

# DISTRIBUTION RELIABILITY ANALYSIS

A Thesis by

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## DISTRIBUTION RELIABILITY ANALYSIS

I have examined the final copy of this thesis for form, and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science with a major in Electrical Engineering.

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## ABSTRACT

This thesis presents an example for optimization of distribution maintenance scheduling of a recloser. It applies a risk reduction technique associated with maintenance of the equipment. Furthermore, this thesis examines how various distribution system designs, including distributed energy resources (DER), affect distribution reliability indices, System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI).

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## LIST OF ABBREVIATIONS

COF	Cost of Failure
CT	Close Time
DER	Distributed Energy Resources
ENS	Energy Not Served
FR	Failure Rate
FUS	Fuse
MFR	Mean Failure Rate
OH	Overhead Line
OCR	Over Current Relay
OT	Open Time
PR	Protection Reliability
R	Recloser
REC	Recloser
RT	Repair Time
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
S	Switch
SWI	Switch

# CHAPTER 1

## INTRODUCTION

The reliability of a power distribution system is important for making the system more economic and efficient. In turn, consumers will receive a more reliable electric supply by the utility company. In order to ensure that the changing utility environment does not adversely affect the reliability of the customer's power supply, regulatory authorities have begun to specify minimum reliability standards that must be maintained by distribution companies [1]. Maintenance of aging distribution systems is an important part of ensuring that the system is performing well and is reliable.

Inspection and maintenance of the equipment of a power distribution system require a large expenditure of financial and human resources. This is a critical issue for a utility to ensure that their spending money will improve equipment performance and system reliability. Maintaining a specific level of reliability and high level of customer satisfaction is difficult for a utility within a limited maintenance budget. Therefore, a sound asset management policy for identifying poor performing equipment and allocating the budget for maintenance is required.

As part of asset management, this thesis applies an optimized method of maintenance scheduling [1]. A spreadsheet-based reliability evaluation tool [1] and a technique for estimating recloser reliability [1] are used to determine the best schedule for maintenance of multiple reclosers on a system. Reclosers that are most likely to degrade system reliability are scheduled for maintenance first, followed by those with lower effects on reliability.

In addition to maintaining equipment, new technologies and an updated system design can also improve system reliability. The second part of this thesis examines different distribution system designs, with and without distributed energy resources (generation and storage). The

effects on distribution reliability indices, that is, system average interruption duration index (SAIDI), and system average interruption frequency index (SAIFI) are estimated using manual techniques [2] and standard distribution reliability evaluation software [3].

## CHAPTER 2

### RECLOSER MAINTENANCE SCHEDULING

The technique used to schedule the maintenance of power distribution system reclosers [1] is an automated procedure that determines an annual maintenance schedule for an entire system. It requires a large amount of data and work before it can be used. In this chapter, a simplified example of scheduling maintenance for reclosers is presented. This example allows a utility, as data collection begins, to apply the technique to two or more reclosers to determine which should be serviced first.

#### 2.1 Optimized Distribution Maintenance Scheduling

In optimized distribution maintenance scheduling, a predictive method is used to analytically evaluate reliability. The reliability level of the system is computed before maintenance of the distribution equipment. It is predicted that the failure rate of the equipment is reduced after maintenance. In turn, reduced failure rate decreases the risk associated with maintenance.

##### 2.1.1 Condition of Recloser and Failure Rate Estimation

Recloser condition and failure rate estimation is provided by Warner [4]. The criteria used to calculate the condition of the recloser [4] is given in Table 2.1. Each criterion is weighted based on its influence on the failure rate (FR) of the recloser. Each criterion is scored from 0 to 1. Finally, the weighted average is the recloser condition score.

TABLE 2.1

SCORING OF THE RECLOSER

Criteria	Weight	Score (0-1)
		Pre- Maintenance
Age of Oil		
Duty Cycle Rate		
Environmental Factor		
Oil Dielectric Strength		
Condition of Contacts		
Age of Recloser		
Experience with this Recloser Type		
Condition of Tank		
Sum		
Weighted Average		

The best, worst, and average failure rates from historical failure rate data [4] are as follows:

$$\lambda(0) = 0.0025 \text{ (Best)}$$

$$\lambda(1/2) = 0.015 \text{ (Average)}$$

$$\lambda(1) = 0.060 \text{ (Worst)}$$

Equation (2.1) is used to calculate average recloser failure rate if, historical data is available [4]:

$$\lambda(1/2) = \frac{\text{Total Number of Recloser Failures}}{(\text{Number of Reclosers}) * (\text{Number of Years})} \quad (2.1)$$

where the number of reclosers is the number of reclosers on the system at the time of the failure, and the number of years is the period of time the data is recorded.

