Research of Distribution Network Reliability Assessment by ETAP Software

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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 troubleshoot 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

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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 LVG is a 0,4 kV voltage gird.

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 using normally open ties. Because 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 (f/period)

$$\lambda_i = \sum_{j \in N_e} \lambda_{e,j} \tag{1}$$

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 (f/period)

$$\lambda'_i = \sum_{j \in N_e} \lambda'_{e,j} \tag{2}$$

$\lambda'_{e,j}$ is the average transient failure rate of element j in N_e

- Total Outage Duration at Load Point i (h/period)

$$u_i = \sum_{j \in N_e} (\lambda_{e,j} \, . \, r_{ij}) \tag{3}$$

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)

$$r_i = \frac{u_i}{\lambda_i} \tag{4}$$

- Expected Energy Not Supplied Index at Load Point i (Wh/period)

$$\mathrm{EENS_i} = \mathrm{P_i}.\mathrm{u_i} \quad (5)$$

P_i is the average load of load point i

- Expected Interruption Cost Index at Load Point i ($/period)

$$\mathrm{ECOST_i} = \mathrm{P_i}.\sum_{j\in N_e}(f_i(r_{ij}).\lambda_{e,j}) \quad (6)$$

$f_i(r_{ij})$ 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)

$$\mathrm{IEAR_i} = \frac{\mathrm{ECOST_i}}{\mathrm{EENS_i}} \quad (7)$$

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/customer.period) – System Average Interruption Frequency Index

$$\mathrm{SAIFI} = \frac{\text{Total number of customer interruptions}}{\text{Total number of customer served}} = \frac{\sum \lambda_i.N_i}{\sum N_i} \quad (8)$$

N_i is the number of customers at load point i

λ_i is the Average Permanent Failure Rate at Load Point i (from the load point reliability indices above)

- SAIDI (h/customer.period) - System Average Interruption Duration Index

$$\mathrm{SAIDI} = \frac{\text{Sum of customer interruption duration}}{\text{total number of customer served}} = \frac{\sum u_i.N_i}{\sum N_i} \quad (9)$$

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

$$\mathrm{CAIDI} = \frac{\text{Sum of customer interruption duration}}{\text{total number of customer interruptions}} = \frac{\mathrm{SAIDI}}{\mathrm{SAIFI}} \quad (10)$$

- ASAI – Average Service Availability Index

$$\mathrm{ASAI} = \frac{\text{Customer hours of available service}}{\text{customer hours demanded}} = \frac{\sum N_i.h - \sum u_i h.}{\sum N_i.h} \quad (11)$$

h is the number of hours in the period

- ASUI - Average Service Unavailability Index

$$\mathrm{ASUI} = 1 - \mathrm{ASAI} \quad (12)$$

- MAIFI (f/customer.period) – Momentary Average Interruption Frequency Index

$$\mathrm{MAIFI} = \frac{\text{Total number of customer interruptions}}{\text{Total number of customer served}} = \frac{\sum \lambda'_i.N_i}{\sum N_i} \quad (13)$$

λ'_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

$$\mathrm{EENS} = \sum \mathrm{P_i}.\mathrm{u_i} = \sum \mathrm{EENS_i} \quad (14)$$

$EENS_i$ is the Expected Energy Not Supplied Index at Load Point i (from the load point reliability indices above).

- System AENS (Wh/customer.period) – System Average Energy Not Supplied Index

$$\mathrm{AENS} = \frac{\text{Total energy not supplied by the system}}{\text{total number of customer served}} = \frac{\sum \mathrm{EENS_i}}{\sum N_i} \quad (15)$$

- System ECOST ($/period) – System Expected Interruption Cost Index

$$\mathrm{ECOST} = \sum \mathrm{ECOST_i} = \sum(\mathrm{P_i}.\sum_{j\in N_e} f(r_{ij}).\lambda_{e,j}) \quad (16)$$

$f_i(r_{ij})$ is Sector Customer Damage Function (SCDF)

- System IEAR ($/Wh) – System Interrupted Energy Assessment Rate Index

$$\mathrm{IEAR} = \frac{\mathrm{ECOST}}{\mathrm{EENS}} \quad (17)$$

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.

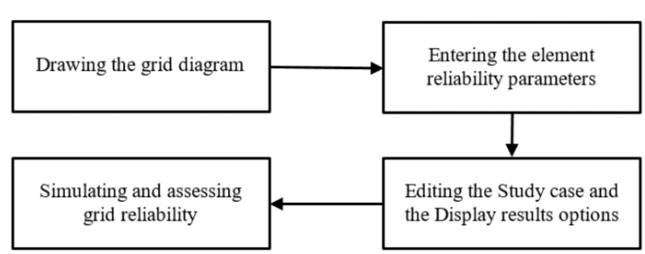

Fig. 1: General implementation steps in Reliability function.

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:

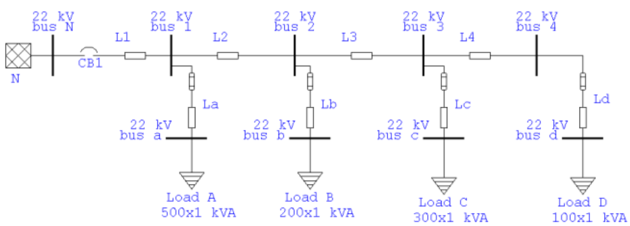

Fig. 2: An example of the one-line diagram in Etap.

