Research of Distribution Network Reliability Assessment by ETAP Software

Huynh Tien Dat1,2,3, Nguyen Thi Bich Tuyen1,2,3,*, Nguyen Ngoc Phuc Diem1,2, and Le Quang Binh5

ARTICLE INFO

Article history:
Received: 20 July 2020
Revised: 1 September 2020
Accepted: 12 November 2020

Keywords:
Distribution network reliability
Distribution network reliability indices
ETAP application for the Distribution network reliability

ABSTRACT

In this day and age, the concern for the power system reliability issue is, indeed, in line with the ever-accelerating world’s economic growth. Besides sociology, politics, and science, the power system reliability is also a pivotal standard in evaluating a nation’s development rate. A highly-reliable power system has always been a stepping stone for investment in massive production, stability in national security, and improvement in citizen satisfaction. As a result, exhaustive researches that gain insight into the power system reliability’s problems become increasingly necessary for society. Based on such researches, we can accurately evaluate the situation leading to reasonable troubleshooting as well as proposing appropriate operating methods and shaping an optimal course of development in the long run. Among problems relevant to the reliability, the ones which are related to the Distribution network reliability, are considered as the most crucial, for they directly affect the customers’ benefits and a deluge of sophisticated technology is often applied to effectively control and operate this sort of network. Furthermore, it is the massive and complex scale of the network’s grid that places the most challenging constraint on detecting its problems such as errors or malfunctions. However, thanks to the proliferation of digital software programs and applications, these problems are now easily be coped with. This paper will illustrate both various characteristics and instructions for applying the Reliability Function of the ETAP into the Distribution network together with some typical instances.

1. INTRODUCTION

The Power system Reliability problem has been such a classic one for numerous decades. The person who laid the foundation for this solution is R. Billinton with his famous book (with R N Allan) “Reliability Evaluation of Power Systems”. In this book [1], Billinton pointed out that the Reliability evaluation of a Distribution network consists of two distinct aspects [2]:

- The first aspect: Evaluating past performance. Most electrical power utilities collect past system data and display the performance using a range of statistics [1]. Some of the basic indices used to assess the past performance of the Distribution network [1]. Reference [3] demonstrates this aspect. Despite being used repeatedly by utilities, there is little potential for research, so researchers are not appealed to this aspect.

- The second aspect: Predicting future performance. The indices obtained from a predictive assessment are the same as those usually calculated in a historical performance assessment [2]. However, instead of using historical data to evaluate the past, we predict the future. References [4] [5] [6] are examples of the application of this aspect.

The second aspect has definitely drawn researchers' attention; as a result, there are more achievements relating to it. Reference [7] summarized mathematical methods for predictive assessment in the power system. To be specific, these methods include the Analytical Graph method, the State Space method, the Failure Tree method, and the Monte-Carlo method. Reference [8] was the research of the State Space method's application. Using the Failure Tree method to assess Distribution network reliability is presented in reference [9]. This method helps us to comprehend more deeply about the grid but is not effective for a large object such as Distribution networks. Monte Carlo method is particularly the most popular. Through references [2] [10] [11] [12], the authors pointed out the advantages and disadvantages of this method as well as its application in practical network problems. Although the Monte-Carlo method is possible to find a probability
distribution of reliability indices via considering more factors, it is unnecessary for the reliability problem in the Distribution network. Currently, with the development of computers, the Analytical Graph method is gaining currency and becomes the main method of calculating reliability in Power system computing software; ETAP [13], PSS-Adept [14], CYMDIST-Reliability Assessment Module (RAM) [15] are examples. Among them, ETAP is arguably the most used. Reference [16] used ETAP to evaluate the reliability of Roy Billinton Test System (RBTS) Bus 2 [17] but the authors did not specify how to perform nor showed the influence of the timed segmental device and the ring network. We present this paper to solve the aforementioned problems in order to prove that ETAP is totally reliable and extremely accurate in assessing all forms of the Distribution network reliability.

Here is the outline of this paper. First, Section 2 presents an overview of the Distribution network reliability. Second, Section 3 introduces the Distribution network reliability indices. Third, Section 4 provides guidance on the Reliability function of ETAP. Next, simulations and numerical results are presented and discussed in Section 5 which is followed by conclusions in Section 6.

2. AN OVERVIEW OF THE DISTRIBUTION NETWORK RELIABILITY

The Distribution network (DN) is a portion of the electrical power system that links the intermediate station to the consuming loads [2].

DN must supply the loads with its reliability and quality within the allowable limits [18].

We often divide DN into 2 types which are medium voltage grid (MVG) and low voltage grid (LVG). In Vietnam, MVG is a 22kV voltage grid and LGV is a 0.4 kV voltage grid.

After there, when mentioning DN reliability, we implicitly assume that it is MVG reliability. This paper doesn’t mention LVG reliability.

DN is also classified by [18]:
- According to the conductor: Overhead DN and Underground cable DN.
- According to the structure: radial DN and ring DN.

According to reference [2], to enhance the power supply reliability, DN is designed in a ring structure but operated in a radial structure. The radial DN is simple in operation, protection, and maintenance while the ring DN provides alternative sources in the case of a failure. These alternative sources are used to supply that section of the main feeder which becomes disconnected from the main supply after the faulted section has been isolated. ‘Fuse cut out’ is usually provided on the distribution branch. Faults on the distribution branch or in the distribution transformer are normally cleared by fuses and therefore service on the main feeder is maintained. If the fuse fails to clear the fault for some reason, the circuit breaker (CB) on the main feeder acts to clear the fault. The faulted distribution branch is then isolated and the supply is restored to the healthy elements by closing the CB.

