 2. The feeder model would be constructed in the MS-DAS to describe the topology of the feeder in the field. Once a fault occurred on the

feeder in the field, the FTU would send overcurrent signal to the MS-DAS through the communication system if overcurrent was detected. The feeder model and the uploaded over-current signals would be used to locate the fault position based on the fault location built-in subroutine in the MS-DAS. And then the optimal fault isolation and service restoration scheme can be generated and selected by the MS-DAS. It would issue control commands to the FTUs to open or close the corresponding sectionalizing switches. Then the duration of the FLISR with centralized intelligent control mode is given by,

$$t_p = t_d + 2t_c + t_m + t_s \qquad\qquad (3)$$

where t_d represents the overcurrent detection time needed for the FTU; t_c represents the communication latency; t_m represents the consuming time of the built-in advanced fault healing subroutine in the MS-DAS; t_s represents the switching time of the switches.

According to the equation (3), the FLISR would be done after time t_p if all components were in normal operation. If MS-DAS or communication channel failed, the whole FLISR system would fail. If wrong fault isolation and service restoration schemes were identified from the MS-DAS, the isolation area would be expanded or the fault area would be expanded, which was determined by the detailed schemes. If the FTUs failed, the isolation area would be expanded.

3. FLISR reliability assessment method in feeder automation

The FLISR only work while one permanent fault occurred on the feeder, while it does not work if no fault occurred. Hence, FLISR belongs to the discrete-type system. Its reliability cannot be represented by the mean time to failure (MTTF) or mean time between failures (MTBF) [16]. In the field, once a fault occurred, FLISR should act in the accurate pre-set logic. So, the engineers in the electricity utilities are only concerned with the number of FLISR failures. For the FLISR reliability assessment method, the number of the test samples should be first identified. Secondly, there are several abovementioned scenarios for the FLISR status, including normal operation, isolation area expansion, whole system failure and fault area expansion scenarios. The reliability evaluation value for each test result should be determined in these four scenarios.

Traditional zero failure reliability testing means the product can be accepted only if no failures occurred in a specified testing time [17]. In our discrete-type FLISR reliability evaluation, the number of test samples should be identified at first. Assuming the acceptable FLISR reliability level equals R, then the FLISR risk P under n test samples in zero failure reliability testing,

$$P = R^n \qquad\qquad (4)$$

If the acceptable FLISR risk equals P_1 and the desirable FLISR reliability level equals R_1, then the minimum test number $n_{\min}$ is determined by,

$$n_{\min} = \text{int}(\frac{\lg P_1}{\lg R_1}) \tag{5}$$

where function int() means the rounding up to the nearest integer.

The FLISR risk should be as small as possible and its desirable reliability level should be as high as possible. The minimum FLISR test number is related to the risk and desirable reliability level. The detailed result is given in the Figure 3 when the risk probability varies from 0.01 to 0.10 and the desirable reliability level varies from 0.980 to 0.999. If the risk probability equals 0.05, the minimum test number varies from 149 to 2994 when the desirable reliability level varies from 0.980 to 0.999. If the risk probability equals 0.01, the minimum test number would equal 228 when the reliability level equals 0.980 and the number would equal 4603 when the reliability level equals 0.999. Typical parameters used in the field is that risk probability equals 0.05 and the desirable reliability level equals 0.985, then the typical test number usually equals 199.
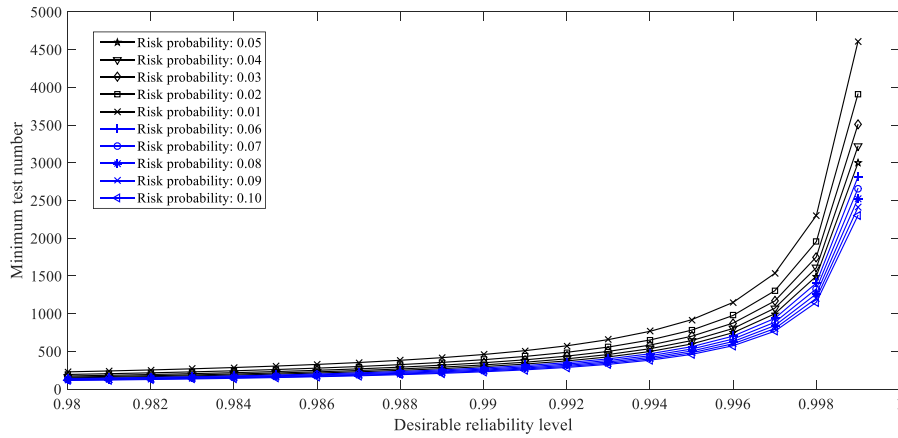