Once the best, worst, and average failure rates for reclosers on a system are determined, either from historical or published data, A, B, and C parameters are calculated as [4]:

$$A = \frac{[\lambda(1/2) - \lambda(0)]^2}{\lambda(1) - 2\lambda(1/2) + \lambda(0)} \quad (2.2)$$

$$B = 2 \ln \frac{[\lambda(1/2) + A - \lambda(0)]}{A}$$

$$C = \lambda(0) - A$$

These parameters are then used to estimate the failure rate for a recloser as

$$\lambda(x) = A e^{B \cdot x} + C \quad (2.3)$$

In equation (2.3),  $\lambda(x)$  is the failure rate calculated from  $x$ , the relative condition score for the recloser. A high value of  $x$  represents a low failure rate, and a low value represents a high failure rate. This equation shows the direct relation between failure rates and scores of the recloser.

### **2.1.2 Effect of Maintenance on Failure Rate of the Recloser**

If maintenance is performed on any criterion presented in Table 2.1, the individual criterion receives a higher score, which results in a higher average score for the recloser. From equation (2.3), a high recloser condition score gives a lower failure rate. Hence, the failure rate of the recloser decreases after its maintenance.

### **2.1.3 Risk Reduction Method**

Every piece of equipment in the distribution system has a finite life, with failure probability that increases with time. Maintenance improves the condition of equipment and thus reduces its likelihood of failure. To define risk, the following effects of equipment failure will be considered [1]:

1. Customer satisfaction, in terms of SAIDI and SAIFI
2. Revenue lost by utility due to energy not served (ENS)
3. Cost to replace or repair failed equipment ( COF)
4. Regulatory or contractual penalties paid by the utility due to missed reliability targets

### **2.1.3.1 Effect on Customer Satisfaction**

The effect on customer satisfactions is described below with reliability indices SAIDI and SAIFI.

#### **System Average Interruption Frequency Index (SAIFI):**

SAIFI is defined as the total customer interruptions per total customer served [2]. Total customer Interruptions is defined as the summation over the considered system of the mean failure rate (MFR) of each element multiplied by the number of customer interruptions on that element. The calculation of total customer interruptions first requires the calculation of mean failure rate of each element in that circuit model. The mean failure rate for an element is defined as the number of interruptions per year that a customer on that element would be expected to experience. Summing the number of customer interruptions for all elements in the given system/model gives the total customer interruptions [5].

#### **Example 2.1:**

The procedure and calculations to find SAIFI for a distributed model, as shown in Figure 2.1, are provided in detail below. All required data to calculate SAIFI are given in Table 2.2. In this example, it is assumed that the coordination failure rate of all overcurrent devices (fuses and overcurrent relays or OCRs) is 0.0. That is, in all fault situations, each fuse or OCR operates as required to clear the fault for all systems up line from the fuse or OCR [5].

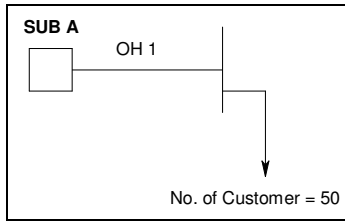


Figure 2.1: Distribution model.

TABLE 2.2

RELIABILITY DATA TABLE

<b>Substation Data</b>	<b>Overhead Line Data</b>	<b>Other</b>
Failure Rate (FR) = 0.1	Failure Rate (FR) = 0.2	Open Time = 0
Repair time (RT) = 5.0 hrs	Repair Time (RT) = 2 hrs	Time to Find Problem = 0
Close time (CT) = 0.5 hrs		Travel time = 0

In this example, 50 consumers are connected to a Substation (SUB A) through an overhead line (OH 1). In the Figure 2.1, there are no switches or overcurrent devices (fuses and OCRs) in this circuit. Any fault at SUB A or OH 1 will interrupt all 50 customers. Since only elements with non-zero customers contribute to the total customer interruptions, the mean failure rate can be calculated for line element only.

$$\text{MFR for OH 1} = \text{FR of SUB A} + \text{FR of OH 1}$$

$$= 0.1 + 0.2$$

$$= 0.3$$

$$\text{Customer Interruptions} = \text{MFR} * \text{Number of Customers}$$

The calculation of SAIFI is summarized in Table 2.3.

TABLE 2.3

SAIFI CALCULATION TABLE

<b>Element</b>	<b>FR</b>	<b>MFR</b>	<b>No. of Customer</b>	<b>Customer Interruptions</b>
SUB A	0.1	-	0	0
OH 1	0.2	0.3	50	15
Total			50	15

Total Customer Interruptions = 15

Total Number of Customer served = 50

Therefore,

$$\begin{aligned}
 \text{SAIFI} &= \frac{\text{Total Customer Interruption}}{\text{Total no. of Customers Served}} \\
 &= 15/50 \\
 &= 0.3
 \end{aligned}$$

**System Average Interruption Duration Index (SAIDI):**

SAIDI is defined as the sum of customer interruption durations per total customers served [2]. The sum of customer interruption durations for a specified part or whole of the system is the total number of annual customer hours out due to all possible faults and problems. SAIDI can be defined as follows:

$$\text{SAIDI} = \frac{\text{Customer Hour/Year}}{\text{Total Customers Served}}$$

**Example 2.2:**

The procedure and calculations to find the reliability index SAIDI for Figure 2.1 are shown in detail below. All required data to calculate SAIDI is given in Table 2.2.