As mentioned, in reliability problems, the Distribution network reliability problem is most concerned [2]. Analysis of customer interruptions of different electrical utilities around the world shows that Distribution networks account for up to 80-90% of reliability problems [16]. Therefore, evaluating and improving the reliability of the distribution network is important for improving customer reliability [16]. The task of researching the reliability problem at the distribution network is to solve the issues of how to design, maintain and operate the DN to provide power to the customer continuously and ensure the most reasonable economic, reduce to minimum damage due to power outage.

3. DISTRIBUTION NETWORK RELIABILITY INDICES

3.1. Generally

To enhance the power supply reliability, DN is designed in a ring structure but operated in a radial structure. Therefore, DN reliability indices revolve around this radial network [19].

3.2. Load point reliability indices

The basic unit to consider of the DN reliability problem is the load point (corresponding to a distribution transformer) [13]:

- **Average Permanent Failure Rate at Load Point i (1/period)**
  \[ \lambda_i = \sum_{j \in N_e} \lambda_{e,j} \]  
  \[ N_e \] is the total number of the elements whose faults will interrupt load point i
  \[ \lambda_{e,j} \] is the average permanent failure rate of element j in \[ N_e \]
  
- **Average Transient Failure Rate at Load Point i (1/period)**
  \[ \lambda'_i = \sum_{j \in N_e} \lambda'_{e,j} \]  
  \[ \lambda'_{e,j} \] is the average transient failure rate of element j in \[ N_e \]
  
- **Total Outage Duration at Load Point i (h/period)**
  \[ u_i = \sum_{j \in N_e} (\lambda_{e,j} \cdot r_{ij}) \]  
  \[ r_{ij} \] is the failure duration at load point i due to a failed element j in \[ N_e \]
  
- **Average Outage Duration at Load Point i (h)**
  \[ r_i = \frac{u_i}{\lambda_i} \]
- Expected Energy Not Supplied Index at Load Point i (Wh/period)
  \[ \text{EENS}_i = P_i \cdot u_i \]  
  \( P_i \) is the average load of load point i  
- Expected Interruption Cost Index at Load Point i ($/period)
  \[ \text{ECOST}_i = P_i \cdot \sum_{j \in \text{N}_i} (f_i(r_{ij}), \lambda_{ij}) \]  
  \( f_i(r_{ij}) \) is Sector Customer Damage Function (SCDF), the function indicates the interruption costs for several discrete outage durations  
- Interrupted Energy Assessment Rate Index at Load Point i ($/Wh)
  \[ \text{IEAR}_i = \frac{\text{ECOST}_i}{\text{EENS}_i} \]  

3.3. Distribution system reliability indices

From the Load point reliability indices above, we calculate the distribution system reliability indices according to IEEE 1366 standard [20]:  
- SAIFI \( (f/\text{customer.\:period}) \) – System Average Interruption Frequency Index
  \[ \text{SAIFI} = \frac{\text{Total number of customer interruptions}}{\text{Total number of customer served}} = \frac{\sum \lambda_i N_i}{\sum N_i} \]  
  \( N_i \) is the number of customers at load point i  
  \( \lambda_i \) is the Average Permanent Failure Rate at Load Point i (from the load point reliability indices above)  
- SAIDI \( (h/\text{customer.\:period}) \) – System Average Interruption Duration Index
  \[ \text{SAIDI} = \frac{\text{Sum of customer interruption duration}}{\text{total number of customer served}} = \frac{\sum u_i N_i}{\sum N_i} \]  
  \( u_i \) is the Total Outage Duration at Load Point i (from the load point reliability indices above)  
- CAIDI \( (h) \) – Customer Average Interruption Duration Index
  \[ \text{CAIDI} = \frac{\text{Sum of customer interruption duration}}{\text{total number of customer interruptions}} = \frac{\text{SAIDI}}{\text{SAIFI}} \]  
- ASAI – Average Service Availability Index
  \[ \text{ASAI} = \frac{\text{Customer hours of available service}}{\text{customer hours demanded}} = \frac{\sum N_i h - \sum u_i h}{\sum N_i h} \]  
  \( h \) is the number of hours in the period  
- ASUI - Average Service Unavailability Index
  \[ \text{ASUI} = 1 - \text{ASAI} \]  
- MAIFI \( (f/\text{customer.\:period}) \) – Momentary Average Interruption Frequency Index
  \[ \text{MAIFI} = \frac{\text{Total number of customer interruptions}}{\text{Total number of customer served}} = \frac{\sum \lambda_i N_i}{\sum N_i} \]  
  \( \lambda_i \) is the Average Transient Failure Rate at Load Point i (from the load point reliability indices above)  
- System EENS – System Expected Energy Not Supplied Index
  \[ \text{EENS} = \sum P_i \cdot u_i = \sum \text{EENS}_i \]  
  \( \text{EENS}_i \) is the Expected Energy Not Supplied Index at Load Point i (from the load point reliability indices above)  
- System AENS \( (\text{Wh/\:customer.\:period}) \) – System Average Energy Not Supplied Index
  \[ \text{AENS} = \frac{\text{Total energy not supplied by the system}}{\text{total number of customer served}} = \frac{\sum \text{EENS}_i}{\sum N_i} \]  
- System ECOST \( ($) / \text{period} \) – System Expected Interruption Cost Index
  \[ \text{ECOST} = \sum \text{ECOST}_i = \sum (P_i \cdot \sum_{j \in \text{N}_i} f_i(r_{ij}), \lambda_{ij}) \]  
  \( f_i(r_{ij}) \) is Sector Customer Damage Function (SCDF)  
- System IEAR \( ($) / \text{Wh} \) – System Interrupted Energy Assessment Rate Index
  \[ \text{IEAR} = \frac{\text{ECOST}}{\text{EENS}} \]  