Fig. 3. The relationship between the minimum test number and the desirable reliability level

The final FLISR reliability assessment value R_s should be identified according to every test result by,

$$R_s = \frac{\sum_{i=1}^{n_{\min}} R_{si}}{n_{\min}} \tag{6}$$

where R_s represents the final FLISR reliability assessment value, R_{si} represents the reliability assessment value of the ith test result, $n_{\min}$ represents the minimum test number obtained by the equation (5).

Based on the failure mechanism analysis results, the test results could be categorized into two groups in the FLISR with local reclosing control mode, one is the normal operation and the other is the isolation area expansion. The test results could be categorized into four groups in the FLISR with centralized

intelligent control mode, which are normal operation, isolation area expansion, whole system failure and fault area expansion separately.

The reliability assessment value of each test result should be given according to the test result. If the test result is that the FLISR work in the normal operation, the reliability assessment value R_{si} equals 1.0. If the test result is that the whole FLISR system fail, the reliability assessment value R_{si} equals 0. If the test result is that the fault area is expanded, the equipment associated with the feeder is damaged for the second time. So, the corresponding reliability assessment value is selected as negative value of the test number. And then the final assessment value R_s would be negative and the reliability assessment cannot be acceptable by the utilities if any fault area expansion appeared. If the test result is that the isolation area is expanded, the FLISR can reduce the outage cost. So, the reliability assessment value ranges from 0 to 1.0. The assessment value for the test result with isolation area expansion is determined by,

$$R_{si} = \frac{A_s - A_t}{A_s - A_f} \tag{7}$$

where A_s represents the whole electricity load supplied by the feeder, A_t represents the electricity load in the isolation area of the test result, A_f represents the electricity load in the theoretical isolation area if the FLISR works in the normal operation. The abovementioned reliability assessment value of each test result is summarized and given in Table 1 and Table 2.
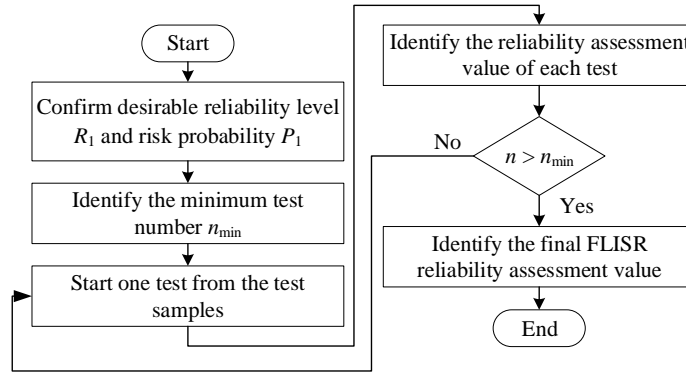

Fig. 4. The flow chart of the proposed FLISR reliability assessment method

The flow chart of the FLISR reliability assessment method is shown in Figure 4. It can be done with the following steps.

Step 1: The desirable reliability level R_1 and risk probability P_1 should be determined based on the actual demand in the field at first.

Step 2: The minimum test number for the FLISR is identified based on the equation (5).

Step 3: The reliability assessment value of each test result is given based on Table 1 and Table 2.

Reliability assessment value of each test result for FLISR with local reclosing control

FLISR test result	Reliability assessment value
Normal operation	1.0
Isolation area expansion	$(A_s - A_t)/(A_s - A_f)$, given in equation (7)

Reliability assessment value of each test result for FLISR with centralized intelligent control

FLISR test result	Reliability assessment value
Normal operation	1.0
Isolation area expansion	$(A_s - A_t)/(A_s - A_f)$, given in equation (7)
Whole system failure	0
Fault area expansion	$-n_{min}$, n_{min} represents the test number

Step 4: The final FLISR reliability assessment value is identified based on the equation (6).