Note: L_1, L_2, L_3, L_4, L_a, L_b, L_c, L_d 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]:

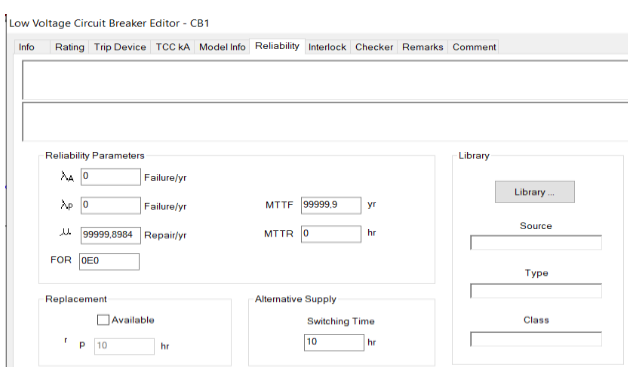

Fig. 3: Reliability tab of each element in ETAP.

- λ_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).

- λ_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).

- μ (r/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:

$$FOR = MTTR/(MTTR + 8760/\lambda_A) \tag{19}$$

- 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]:

<u>Info tab</u>

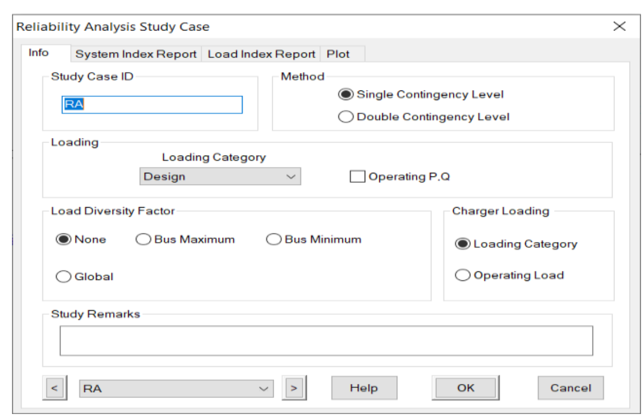

Fig. 4: Info tab of Reliability Analysis Study Case.

✓ 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

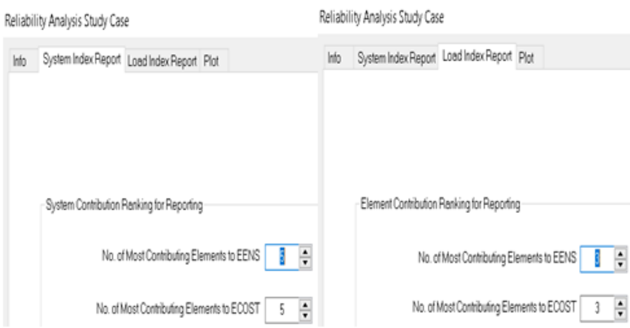

Fig. 5: System Index Report tab and Load Index Report tab of Reliability Analysis Study Case.

✓ 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

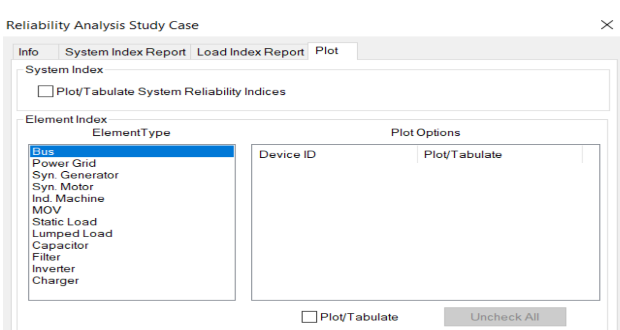

Fig. 6: Plot tab of Reliability Analysis Study Case.

✓ 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]:

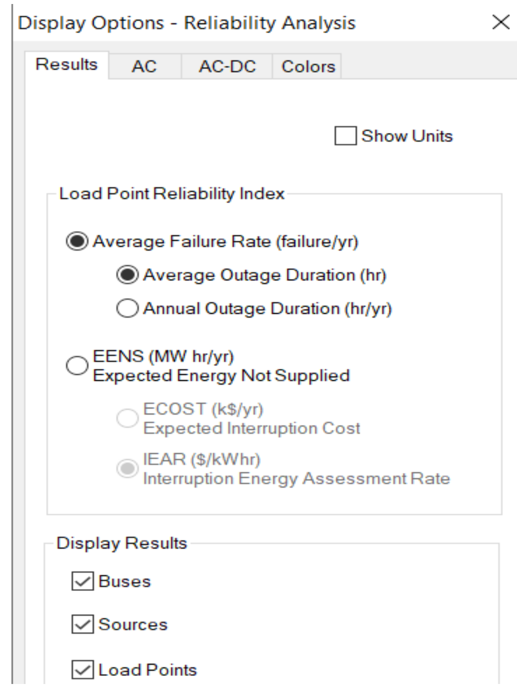

Fig. 7: Results tab of Display results options.

✓ Select the information annotations to display on the one-line diagram.

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:

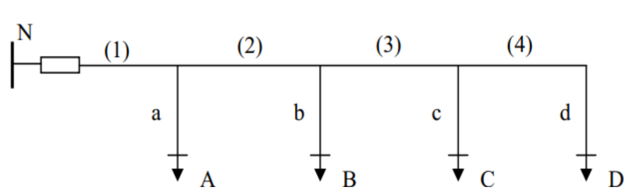

Fig. 8: Unsegmented radial DN without FCO on branches model.