4. RELIABILITY FUNCTION OF ETAP

4.1. General implementation steps

The first 3 steps will be described below in this section, the last step will be demonstrated in Section 5.

![Fig. 1: General implementation steps in Reliability function.](image-url)
4.2. Drawing the grid diagram

Firstly, we have to draw the One-Line diagram of the network that we want to assess. The diagram has the following components: sources, buses, conductors, switches, fuses, loads. Then we name it logically. There is a simple example below:

Fig. 2: An example of the one-line diagram in Etap.

Note: L₁, L₂, L₃, L₄, L₅, L₆, L₇, L₈ represent the lines (conductors).

4.3. Entering the element reliability parameters

After drawing the network diagram, we need to enter the reliability parameters in the Reliability tab of each element [13]:

Fig. 3: Reliability tab of each element in ETAP.

- $\lambda_A$ (f/yr): This is the Active failure rate in the number of failures per year per unit length. The active failure rate is associated with the component failure mode that causes the operation of the primary protection zone around the failed component and can therefore cause the removal of the other healthy components and branches from service (ex: short circuit fault).
- $\lambda_P$ (f/yr): This is the Passive failure rate in the number of failures per year per unit length. The passive failure rate is associated with the component failure mode that does not cause the operation of protection breakers and therefore does not have an impact on the remaining healthy components (ex: open circuit fault).
- The formula for the Total failure rate in the number of failures per year per unit length: $\lambda = \lambda_A + \lambda_P$ (18)
- MTTF (yr): Mean Time To Failure (Average time between 2 failures).
- $\mu$ (f/yr): Mean repair rate in the number of repairs per year per unit length.
- MTTR (hr): Mean Time To Repair.
- FOR: Forced Outage Rate (unavailability). It is automatically calculated based on:

$$\text{FOR} = \frac{\text{MTTR}}{\text{MTTR} + \frac{8760}{\lambda_A}}$$

(19)

- Replacement: Check this box to enable $r_P$. $r_P$ is the replacement time in hours for replacing a failed element with a spare one.
- Switching time: This is the time in hours for switching to an alternative supply after the element failure. ETAP considers Switching time to be the time to re-energize the healthy elements after isolating the failed element.
- Besides, we need to enter some other parameters:
  - Length of the conductor (transmission line, cable).
  - Load editor: The Number of customers in the Info tab; the Load capacity in the Loading tab; the Type of load (Load Sector) in the Reliability tab.

4.4. Editing the Study case

Before running the analysis, we need to edit the options in the Study case [13]:

Info tab

Fig. 4: Info tab of Reliability Analysis Study Case.

- Method: This section allows you to specify whether you wish to use the single or double contingency levels for the Distribution System Reliability Analysis.
  - Single Contingency Level.
  - Double Contingency Level (considering cases when two parallel elements are damaged at the same time, ex: 2 parallel transmission line).
- Loading: You can specify the system loading conditions for the Distribution System Reliability Analysis in this section.
  - Load Diversity Factor: You can specify the load diversity factors in this section.
  - Charger Loading.
System Index Report tab and Load Index Report tab

- No. of Most Contributing Elements to EENS: Select the number of the elements that contribute most to the index EENS from the pull-down list.
- No. of Most Contributing Elements to ECOST: Select the number of the elements that contribute most to the index ECOST from the pull-down list.
- These options are primarily for plotting and tabulating.

Plot tab

- System Index: Check this box to plot/tabulate system reliability indices.
- Element Index: You can specify the load points that will be plotted in this section. Element type: Select types of components or devices from the list. Only the components associated with the listed types can be selected for plotting/tabulating.

4.5. Editing the Display results options

Results tab [13]:

- No. of Most Contributing Elements to EENS
- No. of Most Contributing Elements to ECOST
- These options are primarily for plotting and tabulating.

Plot tab

- System Index: Check this box to plot/tabulate system reliability indices.
- Element Index: You can specify the load points that will be plotted in this section. Element type: Select types of components or devices from the list. Only the components associated with the listed types can be selected for plotting/tabulating.

5. ETAP APPLICATION FOR DISTRIBUTION NETWORK

In this section, we manually analyzed reliability for some simple and typical network models. Then, we use ETAP to simulate and compare the results.