In this given model, SUB A and OH 1 are the elements for any possible faults and problems for Customer Interruption Duration. Interruption Duration (ID) can be calculated as [5]

$$ID = \text{Repair Time} + \text{Close Time} + \text{Open Time} + \text{Travel Time} + \text{Time to Find Problem}$$

For the given model, ID, because of SUB A or outage on SUB A is given by

$$ID (\text{SUB A}) = \text{Repair Time for Substation A} + \text{Close Time for Substation A}$$

Since travel time and time to find problem are assumed to be zero, then

$$\begin{aligned} ID (\text{SUB A}) &= 5 + 0.5 \\ &= 5.5 \end{aligned}$$

Interruption Duration because of OH1 or outage on OH 1 is given by

$$ID (\text{OH1}) = \text{Repair Time for OH 1} + \text{Close Time for SUB A}$$

(Note: Close time for a substation is added to the repair time for the overhead line to calculate the interruption duration because of the overhead line. If there is any fault in OH 1, the circuit breaker or any protecting device inside SUB A will open instantly with zero open time, and after maintenance of OH 1 will be closed with close time of 0.5 hour to resume the supply.)

TABLE 2.4

SAIDI CALCULATION TABLE

Outage on Device	Number of Customer Interruption	Interruption Duration (hour)	Failure Rate (per year)	Customer Hours Per Year
SUB A	50	5.5	0.1	27.5
OH 1	50	2.5	0.2	25
Total				52.5
Total Customer Served: 50				

Therefore,

$$\begin{aligned}
\text{SAIDI} &= \frac{\text{Customer Hour/Year}}{\text{Total Customer Served}} \\
&= 52.5 \\
&= 1.05
\end{aligned}$$

### 2.1.3.2 Revenue Lost by the Utility

Revenue lost because of energy not served (ENS) is defined as [1]

$$\text{ENS (k)} = \lambda (k). \sum_{j=1}^{nk} P_j d_j$$

### 2.1.3.3 Cost of Equipment Failure

The cost of equipment failure is defined as [1]

$$\text{DevRisk (k)} = \lambda (k). \text{Cost (k)}$$

### 2.1.3.4 Regulatory Penalties Due to Violation of Regulatory Limits

Performance-based regulatory penalties for SAIFI (PBRF) and SAIDI (PBRD) are defined as [1]

$$\begin{aligned}
\text{PBRF (k)} &= \int_{TF}^{\infty} \text{PBR (SAIFI). } f(\text{SAIFI (k)}) d(\text{SAIFI (k)}) \\
\text{PBRD (k)} &= \int_{TD}^{\infty} \text{PBR (SAIDI). } f(\text{SAIDI (k)}) d(\text{SAIDI (k)}) \quad (2.4)
\end{aligned}$$

Where

$\lambda (k)$  = Failure rate of component 'k'

$d$  = Duration of the interruption seen by the customer due to failure of component 'k'

$\text{Cost (k)}$  = Cost of failure for component 'k'

$\text{PBR (SAIFI)}$  = Performance-based penalty for a SAIFI violation beyond threshold TF

$\text{PBR (SAIDI)}$  = Performance-based penalty for a SAIDI violation beyond threshold TD

$f(\text{SAIDI}(k))$  = Probability distribution of SAIDI obtained by non-sequential Monte Carlo simulation for component 'k'

$f(\text{SAIFI}(k))$  = Probability distribution of SAIFI obtained by non-sequential Monte Carlo simulation for component 'k'

Equation (2.4) gives the risk of penalty before maintenance. Repeating the computation using the failure rate after maintenance, gives the risk of penalty after maintenance. Risk reduction is the difference in risk before and after maintenance.

The overall risk reduction obtained from maintaining a component 'k' can be written as a linear combination of each factor as [1]

$$\begin{aligned} \Delta \text{Risk}(k) = & \alpha_1 \cdot \Delta \text{SAIFI}(k) + \alpha_2 \cdot \Delta \text{SAIDI}(k) + \alpha_3 \cdot \Delta \text{ENS}(k) \\ & + \alpha_4 \cdot \text{DevRisk}(k) + \alpha_5 \cdot \Delta \text{PBRF}(k) + \alpha_6 \cdot \Delta \text{PBRD}(k) \end{aligned} \quad (2.5)$$

The coefficients ( $\alpha_i$ ) in equation (2.5) correspond to the weights assigned by an asset manager assigns to the different factors, based on their relative importance or confidence in their accuracy.

#### 2.1.4 Example of Maintenance Scheduling of Recloser

An example of maintenance scheduling of recloser by the risk reduction method is done using a reliability evaluation tool (spreadsheet-based software for computing the reliability levels of a system) [1]. For this example, a distribution feeder [6] is chosen, as shown in Figure 2.2. This feeder is 95.7 km with a total of 23 nodes. The feeder is divided into 21 segments, starting from the substation to segment 22. A portion between two nodes is called a segment. The number of customers represents the number of energy meters installed and are chosen according to the length of the segment. The given feeder has three different types of overcurrent protection devices. They are recloser (R or REC), switch (S or SWI) and fuse. The given feeder has seven

reclosers. Their maintenance is scheduled based on their condition and effects on system reliability. All reclosers at each section are given a number from 1 to 7. The feeder is summarized in Table 2.5.