The network assuming parameters:

✓ The average permanent failure rate of lines per km is λ_0 = 0,15 (f/km.yr):

Table 1: The average permanent failure rate of lines

	(1)	(2)	(3)	(4)	(a)	(b)	(c)	(d)
L(km)	2	1	2	3	3	2	1	2
$\lambda_{e,j}$ (f/yr)	0,3	0,15	0,3	0,45	0,45	0,3	0,15	0,3
r (h)	2	2	2	2	2	2	2	2

✓ Customer number of load points:

Table 2: Customer number of load points

Load point	A	B	C	D
Customer number	500	200	300	100

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), (a), (b), (c), (d)]. Applying *Formulas (1)* and *(3)*, we calculate 2 reliability indices (λ_i, u_i) of the load points:

Table 3: Manual calculation of 2 reliability indices (λ_i, u_i) of Unsegmented radial DN without FCO on branches load points

Failed part (j)	Load point A			Load point B		
	$\lambda_{e,j}$ (f/yr)	r_{Aj} (h)	$\lambda_{e,j}.r_{Aj}$ (h)	$\lambda_{e,j}$ (f/yr)	r_{Bj} (h)	$\lambda_{e,j}.r_{Bj}$ (h)
(1)	0,3	2	0,6	0,3	2	0,6
(2)	0,15	2	0,3	0,15	2	0,3
(3)	0,3	2	0,6	0,3	2	0,6
(4)	0,45	2	0,9	0,45	2	0,9
a	0,45	2	0,9	0,45	2	0,9
b	0,3	2	0,6	0,3	2	0,6
c	0,15	2	0,3	0,15	2	0,3
d	0,3	2	0,6	0,3	2	0,6
Total	λ_A = 2,4		u_A = 4,8	λ_B = 2,4		u_B = 4,8
Failed part (j)	**Load point C**			**Load point D**		
	$\lambda_{e,j}$ (f/yr)	r_{Cj} (h)	$\lambda_{e,j}.r_{Cj}$ (h)	$\lambda_{e,j}$ (f/yr)	r_{Dj} (h)	$\lambda_{e,j}.r_{Dj}$ (h)
(1)	0,3	2	0,6	0,3	2	0,6
(2)	0,15	2	0,3	0,15	2	0,3
(3)	0,3	2	0,6	0,3	2	0,6
(4)	0,45	2	0,9	0,45	2	0,9
a	0,45	2	0,9	0,45	2	0,9
b	0,3	2	0,6	0,3	2	0,6
c	0,15	2	0,3	0,15	2	0,3
d	0,3	2	0,6	0,3	2	0,6
Total	λ_C = 2,4		u_C = 4,8	λ_D = 2,4		u_D = 4,8

- Based on Formulas (8) to (17). We calculate the System reliability indices:

✓ $\mathrm{SAIFI} = \frac{\sum \lambda_i.N_i}{\sum N_i} = \frac{2,4.500+2,4.200+2,4.300+2,4.100}{500+200+300+100}$

$$= 2,4\ (\mathrm{f/customer.yr})$$

✓ $\mathrm{SAIDI} = \frac{\sum u_i.N_i}{\sum N_i} = \frac{4,8.500+4,8.200+4,8.300+4,8.100}{500+200+300+100}$

$$= 4,8\ (\mathrm{h/customer.yr})$$

✓ $\mathrm{CAIDI} = \frac{\sum u_i.N_i}{\sum \lambda_i.N_i} = \frac{4,8.500+4,8.200+4,8.300+4,8.100}{2,4.500+2,4.200+2,4.300+2,4.100}$

$$= 2(\mathrm{h})$$

✓ $\mathrm{ASAI} = \frac{\sum N_i.8760 - \sum u_i.N_i}{\sum N_i.8760}$

$$= \frac{1100.8760 - (4,8.500 + 4,8.200 + 4,8.300 + 4,8.100)}{1100.8760}$$

$$= 0,99945$$

✓ $\mathrm{ASUI} = 1 - \mathrm{ASAI} = 0,00055$

✓ $\mathrm{EENS} = \sum P_i.u_i = 4,8.500 + 4,8.200 + 4,8.300 + 4,8.100 = 5280\ (\mathrm{kWh/yr})$

✓ $\mathrm{AENS} = \frac{\mathrm{EENS}}{\sum N_i} = \frac{5280}{500+200+300+100}$

$$= 4,8\ (\mathrm{kWh/custumer})$$

✓ 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:

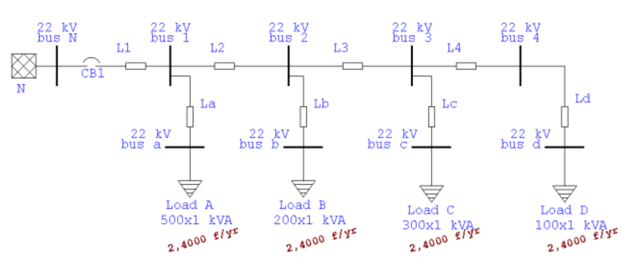

Fig. 9: Software calculation of Load point indices of Unsegmented radial DN without FCO on branches.

We choose to display the Average Permanent Failure Rate λ_i and the Total Outage Duration u_i at load points in Display results options.

✓ System reliability indices:

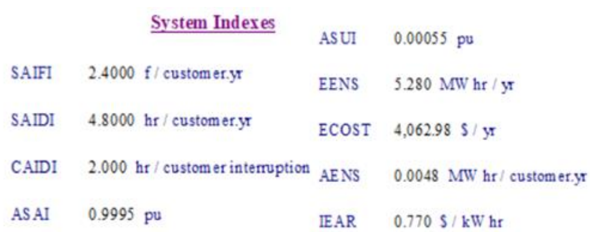

Fig. 10: Software calculation of System reliability indices of Unsegmented radial DN without FCO on branches.