5.1. Unsegmented radial Distribution network without 'Fuses Cut Out' (FCO) on branches

We consider a typical Unsegmented radial DN without FCO on branches as shown in Figure 8, with some assumptions: the reliability of the sources, buses, switch gears, loads are absolute:

![Unsegmented radial DN without FCO on branches](image)

Fig. 8: Unsegmented radial DN without FCO on branches model.
The network assuming parameters:

- The average permanent failure rate of lines per km is \( \lambda_0 = 0.15 \) (f/km.yr):

**Table 1: The average permanent failure rate of lines**

<table>
<thead>
<tr>
<th>Part</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_0 ) (km)</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>( \lambda_{e,j} ) (f/yr)</td>
<td>0.3</td>
</tr>
<tr>
<td>( r ) (h)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

- Customer number of load points:

**Table 2: Customer number of load points**

<table>
<thead>
<tr>
<th>Load point</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customer number</td>
<td>500</td>
<td>200</td>
<td>300</td>
<td>100</td>
</tr>
</tbody>
</table>

Assuming each client’s capacity is 1kW and all loads are Civil.

**Manual calculation:**

- Reliability analysis: faults on each of the segments (1), (2), (3), (4), or on branches (a), (b), (c), (d) will lead to open the circuit breaker (CB). After troubleshooting, the CB will reclose and re-energize the feeder. So, the set \( N_e \) in Equation (1) of the load points A, B, C, D are all elements \( \{1, 2, 3, 4, 5, 6\} \). Applying Formulas (1) and (3), we calculate 2 reliability indices \( (\lambda, u) \) of the load points:

**Table 3: Manual calculation of 2 reliability indices \( (\lambda, u) \) of Unsegmented radial DN without FCO on branches load points**

<table>
<thead>
<tr>
<th>Failed part (j)</th>
<th>Load point A</th>
<th>Load point B</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_{e,j} ) (f/yr)</td>
<td>( r_{A,j} ) (h)</td>
<td>( \lambda_{e,j} r_{A,j} ) (h)</td>
</tr>
<tr>
<td>(1)</td>
<td>0.3</td>
<td>2</td>
</tr>
<tr>
<td>(2)</td>
<td>0.15</td>
<td>2</td>
</tr>
<tr>
<td>(3)</td>
<td>0.3</td>
<td>2</td>
</tr>
<tr>
<td>(4)</td>
<td>0.45</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Failed part (j)</th>
<th>Load point C</th>
<th>Load point D</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_{e,j} ) (f/yr)</td>
<td>( r_{C,j} ) (h)</td>
<td>( \lambda_{e,j} r_{C,j} ) (h)</td>
</tr>
<tr>
<td>(1)</td>
<td>0.3</td>
<td>2</td>
</tr>
<tr>
<td>(2)</td>
<td>0.15</td>
<td>2</td>
</tr>
<tr>
<td>(3)</td>
<td>0.3</td>
<td>2</td>
</tr>
<tr>
<td>(4)</td>
<td>0.45</td>
<td>2</td>
</tr>
</tbody>
</table>

Total: \( \lambda_C = 2.4 \), \( u_C = 4.8 \), \( \lambda_D = 2.4 \), \( u_D = 4.8 \)

- Based on Formulas (8) to (17), we calculate the System reliability indices:

- **SAIFI** = \( \frac{\sum \lambda_{e,j} N_i}{\sum N_i} = \frac{2.4 \times 500 + 2.4 \times 200 + 2.4 \times 300 + 2.4 \times 800}{500 + 200 + 300 + 100} = 2.4 \text{ (f/customer yr)} \)

- **SAIDI** = \( \frac{\sum u_{i,j} N_i}{\sum N_i} = \frac{4.8 \times 500 + 4.8 \times 200 + 4.8 \times 300 + 4.8 \times 100}{500 + 200 + 300 + 100} = 4.8 \text{ (h/customer yr)} \)

- **CAIDI** = \( \frac{\sum u_{i,j} N_i}{\sum \lambda_{e,j} N_i} = \frac{4.8 \times 500 + 4.8 \times 200 + 4.8 \times 300 + 4.8 \times 100}{2.4 \times 500 + 2.4 \times 200 + 2.4 \times 300 + 2.4 \times 100} = 2 \text{ (h)} \)

- **ASAI** = \( \frac{\sum N_i \times 8760 - \sum u_{i,j} N_i}{\sum N_i \times 8760} = \frac{1100 \times 8760 - (4.8 \times 500 + 4.8 \times 200 + 4.8 \times 300 + 4.8 \times 100)}{1100 \times 8760} = 0.99945 \)

- **ASUI** = 1 - **ASAI** = 0.00055

- **EENS** = \( \sum P_i u_i = 4.8 \times 500 + 4.8 \times 200 + 4.8 \times 300 + 4.8 \times 100 = 5280 \text{ (kWh/yr)} \)

- **AENS** = \( \frac{\sum EENS}{\sum N_i} = \frac{5280}{500 + 200 + 300 + 100} = 4.8 \text{ (kWh/customer yr)} \)

- **ECOST** and **IEAR** depend on the SCDF of ETAP so we do not calculate manually.

**Software calculation:**

- After performing the simulation, we have the results:

- Load point reliability indices:

![Fig. 9: Software calculation of Load point indices of Unsegmented radial DN without FCO on branches.](image-url)
We choose to display the Average Permanent Failure Rate \( \lambda_i \) and the Total Outage Duration \( u_i \) at load points in Display results options.

- System reliability indices:

Fig. 10: Software calculation of System reliability indices of Unsegmented radial DN without FCO on branches.