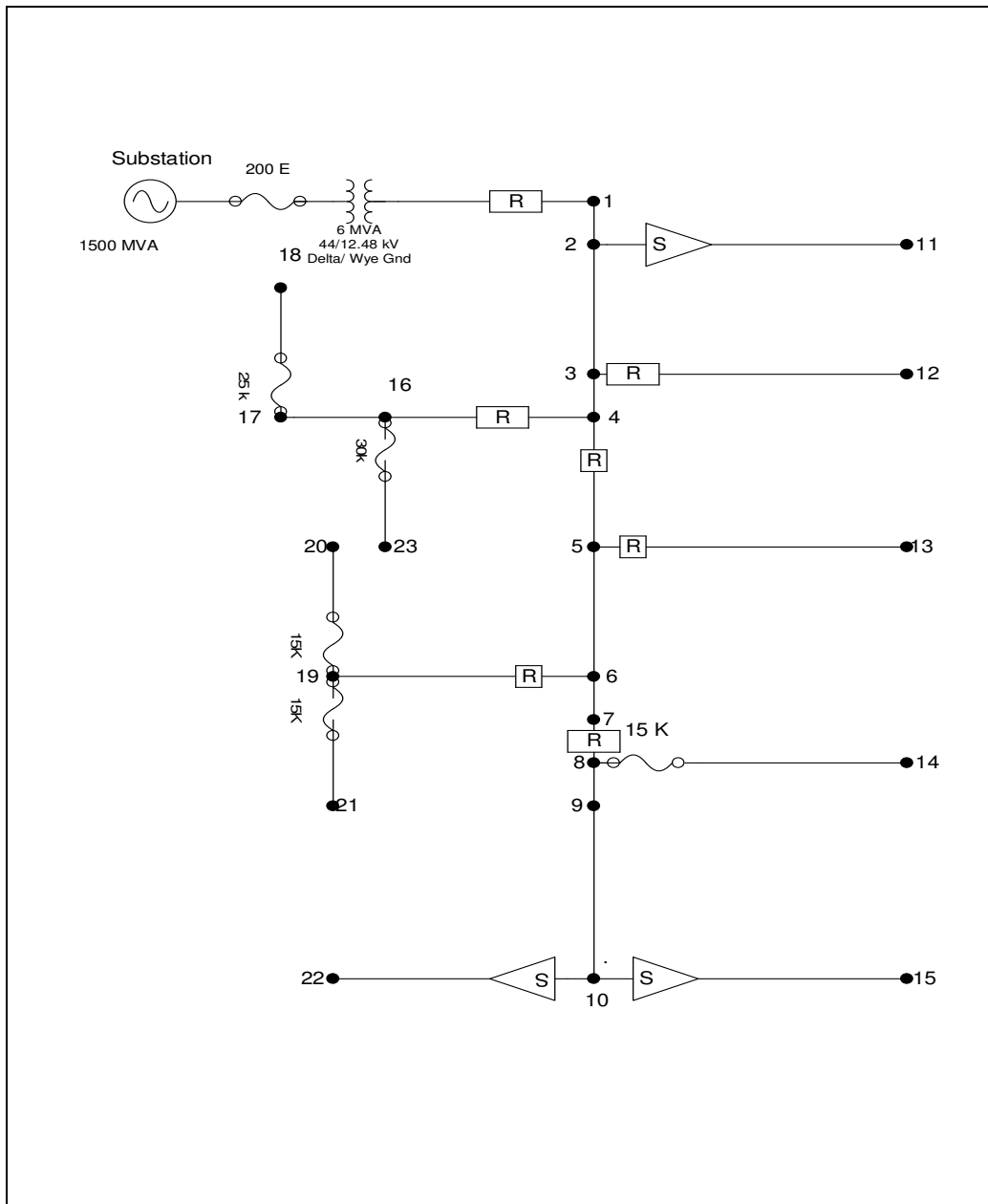


Figure 2.2: Distribution feeder [6].

TABLE 2.5

## DESCRIPTION OF FEEDER

Segment #	From Node #	To Node #	Length (km)	Type of Protection Devices
Substation	Substation	1	-	REC
1	1	2	1	
2	2	3	8	
3	3	4	1.5	
4	4	5	3	REC
5	5	6	4	
6	6	7	1.5	
7	7	8	1.5	REC
8	8	9	1.5	
9	9	10	8	
10	10	15	2	SWI
11	10	22	5	SWI
12	8	14	2	FUS
13	6	19	8	REC
14	19	20	8	FUS
15	19	21	3	FUS
16	5	13	12	REC
17	4	16	3	REC
18	16	17	1.5	
19	16	23	3	FUS
20	17	18	5	FUS
21	3	12	12	REC
22	2	11	1.2	SWI

For the risk calculation, the following coefficients are assumed [1]:

Customer satisfaction ( $\Delta$  SAIFI,  $\Delta$  SAIDI):  $\alpha_1, \alpha_2 = 100.00$