❖ <u>Comment:</u> 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*:

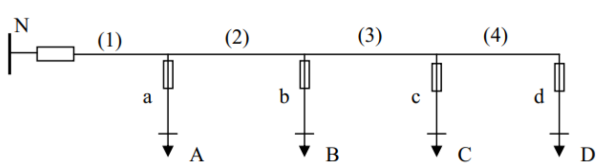

Fig. 11: Unsegmented radial DN with FCO on branches model.

❖ <u>Manual calculation</u>:

• 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 (λ_i, u_i) of the load points:

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

Failed part (j)	**Load point A**			**Load point B**		
	$\lambda_{e,j}$ (f/yr)	r_{Aj} (h)	$\lambda_{e,j}.r_{Aj}$ (h)	$\lambda_{e,j}$ (f/yr)	r_{Bj} (h)	$\lambda_{e,j}.r_{Bj}$ (h)
(1)	0,3	2	0,6	0,3	2	0,6
(2)	0,15	2	0,3	0,15	2	0,3
(3)	0,3	2	0,6	0,3	2	0,6
(4)	0,45	2	0,9	0,45	2	0,9
a	0,45	2	0,9			
b				0,3	2	0,6
Total	**λ_A = 1,65**		**u_A = 3,3**	**λ_B = 1,5**		**u_B = 3,0**
Failed part (j)	**Load point C**			**Load point D**		
	$\lambda_{e,j}$ (f/yr)	r_{Cj} (h)	$\lambda_{e,j}.r_{Cj}$ (h)	$\lambda_{e,j}$ (f/yr)	r_{Dj} (h)	$\lambda_{e,j}.r_{Dj}$ (h)
(1)	0,3	2	0,6	0,3	2	0,6
(2)	0,15	2	0,3	0,15	2	0,3
(3)	0,3	2	0,6	0,3	2	0,6
(4)	0,45	2	0,9	0,45	2	0,9
c	0,15	2	0,3			
d				0,3	2	0,6
Total	**λ_C = 1,35**		**u_C = 2,7**	**λ_D = 1,5**		**u_D = 3,0**

• We calculate the system reliability indices:

✓ $\text{SAIFI} = \frac{\sum \lambda_i.N_i}{\sum N_i} = \frac{1{,}65.500+1{,}5.200+1{,}35.300+1{,}5.100}{500+200+300+100}$

$$= 1{,}527\ (\text{f/customer.yr})$$

✓ $\text{SAIDI} = \frac{\sum u_i.N_i}{\sum N_i} = \frac{3{,}3.500+3{,}0.200+2{,}7.300+3{,}0.100}{500+200+300+100}$

$$= 3{,}055\ (\text{h/customer.yr})$$

✓ $\text{CAIDI} = \frac{\sum u_i.N_i}{\sum \lambda_i.N_i} = \frac{3{,}3.500+3{,}0.200+2{,}7.300+3{,}0.100}{1{,}65.500+1{,}5.200+1{,}35.300+1{,}5.100}$

$$= 2(\text{h})$$

✓ $\text{ASAI} = \frac{\sum N_i.8760 - \sum u_i.N_i}{\sum N_i.8760}$

$$= \frac{1100.8760 - (3{,}3.500 + 3{,}0.200 + 2{,}7.300 + 3{,}0.100)}{1100.8760}$$

$$= 0{,}99965$$

✓ $\text{ASUI} = 1 - \text{ASAI} = 0{,}00035$

✓ $\text{EENS} = \sum P_i.u_i = 3{,}3.500 + 3{,}0.200 + 2{,}7.300 + 3{,}0.100 = 3360\ (\text{kWh/yr})$

✓ $\text{AENS} = \frac{\text{EENS}}{\sum N_i} = \frac{3360}{500+200+300+100}$

$$= 3{,}055\ (\text{kWh/custumer})$$

❖ <u>Software calculation:</u>

• 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:

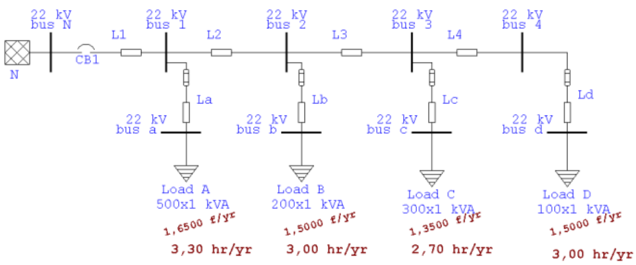

Fig. 12: Software calculation of Load point indices of Unsegmented radial DN with FCO on branches.

✓ 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*:

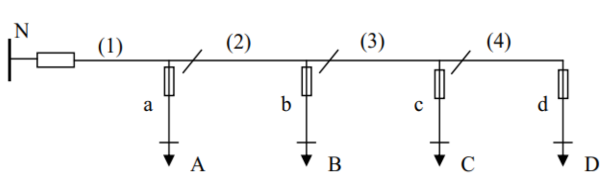

Fig. 14: Segmental radial DN with FCO on branches model.