- Comment: Software calculation results are similar to Manual calculation results.

5.2. Unsegmented radial Distribution network with FCO on branches

We examine the Unsegmented radial DN with FCO on branches as shown in Figure 11:

Fig. 11: Unsegmented radial DN with FCO on branches model.

- Manual calculation:

- Reliability analysis: faults on the spindle segments will lead to open the CB, while faults on the branch will only cause blackouts at that branch. So, the set \( N_e \) in Equation (1) of the load points A, B, C, D are the elements [(1), (2), (3), (4), and the (branch containing the load point)]. Applying Formulas (1) and (3), we calculate 2 reliability indices (\( \lambda_i \), \( u_i \)) of the load points:

Table 4: Manual calculation of 2 reliability indices (\( \lambda_i \), \( u_i \)) of Unsegmented radial DN with FCO on branches load points

<table>
<thead>
<tr>
<th>Failed part (j)</th>
<th>Load point A</th>
<th>Load point B</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_{e,j} ) (f/yr)</td>
<td>( r_{Aj} ) (h)</td>
<td>( \lambda_{e,j}r_{Aj} ) (h)</td>
</tr>
<tr>
<td>(1) 0.3</td>
<td>2</td>
<td>0.6</td>
</tr>
<tr>
<td>(2) 0.15</td>
<td>2</td>
<td>0.3</td>
</tr>
<tr>
<td>(3) 0.3</td>
<td>2</td>
<td>0.6</td>
</tr>
<tr>
<td>(4) 0.45</td>
<td>2</td>
<td>0.9</td>
</tr>
</tbody>
</table>

- We calculate the system reliability indices:

- SAIFI = \( \frac{\sum N_i \lambda_i}{\sum N_i} = \frac{1.65 + 0.45 + 0.3 + 0.15}{500 + 200 + 300 + 100} = 1.527 \text{ (f/customer yr)} \)

- SAIDI = \( \frac{\sum u_i N_i}{\sum N_i} = \frac{0.6 + 0.3 + 0.3 + 0.6}{500 + 200 + 300 + 100} = 3.055 \text{ (h/customer yr)} \)

- CAIDI = \( \frac{\sum u_i N_i}{\sum N_i} = \frac{0.6 + 0.3 + 0.3 + 0.6}{1.65 + 0.45 + 0.3 + 0.15} = 2 \text{ (h)} \)

- ASUI = \( \frac{1}{\lambda_i} = 0.99965 \)

- EENS = \( \sum P_i u_i = 3.3500 + 3.0200 + 2.7300 + 3.0100 = 3360 \text{ (kWh/yr)} \)

- AENS = \( \frac{EENS}{\sum N_i} = \frac{3360}{500 + 200 + 300 + 100} = 3.055 \text{ (kWh/customer)} \)

- Software calculation:

- If we add a FCO to the diagram, ETAP will understand the FCO is an instantaneous isolator.

- After performing the simulation, we have the results:
Load point reliability indices:

Fig. 12: Software calculation of Load point indices of Unsegmented radial DN with FCO on branches.

System reliability indices:

Fig. 13: Software calculation of System reliability indices of Unsegmented radial DN with FCO on branches.

Comments:
Software calculation results are similar to Manual calculation results.

In this case, after adding some branch fuses, the reliability is improved for all load points.

5.3. Segmental radial Distribution network with FCO on branches

To enhance the DN reliability, we can segment the spindle with Distance switches (DS) (or some other switch gears) as shown in Figure 14:

Therefore:

Load point A: Faults on segment (1) and branch (a) cause complete blackouts, faults on segments (2), (3), (4) only cause blackouts during the isolation process. A similar analysis for the other load points.

- Assuming the fault isolation process time is 15 (minutes) = 0.25 (h), we calculate 2 reliability indices ($\lambda_i$, $u_i$) of the load points:

Table 5: Manual calculation of 2 reliability indices ($\lambda_i$, $u_i$) of Segmental radial DN with FCO on branches load points

Manual calculation:

- Reliability analysis: When there is a fault on the spindle behind segmental DS, the CB will open. Then we will isolate the failed element by opening the segmental DS and reclose the CB to re-energize the feeder. This will take a while to complete, depending on many factors.

- We calculate the system reliability indices:

\[
SAIFI = \frac{\sum \lambda_{e,j} N_j}{\sum N_i} = \frac{1.65.500 + 1.5.200 + 1.35.300 + 1.5.100}{500 + 200 + 300 + 100} = 1.5273 \text{ (f/customer.yr)}
\]

\[
SAIDI = \frac{\sum u_{e,j} r_{e,j} N_j}{\sum N_i} = \frac{1.725.500 + 1.6875.200 + 1.9125.300 + 3.0.100}{500 + 200 + 300 + 100} = 1.8852 \text{ (h/customer.yr)}
\]
\[ \text{CAIDI} = \frac{\sum u_i N_i}{\sum N_i} = \frac{1,725.500 + 1,6875.200 + 1,9125.300 + 3,0.100}{1,65.500 + 1.5.200 + 1,35.300 + 1,5.100} = 1,234 \text{ (h)} \]

\[ \text{ASAI} = \frac{\sum N_i \Delta t_{760} - \sum u_i N_i}{\sum N_i \Delta t_{760}} = \frac{1100.8760 - (1,725.500 + 1,6875.200 + 1,9125.300 + 3,0.100)}{1100.8760} = 0.99978 \]

\[ \text{ASUI} = 1 - \text{ASAI} = 0.00022 \]

\[ \text{EENS} = \sum P_i u_i = 1,725.500 + 1,6875.200 + 1,9125.300 + 3,0.100 = 2074 \text{ (kWh/yr)} \]

\[ \text{AENS} = \frac{\text{EENS}}{\sum N_i} = \frac{2074}{500+200+300+100} = 1,8852 \text{ (kWh/customer)} \]