Lost Revenue ( $\Delta$  ENS):  $\alpha_3 = 10$

Cost of Component Failure ( $\Delta$  COF):  $\alpha_4 = 1$

Regulator Penalties ( $\Delta$  PBRF +  $\Delta$  PBRD):  $\alpha_5, \alpha_6 = 0$

Considering these coefficients, equation (2.5) can be rewritten as

$$\Delta \text{Risk} = 100 * [\Delta \text{SAIFI} + \Delta \text{SAIDI}] + 10 * \Delta \text{ENS} + 1 * \text{DevRisk} \quad (2.6)$$

### 2.1.4.1 Methodology for Maintenance Scheduling of Reclosers

Using the technique and methodology presented above, the stepwise methods applied for maintenance scheduling of reclosers for a given feeder is briefly described as follows:

1. PR before maintenance and expected PR after maintenance are tabulated for each Recloser [1]. (shown in Table 2.6)
2. The outage effects (SAIDI, SAIDI, ENS, and COF) are calculated and tabulated for the system with all reclosers with before-maintenance PR.
3. These steps are followed after step 2:
  - a. PR before maintenance is replaced by PR after maintenance for each recloser, one at a time.
  - b. The outage effects (SAIDI, SAIDI, ENS, and COF) are calculated for each recloser with after-maintenance PR, one at a time.
  - c. The change in outage effects ( $\Delta$  SAIFI,  $\Delta$  SAIDI,  $\Delta$  ENS, and  $\Delta$  COF), is calculated by subtracting the result of step 3 (b) from the result of step 2 (shown in Table 2.7).
  - d. Using the risk reduction formula given in equation (2.6),  $\Delta$  RISK is calculated (shown in Table 2.8).
  - e. Using this  $\Delta$  RISK, the maintenance scheduling is done. The recloser with the lowest to highest  $\Delta$  RISK to the first to last in priority of maintenance is set (shown in Table 2.8).
4. Now, step 3 is repeated for two reclosers at a time. The other recloser chosen was Recloser # 7 because it had the lowest  $\Delta$  RISK. All indices are calculated with the after-

maintenance PR value for Recloser # 7 and each Recloser from 1 to 7 simultaneously (in combination of two reclosers at a time).

5. In next step, three reclosers are chosen, two from step 4 and the other as recloser # 3 with the second lowest  $\Delta$ RISK.
6. A similar procedure is repeated until all seven reclosers got a new PR value at the same time (shown in Table 2.10).
7. After step 6, all indices are calculated until the value of zero is obtained for all. This proves that the prediction of maintenance scheduling of the reclosers is done correctly and no more maintenance is required (shown in Table 2.10)

TABLE 2.6

PR BEFORE MAINTENANCE AND EXPECTED PR AFTER MAINTENANCE FOR EACH RECLOSER

Segment#	PR ( Before Maintenance)	PR ( After Maintenance)	Recloser #
Substation	0.97467943	0.99121138	1
1			
2	0.95		
3	0.95		
4	0.97467943	0.99121138	2
5	0.95		
6	0.95		
7	0.97467943	0.99121138	3
8	0.95		
9	0.95		
10	0		
11	0		
12	0.95		
13	0.97467943	0.99121138	4
14	0.95		
15	0.95		
16	0.97467943	0.99121138	5
17	0.97467943	0.99121138	6
18	0		
19	0.95		
20	0.95		
21	0.97467943	0.99121138	7
22	0		

TABLE 2.7

CHANGE IN OUTAGE EFFECTS FOR EACH RECLOSER WITH AFTER MAINTENANCE  
PR VALUE

Recloser No.	1	2	3	4	5	6	7
$\Delta$ SAIFI	0	-0.0011652	-0.003326	-0.0007494	-0.0020053	-0.0013099	-0.0036503
$\Delta$ SAIDI	-0.0075648	-0.006661	-0.0106285	-0.0037543	-0.0068853	-0.0041212	0.011409
$\Delta$ ENS	-181.10065	-158.70228	-259.34212	-92.815604	-167.92132	-99.746459	273.26286
$\Delta$ COF	-4.3227271	-3.1404428	-6.5886956	-2.6166144	-4.4335663	-1.4159718	-4.4335663

TABLE 2.8

CALCULATION  $\Delta$  RISK FOR EACH RECLOSER

Recloser No.	1	2	3	4	5	6	7
$\Delta$ Risk	-1816.0857	-1590.9458	-2601.4053	-928.60641	-1684.5359	-999.42367	-2738.5681

TABLE 2.9

ORDER OF RECLOSER MAINTENANCE BASED ON ITS  $\Delta$  RISK VALUE

ORDER OF RECLOSER MAINTENANCE (REC #)	$\Delta$ SAIFI	$\Delta$ SAIDI	$\Delta$ ENS	$\Delta$ COF	$\Delta$ RISK
7	-0.00365025	-0.011409	-273.262859	-4.43356631	-2738.56808
3	-0.00332604	-0.0106285	-259.342119	-6.58869556	-2601.40533
1	0	-0.0075648	-181.100654	-4.32272715	-1816.08574
5	-0.00200529	-0.0068853	-167.921324	-4.43356631	-1684.53587
2	-0.00116518	-0.006661	-158.702277	-3.1404428	-1590.94583
6	-0.00130986	-0.0041212	-99.7464593	-1.41597178	-999.423672
4	-0.00074935	-0.0037543	-92.8156043	-2.61661444	-931.223023