❖ 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. 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 (λ_i, u_i) of the load points:

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

Failed part (j)	**Load point A**			**Load point B**		
	$\lambda_{e,j}$ (f/yr)	r_{Aj} (h)	$\lambda_{e,j}.r_{Aj}$ (h)	$\lambda_{e,j}$ (f/yr)	r_{Bj} (h)	$\lambda_{e,j}.r_{Bj}$ (h)
(1)	0,3	2	0,6	0,3	2	0,6
(2)	0,15	0,25	0,0375	0,15	2	0,3
(3)	0,3	0,25	0,075	0,3	0,25	0,075
(4)	0,45	0,25	0,1125	0,45	0,25	0,1125
a	0,45	2	0,9			
b				0,3	2	0,6
Total	**λ_A = 1,65**		**u_A = 1,725**	**λ_B = 1,5**		**u_B = 1,6875**
Failed part (j)	**Load point C**			**Load point D**		
	$\lambda_{e,j}$ (f/yr)	r_{Cj} (h)	$\lambda_{e,j}.r_{Cj}$ (h)	$\lambda_{e,j}$ (f/yr)	r_{Dj} (h)	$\lambda_{e,j}.r_{Dj}$ (h)
(1)	0,3	2	0,6	0,3	2	0,6
(2)	0,15	2	0,3	0,15	2	0,3
(3)	0,3	2	0,6	0,3	2	0,6
(4)	0,45	0,25	0,1125	0,45	2	0,9
c	0,15	2	0,3			
d				0,3	2	0,6
Total	**λ_C = 1,35**		**u_C = 1,9125**	**λ_D = 1,5**		**u_D = 3**

• We calculate the system reliability indices:

✓ $\mathrm{SAIFI} = \frac{\sum \lambda_i.N_i}{\sum N_i} = \frac{1{,}65.500+1{,}5.200+1{,}35.300+1{,}5.100}{500+200+300+100}$

$= 1{,}5273\ (\mathrm{f/customer.yr})$

✓ $\mathrm{SAIDI} = \frac{\sum u_i.N_i}{\sum N_i}$

$$= \frac{1{,}725.500 + 1{,}6875.200 + 1{,}9125.300 + 3{,}0.100}{500 + 200 + 300 + 100}$$

$= 1{,}8852\ (\mathrm{h/customer.yr})$

✓ $\text{CAIDI} = \frac{\sum u_i.N_i}{\sum \lambda_i.N_i}$

$$= \frac{1{,}725.500 + 1{,}6875.200 + 1{,}9125.300 + 3{,}0.100}{1{,}65.500 + 1{,}5.200 + 1{,}35.300 + 1{,}5.100}$$

$$= 1{,}234 \text{ (h)}$$

✓ $\text{ASAI} = \frac{\sum N_i.8760 - \sum u_i.N_i}{\sum N_i.8760}$

$$= \frac{1100.8760 - (1{,}725.500 + 1{,}6875.200 + 1{,}9125.300 + 3{,}0.100)}{1100.8760}$$

$$= 0{,}99978$$

✓ $\text{ASUI} = 1 - \text{ASAI} = 0{,}00022$

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

✓ $\text{AENS} = \frac{\text{EENS}}{\sum N_i} = \frac{2074}{500+200+300+100}$

$$= 1{,}8852 \text{ (kWh/custumer)}$$

❖ Software calculation:

• ETAP understands DS as a timed segmental device [13] so to implement this case, we fill out the Switching time of the Alternative supply of spindle segments:

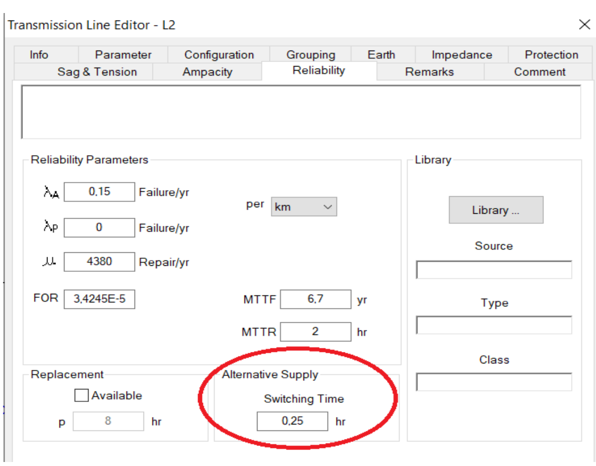

Fig. 15: Switching time indices in Reliability tab.

• The fault isolation process time is 0.25 (h), we set Switching time = 0.25 (h) at the segments (1), (2), (3), (4) as shown in *Figure 15* above. This means when these elements fail, after 0.25 (h) isolation time, ETAP will reclose the CB to re-energize the part in front of the opened segmental DS.

• After performing the simulation, we have the results:

✓ Load point reliability indices:

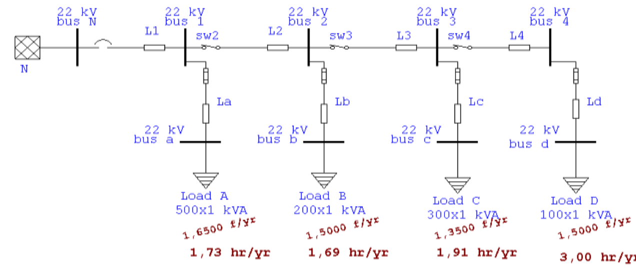

Fig. 16: Software calculation of Load point indices of Segmental radial DN with FCO on branches.

✓ System reliability indices:

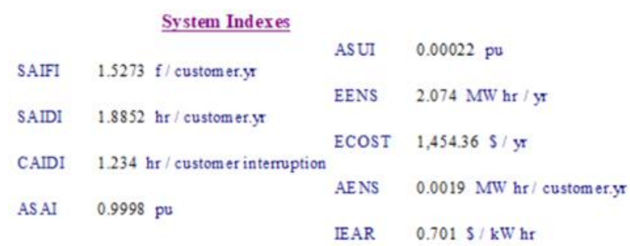

Fig. 17: Software calculation of System reliability indices of Segmental radial DN with FCO on branches.