**Software calculation:**

- ETAP understands DS as a timed segmented device so to implement this case, we fill out the Switching time of the Alternative supply of spindle segments:

**Comments:**

- Software calculation results are similar to Manual calculation results.
- We can see that the Average Permanent Failure Rate \( \lambda_i \) at load points are unchanged, but the Total Outage Duration \( u_i \) at load points are significantly enhanced (especially the ones closer to the source).

**5.4. Segmental ring Distribution network with FCO on branches**

To enhance the DN reliability, we often build the ring network as shown in Figure 18 (but still operate openly through normally open ties):

**Manual calculation:**

- Reliability analysis: When the power flow from the main source is interrupted, it is possible to switch to another source by closing the normally open ties. For load points that are switched to other sources, the time of
blackout corresponds to the switching source time.

✓ Load point B: Faults on segment (2) and branch (b) cause complete blackouts, faults on segments (1), (3), (4) only cause blackouts during switching source time. A similar analysis for the other load points.

Table 6: Manual calculation of 2 reliability indices ($\lambda_i, u_i$) of Segmental ring DN with FCO on branches load points

<table>
<thead>
<tr>
<th>Failed part (j)</th>
<th>Load point A</th>
<th>Load point B</th>
<th>Load point C</th>
<th>Load point D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\lambda_{e,j}$ (f/yr)</td>
<td>$r_{e_j}$ (h)</td>
<td>$\lambda_{e_j} - r_{e_j}$ (f/yr)</td>
<td>$\lambda_{e,j}$ (f/yr)</td>
</tr>
<tr>
<td>(1)</td>
<td>0.3</td>
<td>2</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>(2)</td>
<td>0.3</td>
<td>0.25</td>
<td>0.075</td>
<td>0.3</td>
</tr>
<tr>
<td>(4)</td>
<td>0.45</td>
<td>0.25</td>
<td>0.1125</td>
<td>0.45</td>
</tr>
<tr>
<td>b</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>$\lambda_A$ = 1.65</td>
<td>$u_A$ = 1.725</td>
<td>$\lambda_B$ = 1.5</td>
<td>$u_B$ = 1.1625</td>
</tr>
</tbody>
</table>

- We calculate the system reliability indices:
  ✓ SAIFI = $\frac{\sum i_n_i_j}{\sum N_i} = \frac{1.65.500+1.5.200+1.35.300+1.5.100}{500+200+300+100} = 1.5273$ (f/customer, yr)
  ✓ SAIDI = $\frac{\sum u_i N_i}{\sum N_i} = \frac{1.725.500+1.1625.200+1.125.300+1.6875.100}{500+200+300+100} = 1.4557$ (h/customer, yr)
  ✓ CAIDI = $\frac{\sum u_i N_i}{\sum N_i} = \frac{1.725.500+1.1625.200+1.125.300+1.6875.100}{1.65.500+1.5.200+1.35.300+1.5.100} = 0.953$ (h)
  ✓ ASAI = $\frac{\sum N_i 8760 - \sum u_i N_i}{\sum N_i 8760} = 0.99983$

✓ System reliability indices:

- We can see that the Average Permanent Failure Rate $\lambda_i$ at load points are unchanged, but the Total Outage Duration $u_i$ at load points are considerably improved (especially at the load point D).

5.5. Summary

We will sum up a table comparing the above cases.
Table 7: A summary of cases

<table>
<thead>
<tr>
<th>Load point</th>
<th>Unsegmented radial DN without FCO on branches</th>
<th>Unsegmented radial DN with FCO on branches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \lambda ) (f/yr)</td>
<td>( u ) (hr)</td>
</tr>
<tr>
<td>A</td>
<td>2.4</td>
<td>4.8</td>
</tr>
<tr>
<td>B</td>
<td>2.4</td>
<td>4.8</td>
</tr>
<tr>
<td>C</td>
<td>2.4</td>
<td>4.8</td>
</tr>
<tr>
<td>D</td>
<td>2.4</td>
<td>4.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load point</th>
<th>Segmental radial DN with FCO on branches</th>
<th>Segmental ring DN with FCO on branches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \lambda ) (f/yr)</td>
<td>( u ) (hr)</td>
</tr>
<tr>
<td>A</td>
<td>1.65</td>
<td>1.725</td>
</tr>
<tr>
<td>B</td>
<td>1.50</td>
<td>1.6875</td>
</tr>
<tr>
<td>C</td>
<td>1.35</td>
<td>1.9125</td>
</tr>
<tr>
<td>D</td>
<td>1.50</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Comments:

✓ We can see that the additional investments will provide improvements for DN reliability. However, we need to consider carefully between the price and the performance whether it has good value for money.