TABLE 2.10

ALL SEVEN RECLOSERS WITH AFTER MAINTENANCE PR VALUE  
AND CALCULATION OF  $\Delta$  RISK

PR before Maintenance	PR after Maintenance	Changing PR with After Maintenance Value One at Time for Each Recloser						
0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138
0.95		0.95	0.95	0.95	0.95	0.95	0.95	0.95
0.95		0.95	0.95	0.95	0.95	0.95	0.95	0.95
0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138
0.95		0.95	0.95	0.95	0.95	0.95	0.95	0.95
0.95		0.95	0.95	0.95	0.95	0.95	0.95	0.95
0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138
0.95		0.95	0.95	0.95	0.95	0.95	0.95	0.95
0.95		0.95	0.95	0.95	0.95	0.95	0.95	0.95
0		0	0	0	0	0	0	0
0		0	0	0	0	0	0	0
0.95		0.95	0.95	0.95	0.95	0.95	0.95	0.95
0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138
0.95		0.95	0.95	0.95	0.95	0.95	0.95	0.95
0.95		0.95	0.95	0.95	0.95	0.95	0.95	0.95
0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138
0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138
0		0	0	0	0	0	0	0
0.95		0.95	0.95	0.95	0.95	0.95	0.95	0.95
0.95		0.95	0.95	0.95	0.95	0.95	0.95	0.95
0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138	0.99121138
0		0	0	0	0	0		
SAIFI	0.655097135	0.655097135	0.655097135	0.655097135	0.655097135	0.655097135	0.655097135	0.655097135
SAIDI	0.689491128	0.689491128	0.689491128	0.689491128	0.689491128	0.689491128	0.689491128	0.689491128
ENS	16603.07309	16603.07309	16603.07309	16603.07309	16603.07309	16603.07309	16603.07309	16603.07309
COF	1097.870146	1097.870146	1097.870146	1097.870146	1097.870146	1097.870146	1097.870146	1097.870146
Customer satisfaction; $\alpha_1, \alpha_2$		100						
Lost revenue; $\alpha_3$		10						
Cost of component failure; $\alpha_4$		1						
	$\Delta$ SAIFI	0	0	0	0	0	0	0
	$\Delta$ SAIDI	0	0	0	0	0	0	0
	$\Delta$ ENS	0	0	0	0	0	0	0
	$\Delta$ COF	0	0	0	0	0	0	0
	$\Delta$ risk	0	0	0	0	0	0	0

### **2.1.5 Summary**

This technique allows a distribution utility to schedule maintenance on reclosers based on each recloser's condition and its potential effect on system reliability. Reliability is measured by reliability indices SAIDI and SAIFI, energy not served (ENS), cost of failure (COF), and regulatory penalties. This technique can be applied to two or more pieces of equipment. The example in this thesis applies to reclosers, but other equipment can be similarly evaluated. This allows a utility with limited condition data, or one that is just beginning to collect condition data, to begin using the data immediately.

## CHAPTER 3

### DISTRIBUTION SYSTEM RELIABILITY

Chapter 2 focused on the effects of maintenance on feeder and distribution system reliability. Chapters 3 and 4 address adding another power source to the feeder, which also has potential to improve reliability. The same technique for estimating feeder reliability demonstrated in Chapter 2 is used here. Results are also verified with commercial software [3].

#### 3.1 Calculation of Reliability Indexes

In this section, reliability indices SAIDI and SAIFI of a distribution system are calculated with before- and after-maintenance recloser failure rates. Furthermore, reliability is analyzed on the same model with the before-maintenance failure rate of the recloser and a distributed energy resource (DER). For the reliability indices calculation, reliability analysis software [3] is used.

#### Example 3.1:

This example verifies that the reliability of the system improves after maintenance of the equipment. A distribution system model having seven reclosers is shown in Figure 3.1. The failure rates of reclosers before and after maintenance estimated for the maintenance scheduling in Chapter 2 is given in Table 3.1.

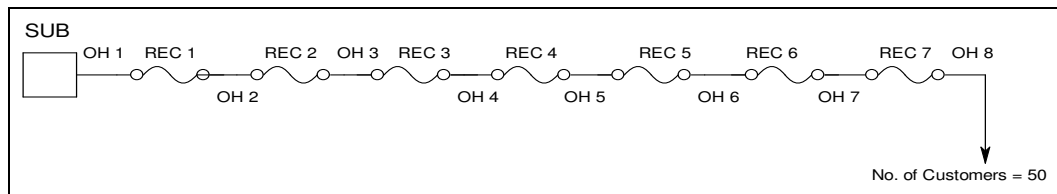


Figure 3.1: Distribution system model 1.