❖ Comments:

✓ Software calculation results are similar to Manual calculation results.

✓ We can see that the Average Permanent Failure Rate λ_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):

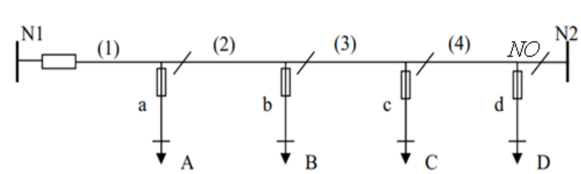

Fig. 18: Segmental ring DN with FCO on branches model.

❖ 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 (λ_i, u_i) of Segmental ring DN with FCO on branches load points

Failed part (j)	Load point A			Load point B		
	$\lambda_{e,j}$ (f/yr)	r_{Aj} (h)	$\lambda_{e,j}.r_{Aj}$ (h)	$\lambda_{e,j}$ (f/yr)	r_{Bj} (h)	$\lambda_{e,j}.r_{Bj}$ (h)
(1)	0,3	2	0,6	0,3	0,25	0,075
(2)	0,15	0,25	0,0375	0,15	2	0,3
(3)	0,3	0,25	0,075	0,3	0,25	0,075
(4)	0,45	0,25	0,1125	0,45	0,25	0,1125
a	0,45	2	0,9			
b				0,3	2	0,6
Total	$\lambda_A =$ **1,65**		$u_A =$ **1,725**	$\lambda_B =$ **1,5**		$u_B =$ **1,1625**
Failed part (j)	**Load point C**			**Load point D**		
	$\lambda_{e,j}$ (f/yr)	r_{Cj} (h)	$\lambda_{e,j}.r_{Cj}$ (h)	$\lambda_{e,j}$ (f/yr)	r_{Dj} (h)	$\lambda_{e,j}.r_{Dj}$ (h)
(1)	0,3	0,25	0,075	0,3	0,25	0,075
(2)	0,15	0,25	0,0375	0,15	0,25	0,0375
(3)	0,3	2	0,6	0,3	0,25	0,075
(4)	0,45	0,25	0,1125	0,45	2	0,9
c	0,15	2	0,3			
d				0,3	2	0,6
Total	$\lambda_C =$ **1,35**		$u_C =$ **1,125**	$\lambda_D =$ **1,5**		$u_D =$ **1,6875**

- We calculate the system reliability indices:

✓ $\mathrm{SAIFI} = \frac{\sum \lambda_i.N_i}{\sum N_i} = \frac{1{,}65.500+1{,}5.200+1{,}35.300+1{,}5.100}{500+200+300+100} = 1{,}5273\ (\mathrm{f/customer.yr})$

✓ $\mathrm{SAIDI} = \frac{\sum u_i.N_i}{\sum N_i} = \frac{1{,}725.500+1{,}1625.200+1{,}125.300+1{,}688.100}{500+200+300+100} = 1{,}4557\ (\mathrm{h/customer.yr})$

✓ $\mathrm{CAIDI} = \frac{\sum u_i.N_i}{\sum \lambda_i.N_i} = \frac{1{,}725.500+1{,}1625.200+1{,}125.300+1{,}6875.100}{1{,}65.500+1{,}5.200+1{,}35.300+1{,}5.100} = 0{,}953\ (\mathrm{h})$

✓ $\mathrm{ASAI} = \frac{\sum N_i.8760 - \sum u_i.N_i}{\sum N_i.8760} = \frac{1100.8760-(1{,}725.500+1{,}163.200+1{,}125.300+1{,}688.100)}{1100.8760} = 0{,}99983$

✓ $\mathrm{ASUI} = 1 - \mathrm{ASAI} = 0{,}00017$

✓ $\mathrm{EENS} = \sum P_i.u_i = 1{,}725.500 + 1{,}1625.200 + 1{,}125.300 + 1{,}6875.100 = 1601\ (\mathrm{kWh/yr})$

✓ $\mathrm{AENS} = \frac{\mathrm{EENS}}{\sum N_i} = \frac{1601}{500+200+300+100} = 1{,}4557\ (\mathrm{kWh/custumer})$

❖ Software calculation:

- We also use the Alternative supply function. After performing the simulation as above, we have the results:

✓ Load point reliability indices:

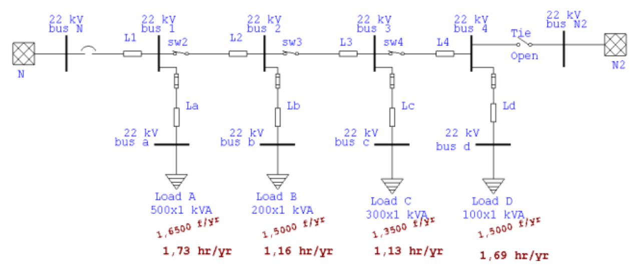

Fig. 19: Software calculation of Load point indices of Segmental ring DN with FCO on branches.

✓ System reliability indices:

Fig. 20: Software calculation of System reliability indices of Segmental ring DN with FCO on branches.

❖ Comments:

✓ Software calculation results are similar to Manual calculation results.