4. Case study

One ring main feeder in the field is shown in Figure 5. There are seven sections in the main distribution line. The FLISR with centralized intelligent control mode is used in this case.
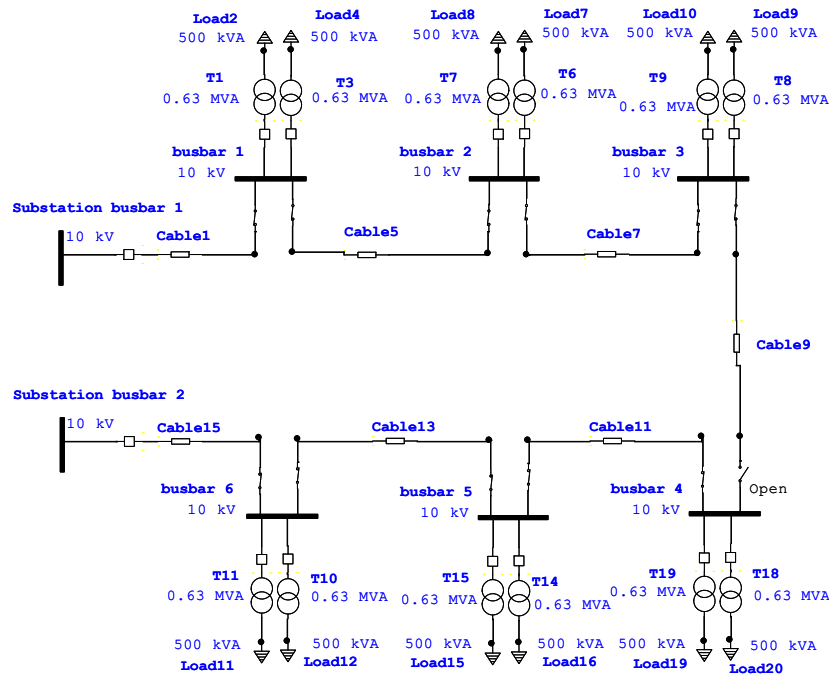

Fig. 5. The schematic diagram of one ring main feeder in the field

The FLISR reliability should be evaluated before it is put into production.

Step 1: According to the FLISR failure mechanism analysis results, FLISR with centralized intelligent control mode may work in normal operation, isolation area expansion, whole system failure and fault area expansion scenarios.

Step 2: The risk probability was set to 0.05 and the desirable reliability level was set to 0.985, then the minimum test number equals 199.

Step 3: All test cases were set up with different fault locations, fault types and fault resistances.

Step 4: The FLISR reliability assessment value of each test results were identified and recorded. There is no fault area expansion scenario existing in the test results.

Step 5: The final FLISR reliability assessment value was identified and equals 0.89.

The fault healing capability of the FLISR can be evaluated and verified based on the proposed reliability assessment method. The final FLISR reliability assessment value can reflect the practical value of the FLISR in feeder automation.

5. Conclusion

Fault location, isolation and service restoration (FLISR) in feeder automation is usually used to improve the power supply reliability and provide outage management. FLISR failure mechanism is analyzed, and its reliability assessment method is proposed to evaluate FLISR practical value in fault healing. The case study has proved the effectiveness of the proposed FLISR reliability assessment method.

(1) The action sequences of FLISR with centralized intelligent control mode and local reclosing control mode are analyzed. The FLISR with local reclosing control mode may work in normal operation or isolation area expansion scenarios. The FLISR with centralized intelligent control mode may work in normal operation, isolation area expansion, whole system failure and fault area expansion scenarios.

(2) Since FLISR belongs to discrete-type system, the test numbers for the reliability assessment are identified by the acceptable FLISR operation risk and the desirable FLISR reliability level. The final FLISR reliability assessment value can be obtained according to the assessment value of each test results, which are categorized into the abovementioned scenarios.

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