5.6. Compound actual Distribution network

We consider the compound network model as a loop DN with a combination of isolator devices (Recloser, Distance Switch, and FCO or not FCO on branches) as shown in Figure 21:

![Fig. 21: Compound actual DN with a combination of isolator devices model.](image)

The network assuming parameters:

✓ The average permanent failure rate of lines per km is \( \lambda_0 = 0.15 \) (f/km.yr).

Table 8: The average permanent failure rate of lines in Compound actual DN

<table>
<thead>
<tr>
<th></th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
<th>La1</th>
<th>Lb1</th>
<th>Lc1</th>
</tr>
</thead>
<tbody>
<tr>
<td>L(km)</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>( \lambda_{e,j} ) (f/yr)</td>
<td>0.45</td>
<td>0.3</td>
<td>0.3</td>
<td>0.15</td>
<td>0.45</td>
<td>0.3</td>
</tr>
<tr>
<td>r (h)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Switching time (h)</td>
<td>0.1</td>
<td>0.15</td>
<td>0.2</td>
<td>0.1</td>
<td>0.15</td>
<td>0.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>L4</th>
<th>L5</th>
<th>L6</th>
<th>La2</th>
<th>Lb2</th>
<th>Lc2</th>
</tr>
</thead>
<tbody>
<tr>
<td>L(km)</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>( \lambda_{e,j} ) (f/yr)</td>
<td>0.3</td>
<td>0.45</td>
<td>0.15</td>
<td>0.3</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>r (h)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Switching time (h)</td>
<td>0.1</td>
<td>0.15</td>
<td>0.2</td>
<td>0.1</td>
<td>0.15</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 9: The average permanent failure rate of switch gears and transformer in Compound actual DN

<table>
<thead>
<tr>
<th></th>
<th>CB131</th>
<th>T1</th>
<th>CB431</th>
<th>CB1</th>
<th>CB2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_{e,j} ) (f/yr)</td>
<td>0.002</td>
<td>0.015</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>r (h)</td>
<td>4</td>
<td>15</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>REC1</th>
<th>SW1</th>
<th>SW2</th>
<th>SW3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_{e,j} ) (f/yr)</td>
<td>0.004</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>r (h)</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Switching time (h)</td>
<td>0.15</td>
<td>0.2</td>
<td>0.15</td>
<td>0.2</td>
</tr>
</tbody>
</table>

✓ Customer number of load points:

Table 10: Customer number of load points in Compound actual DN model

<table>
<thead>
<tr>
<th>Load point</th>
<th>A1</th>
<th>B1</th>
<th>C1</th>
<th>A2</th>
<th>B2</th>
<th>C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customer number</td>
<td>500</td>
<td>200</td>
<td>300</td>
<td>200</td>
<td>400</td>
<td>100</td>
</tr>
</tbody>
</table>

Assuming each client’s capacity is 1kW and all loads are Civil.

Manual calculation:

- Reliability analysis: When the power flow of Feeder 1 from the source is interrupted, it is possible to switch to Feeder 2 by closing the normally open points. For load points that are switched to the other direction of the source, the time of blackout corresponds to the time of switching source. Therefore:
✓ Load point A1: Faults on CB131, T1, CB431, CB1, CB2, (L1), REC1, and branch (La1) cause complete blackouts, faults on other components doesn’t cause blackouts.

✓ Load point B1: Faults on CB131, T1, CB431, CB1, CB2, REC1, (L2), SW1, and branch (Lb1) cause complete blackouts, faults on (L1), (L3) only cause blackouts during switching source time.

✓ Load point C1: Faults on CB131, T1, CB431, CB1, CB2, SW1, (L3) and branch (Lc1) cause complete blackouts during switching source time.

✓ Load point A2: Faults on CB131, T1, CB431, CB1, CB2, (L4), SW2, and branch (La2) cause complete blackouts, faults on (L5), SW3, (L6), (Lc2) only cause blackouts during switching source time.

✓ Load point B2: Faults on CB131, T1, CB431, CB1, CB2, SW2, (L5), SW3, and branch (Lb2) cause complete blackouts, faults on (L4), (L6), (Lc2) only cause blackouts during switching source time.

✓ Load point C2: Faults on CB131, T1, CB431, CB1, CB2, SW3, (L6) and branch (Lc2) cause complete blackouts, faults on (L4), SW2, (L5) only cause blackouts during switching source time.

Based on the above analysis, we calculate 2 reliability indices (λᵢ, 𝑢ᵢ) of the load points:

Table 11: Manual calculation of 2 reliability indices (λᵢ, 𝑢ᵢ) of Compound actual Distribution network load points