✓ We can see that the Average Permanent Failure Rate λ_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

Load point	Unsegmented radial DN without FCO on branches		Unsegmented radial DN with FCO on branches	
	λ (f/yr)	u (hr)	λ (f/yr)	u (hr)
A	2,4	4,8	1,65	3,3
B	2,4	4,8	1,50	3,0
C	2,4	4,8	1,35	2,7
D	2,4	4,8	1,50	3,0
Load point	**Segmental radial DN with FCO on branches**		**Segmental ring DN with FCO on branches**	
	λ (f/yr)	u (hr)	λ (f/yr)	u (hr)
A	1,65	1,725	1,65	1,725
B	1,50	1,6875	1,50	1,1625
C	1,35	1,9125	1,35	1,125
D	1,50	3,0	1,50	1,6875

❖ <u>Comments:</u>

✓ 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*:

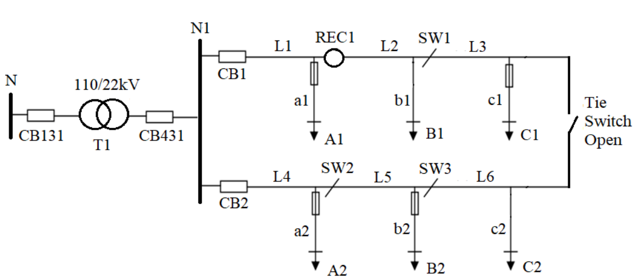

Fig. 21: Compound actual DN with a combination of isolator devices model.

The network assuming parameters:

✓ The average permanent failure rate of lines per km is λ_0 = 0,15 (f/km.yr).

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

	L1	**L2**	**L3**	**La1**	**Lb1**	**Lc1**
L(km)	3	2	2	1	3	2
$\lambda_{e,j}$ (f/yr)	0,45	0,3	0,3	0,15	0,45	0,3
r (h)	2	2	2	2	2	2
Switching time (h)	0.1	0.15	0.2	0.1	0.15	0.2
	L4	**L5**	**L6**	**La2**	**Lb2**	**Lc2**
L(km)	2	3	1	2	2	3
$\lambda_{e,j}$ (f/yr)	0,3	0,45	0,15	0,3	0,3	0,45
r (h)	2	2	2	2	2	2
Switching time (h)	0.1	0.15	0.2	0.1	0.15	0.2

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

	CB131	**T1**	**CB431**	**CB1**	**CB2**
$\lambda_{e,j}$ (f/yr)	0,002	0,015	0,004	0,004	0,004
r (h)	4	15	4	4	4
	REC1	**SW1**	**SW2**	**SW3**	
$\lambda_{e,j}$ (f/yr)	0,004	0,2	0,2	0,2	
r (h)	4	1	1	1	
Switching time (h)	0.15	0.2	0.15	0.2	

✓ Customer number of load points:

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

Load point	**A1**	**B1**	**C1**	**A2**	**B2**	**C2**
Customer number	500	200	300	200	400	100

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

❖ <u>Manual calculation</u>:

• 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, faults on (L1), REC1, (L2), (Lb1) only cause 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 (λ_i, u_i) of the load points:

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

Failed part (j)	Load point A1			Load point B1			Load point C1		
	$\lambda_{e,j}$ (f/yr)	r_{A1j} (h)	$\lambda_{e,j}.r_{A1j}$ (h)	$\lambda_{e,j}$ (f/yr)	r_{B1j} (h)	$\lambda_{e,j}.r_{B1j}$ (h)	$\lambda_{e,j}$ (f/yr)	r_{C1j} (h)	$\lambda_{e,j}.r_{C1j}$ (h)
CB131	2 10^{-3}	4	8 10^{-3}	2 10^{-3}	4	8 10^{-3}	2 10^{-3}	4	8 10^{-3}
T1	15 10^{-3}	15	225 10^{-3}	15 10^{-3}	15	225 10^{-3}	15 10^{-3}	15	225 10^{-3}
CB431	4 10^{-3}	4	16 10^{-3}	4 10^{-3}	4	16 10^{-3}	4 10^{-3}	4	16 10^{-3}
CB1	4 10^{-3}	4	16 10^{-3}	4 10^{-3}	4	16 10^{-3}	4 10^{-3}	4	16 10^{-3}
CB2	4 10^{-3}	4	16 10^{-3}	4 10^{-3}	4	16 10^{-3}	4 10^{-3}	4	16 10^{-3}
L1	0,45	2	0,9	0,45	0,1	45 10^{-3}	0,45	0,1	45 10^{-3}
REC1	4 10^{-3}	4	16 10^{-3}	4 10^{-3}	4	16 10^{-3}	4 10^{-3}	0,15	0,6 10^{-3}
L2				0,3	2	0,6	0,3	0,15	45 10^{-3}
SW1				0,2	1	0,2	0,2	1	0,2
L3				0,3	0,2	60 10^{-3}	0,3	2	0,6
La1	0,15	2	0,3						
Lb1				0,45	2	0,9	0,45	0,15	67,5 10^{-3}
Lc1							0,3	2	0,6
Total	**λ_{A1} = 0,633**		**u_{A1} = 1,497**	**λ_{B1} = 1,733**		**u_{B1} = 2,102**	**λ_{C1} = 2,033**		**u_{C1} = 1,839**