<table>
<thead>
<tr>
<th>Failing part (j)</th>
<th>λₑᵢ (1/yr)</th>
<th>rᵢ (h)</th>
<th>λₑᵢ (1/yr)</th>
<th>rᵢ (h)</th>
<th>λₑᵢ (1/yr)</th>
<th>rᵢ (h)</th>
<th>λₑᵢ (1/yr)</th>
<th>rᵢ (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB131 1</td>
<td>2 × 10⁻³</td>
<td>4</td>
<td>8 × 10⁻³</td>
<td>4</td>
<td>8 × 10⁻³</td>
<td>4</td>
<td>8 × 10⁻³</td>
<td>4</td>
</tr>
<tr>
<td>T1</td>
<td>15 × 10⁻³</td>
<td>15</td>
<td>225 × 10⁻⁴</td>
<td>15</td>
<td>15 × 10⁻³</td>
<td>15</td>
<td>225 × 10⁻⁴</td>
<td>15</td>
</tr>
<tr>
<td>CB431 1</td>
<td>4 × 10⁻³</td>
<td>4</td>
<td>16 × 10⁻³</td>
<td>4</td>
<td>16 × 10⁻³</td>
<td>4</td>
<td>16 × 10⁻³</td>
<td>4</td>
</tr>
<tr>
<td>CB1</td>
<td>4 × 10⁻³</td>
<td>4</td>
<td>16 × 10⁻³</td>
<td>4</td>
<td>16 × 10⁻³</td>
<td>4</td>
<td>16 × 10⁻³</td>
<td>4</td>
</tr>
<tr>
<td>CB2</td>
<td>4 × 10⁻³</td>
<td>4</td>
<td>16 × 10⁻³</td>
<td>4</td>
<td>16 × 10⁻³</td>
<td>4</td>
<td>16 × 10⁻³</td>
<td>4</td>
</tr>
<tr>
<td>L1</td>
<td>0.45</td>
<td>2</td>
<td>0.9</td>
<td>0.45</td>
<td>0.1</td>
<td>0.45</td>
<td>0.1</td>
<td>0.45</td>
</tr>
<tr>
<td>REC1</td>
<td>4 × 10⁻³</td>
<td>4</td>
<td>16 × 10⁻³</td>
<td>4</td>
<td>16 × 10⁻³</td>
<td>4</td>
<td>0.15</td>
<td>0.6</td>
</tr>
<tr>
<td>L2</td>
<td>0.3</td>
<td>2</td>
<td>0.6</td>
<td>0.3</td>
<td>0.15</td>
<td>0.45</td>
<td>0.15</td>
<td>0.45</td>
</tr>
<tr>
<td>SW1</td>
<td>0.2</td>
<td>1</td>
<td>0.2</td>
<td>0.2</td>
<td>1</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We calculate the system reliability indices:

✓ SAIFI = \( \frac{\sum \lambda_i N_i}{\sum N_i} \) = \( \frac{0.6335000+1.7332000+2.0333000+67.510^{-3}}{500+200+300+200+400+100} \) = 1.5872 (f/customer.yr)

✓ GMSARN International Journal 16 (2022) 33-46

\[ \text{Total} \]

<table>
<thead>
<tr>
<th>Load point A2</th>
<th>Load point B2</th>
<th>Load point C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_{A2} )</td>
<td>( \lambda_{B2} )</td>
<td>( \lambda_{C2} )</td>
</tr>
<tr>
<td>( \sum u_{A2} )</td>
<td>( \sum u_{B2} )</td>
<td>( \sum u_{C2} )</td>
</tr>
<tr>
<td>( 2.07 \times 10^{-9} )</td>
<td>( 2.07 \times 10^{-9} )</td>
<td>( 1.80 \times 10^{-9} )</td>
</tr>
</tbody>
</table>

We calculate the system reliability indices:
\[ \text{SAIDI} = \frac{\sum u_iN_i}{\sum N_i} = \frac{1.497.500+2.102.200+1.839.300+1.908.200+2.331.400+1.809.100}{500+200+300+200+400+100} = 1.8915 \text{ (h/customer.yr)} \]

\[ \text{CAIDI} = \sum \frac{u_iN_i}{N_i} = \frac{1.497.500+2.102.200+1.839.300+1.908.200+2.331.400+1.809.100}{500+200+300+200+400+100} = 1.192 \text{ (h)} \]

\[ \text{ASAI} = \frac{\sum N_i - \sum u_iN_i}{\sum N_i} = \frac{1700.8760 - (1.497.500+2.102.200+1.839.300+1.908.200+2.331.400+1.809.100)}{1700.8760} = 0.99978 \]

\[ \text{ASUI} = 1 - \text{ASAI} = 0.00022 \]

\[ \text{EENS} = \sum p_i u_i = 1.497.500 + 2.102.200 + 1.839.300 + 1.908.200 + 2.331.400 + 1.809.100 = 3215.5 \text{ (kWh/yr)} \]

\[ \text{AENS} = \frac{\text{EENS}}{\sum N_i} = \frac{3215.5}{500+200+300+200+400+100} = 1.8914 \text{ (kWh/customer)} \]

- Software calculation:
  - After performing the simulation, we have the results:
    - Load point reliability indices:

![Fig. 22: Software calculation of Load point indices of Compound actual DN.](image)

- System reliability indices:

![Fig. 23: Software calculation of System reliability indices of Compound actual DN.](image)

- Comments:
  - Software calculation results are similar to Manual calculation results.
  - ETAP can perform exactly for the Compound actual Distribution network.

6. CONCLUSIONS

- The paper provided a general method of solving the Reliability problem by using ETAP computer software and instructions carefully on how the ETAP’s Reliability function operates.

- ETAP can analyze all types of grids and be specifically useful for complex grids which we cannot analyze manually.

- Comprehending ETAP’s Reliability function through some examples, we are confident in applying this software for the DN reliability problem. Thus, it is possible to propose appropriate operation methods as well as a plan for the optimal development of our grid.

ACKNOWLEDGMENT

We acknowledge the support of time and facilities from Ho Chi Minh City University of Technology (HCMUT), VNU-HCM for this study.

REFERENCES