Failed part (j)	Load point A2			Load point B2			Load point C2		
	$\lambda_{e,j}$ (f/yr)	r_{A2j} (h)	$\lambda_{e,j}.r_{A2j}$ (h)	$\lambda_{e,j}$ (f/yr)	r_{B2j} (h)	$\lambda_{e,j}.r_{B2j}$ (h)	$\lambda_{e,j}$ (f/yr)	r_{C2j} (h)	$\lambda_{e,j}.r_{C2j}$ (h)
CB131	2 10^{-3}	4	8 10^{-3}	2 10^{-3}	4	8 10^{-3}	2 10^{-3}	4	8 10^{-3}
T1	15 10^{-3}	15	225 10^{-3}	15 10^{-3}	15	225 10^{-3}	15 10^{-3}	15	225 10^{-3}
CB431	4 10^{-3}	4	16 10^{-3}	4 10^{-3}	4	16 10^{-3}	4 10^{-3}	4	16 10^{-3}
CB1	4 10^{-3}	4	16 10^{-3}	4 10^{-3}	4	16 10^{-3}	4 10^{-3}	4	16 10^{-3}
CB2	4 10^{-3}	4	16 10^{-3}	4 10^{-3}	4	16 10^{-3}	4 10^{-3}	4	16 10^{-3}
L4	0,3	2	0,6	0,3	0,1	30 10^{-3}	0,3	0,1	30 10^{-3}
SW2	0,2	1	0,2	0,2	1	0,2	0,2	0,15	30 10^{-3}
L5	0,45	0,15	67,5 10^{-3}	0,45	2	0,9	0,45	0,15	67,5 10^{-3}
SW3	0,2	0,2	40 10^{-3}	0,2	1	0,2	0,2	1	0,2
L6	0,15	0,2	30 10^{-3}	0,15	0,2	30 10^{-3}	0,15	2	0,3
La2	0,3	2	0,6						
Lb2				0,3	2	0,6			
Lc2	0,45	0,2	90 10^{-3}	0,45	0,2	90 10^{-3}	0,45	2	0,9
Total	**λ_{A2} = 2,079**		**u_{A2} = 1,908**	**λ_{B2} = 2,079**		**u_{B2} = 2,331**	**λ_{C2} = 1,779**		**u_{C2} = 1,809**

• We calculate the system reliability indices:

✓ $$\mathrm{SAIFI} = \frac{\sum \lambda_i.N_i}{\sum N_i} = \frac{0{,}633.500+1{,}733.200+2{,}033.300}{500+200+300+200+400+100} + \frac{2{,}079.200+2{,}079.400+1{,}779.100}{500+200+300+200+400+100} = 1{,}5872\ (\mathrm{f/customer.yr})$$

✓ $\text{SAIDI} = \frac{\sum u_i.N_i}{\sum N_i} = \frac{1{,}497.500+2{,}102.200+1{,}839.300}{500+200+300+200+400+100} + \frac{1{,}908.200+2{,}331.400+1{,}809.100}{500+200+300+200+400+100} = 1{,}8915\ (\text{h/customer.yr})$

✓ $\text{CAIDI} = \frac{\sum u_i.N_i}{\sum \lambda_i.N_i} = \frac{1{,}497.500+2{,}102.200+1{,}839.300+1{,}908.200+2{,}331.400+1{,}809.100}{0{,}633.500+1{,}733.200+2{,}033.300+2{,}079.200+2{,}079.400+1{,}779.100} = 1{,}192\ (\text{h})$

✓ $\text{ASAI} = \frac{\sum N_i.8760 - \sum u_i.N_i}{\sum N_i.8760} = \frac{1700.8760-(1{,}497.500+2{,}102.200+1{,}839.300+1{,}908.200+2{,}331.400+1{,}809.100)}{1700.8760} = 0{,}99978$

✓ $\text{ASUI} = 1 - \text{ASAI} = 0{,}00022$

✓ $\text{EENS} = \sum P_i.u_i = 1{,}497.500 + 2{,}102.200 + 1{,}839.300 + 1{,}908.200 + 2{,}331.400 + 1{,}809.100 = 3215.5\ (\text{kWh/yr})$

✓ $\text{AENS} = \frac{\text{EENS}}{\sum N_i} = \frac{3215.5}{500+200+300+200+400+100} = 1{,}8914\ (\text{kWh/custumer})$

❖ Software calculation:

• We also simulate with ETAP as shown in *Figure 22*. After performing the simulation, we have the results:

✓ Load point reliability indices:

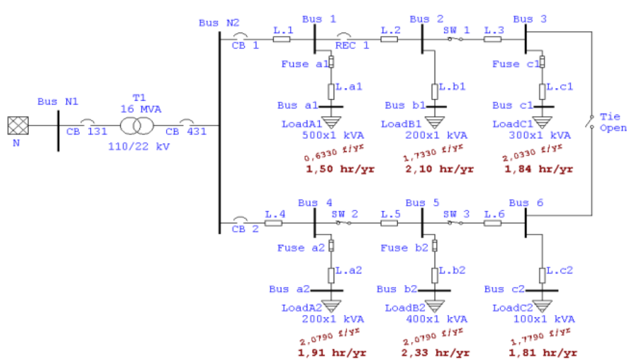

Fig. 22: Software calculation of Load point indices of Compound actual DN.

✓ System reliability indices:

System Indexes

SAIFI	1.5872	f / customer.yr	EENS	3.216	MW hr / yr
SAIDI	1.8915	hr / customer.yr	ECOST	2,719.99	$ / yr
CAIDI	1.192	hr / customer interruption	AENS	0.0019	MW hr / customer.yr
ASAI	0.9998	pu	IEAR	0.846	$ / kW hr
ASUI	0.00022	pu			

Fig. 23: Software calculation of System reliability indices of Compound actual DN.

❖ 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.

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