TABLE 3.1

FAILURE RATE OF RECLOSERS BEFORE AND AFTER MAINTENANCE

Before Maintenance	After Maintenance	Recloser Number
0	0	1
0.067045	0.056818	2
0.067045	0.028409	3
0.178788	0.151515	4
0.268182	0.227273	5
0.067045	0.056818	6
0.268182	0.227273	7

Using reliability analysis software [3], the following reliability indices are calculated for the given distribution model shown in Figure 3.1.

Before Maintenance: SAIFI = 2.6163  
SAIDI = 3.85

After Maintenance: SAIFI = 2.4481  
SAIDI = 3.85

From the above result, it can be seen that the reliability index SAIFI improves after maintenance of the reclosers. SAIFI only depends on the mean failure rate of the system element, and the failure rate decreases after maintenance. SAIDI depends on the failure rate, repair time, close time, and open time of the equipment. In this example, the difference in failure rates of the reclosers before and after maintenance is less; repair time, open time, and close time are the same before and after maintenance, so there is negligible effect on interruption duration. But SAIDI would be improved if there was a greater difference in failure rate before and after maintenance.

**Example 3.2:**

The same distribution model as used in example 3.1 with a distributed energy resource is analyzed. The DER is a backup or alternative power source. It can be a generation unit (e.g., micro turbine, diesel generator, fuel cell) or storage unit (e.g., batteries, flywheel).

All reclosers shown in Figure 3.2 are with before-maintenance failure rates. Note that the DER in this example is used as a backup, not a parallel, source. The DER switch is normally open (N.O.) and is only closed when the primary substation supply fails.

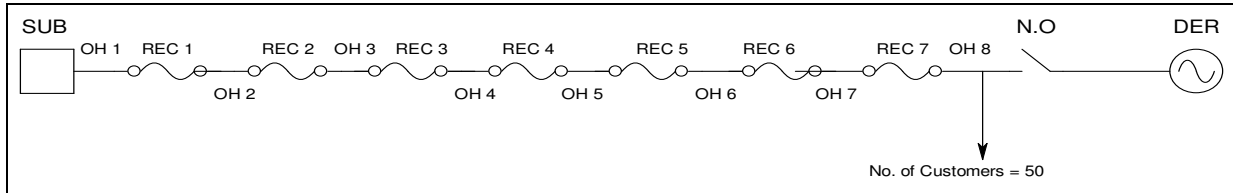


Figure: 3.2 Distribution system model 2.

Results obtained using reliability analysis software [3] are as follows:

$$\text{SAIFI} = 2.6163$$

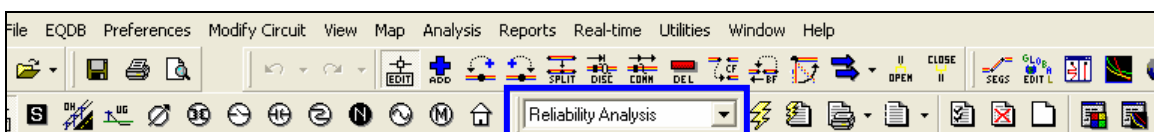
$$\text{SAIDI} = 0.4$$

From the results obtained above, we can see the improvement in reliability index SAIDI, but SAIFI is the same. SAIDI depends on interruption duration because of outages on system elements, and the use of DER decreases the outages. But, SAIFI depends on the failure rate of the equipment so it is not improved with backup DER. If the DER was parallel (N. C. switch) instead of a backup, then SAIFI would improve.

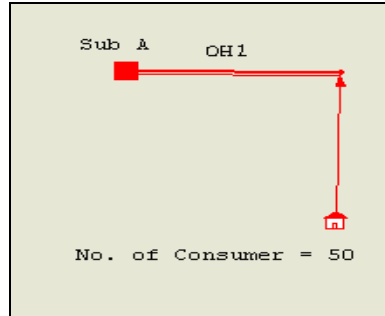
### 3.2 Verification of SAIDI, and SAIFI Using Reliability Evaluation Software


This section presents verification of the calculation of SAIDI and SAIFI for examples 2.1 and example 2.2 using commercial reliability evaluation software [3]. A brief procedure to perform reliability evaluation follows [3]. The detailed procedure could be found in the user manual [5].

1. Select the *Reliability Analysis* module from the Analysis Modes option.

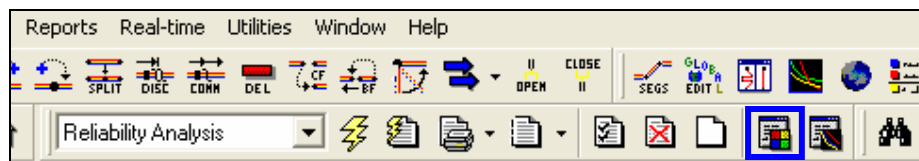


2. Select the required equipment from the tool bar, and draw the distribution model.

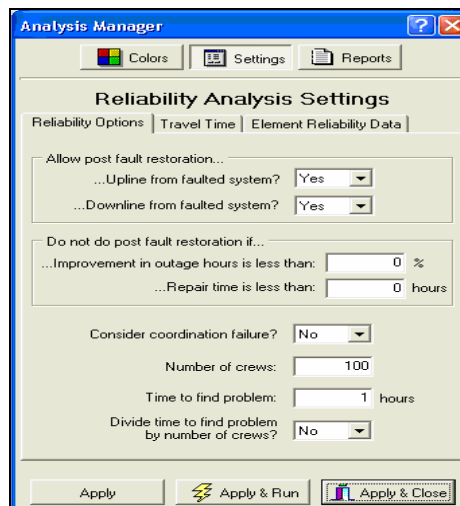


3. Click the *Graphical Analysis* toolbar button  or select *Analysis/Graphical Analysis* from the menu bar, which shows the following options:

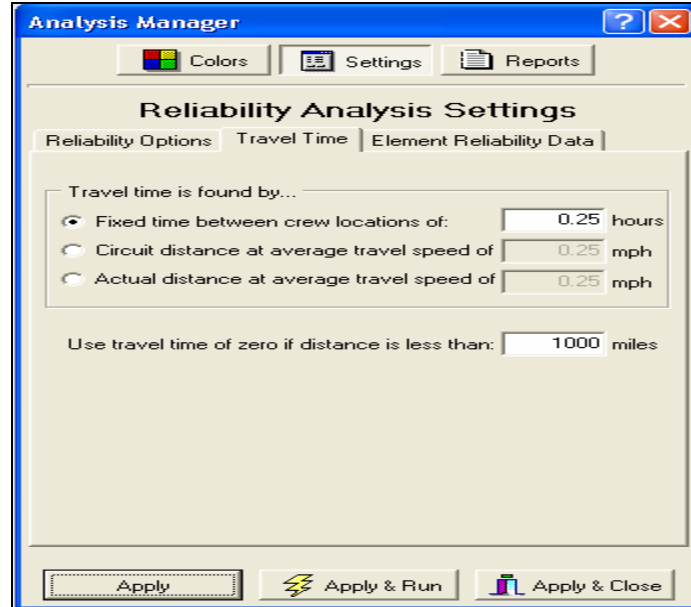
a. Reliability Analysis, b. Travel Time Calculation, c. Element Reliability Data



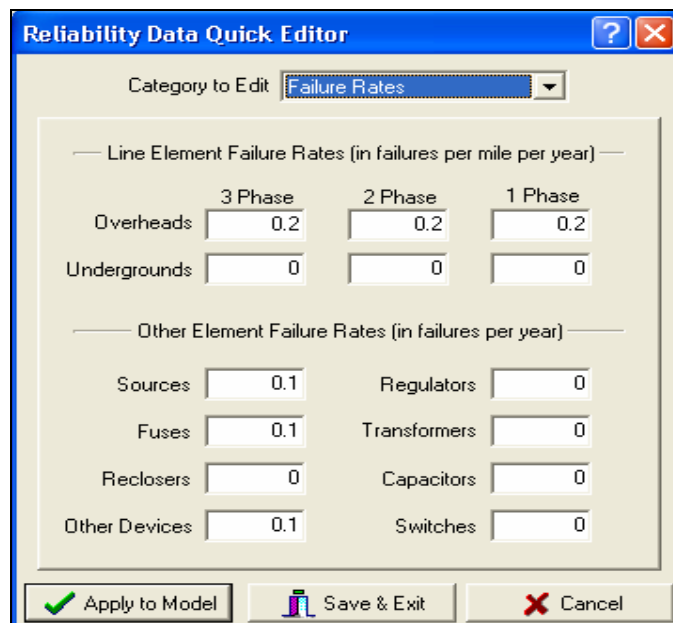
4. Use the *Reliability Analysis* tab for the Reliability analysis settings, as shown below.



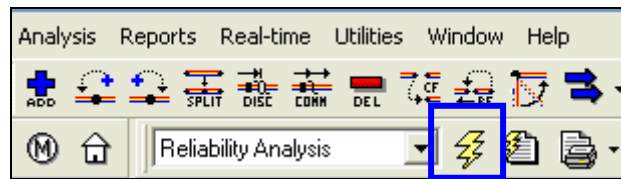
5. Use the *Travel Time Calculation* tab for the time setting, as shown below.



6. The *Element Reliability Data* tab provides a Reliability Data Quick Editor option, which allows setting reliability element data by element category. The reliability data for every element in the work environment by element type, and for overcurrent devices by device type could be set quickly.



7. After completing the model, click the *Recalculate Analysis* tab to run the reliability analysis.



8. After running the Reliability Analysis, click the *Display Current Report* tab for a summary report.



The summary report provides a listing of indexes for each substation (or sources), and the total system.

Report Viewer

Edk

Predictive Reliability Analysis Settings Summary  
Source:

Database: C:\PRABODH BHUSAL\EXAMPLE 1 VERIFIED.WM\  
Title: Thesis - Prabodh  
Case: Example Verification- Prabodh 09/08/2007 16:41 Page 1

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Reliability Analysis Settings:  
Do Upline Fault Isolation  
Do Downline Fault Isolation  
Do NOT Include Coordination Failure  
If Fix Time is less than 0.00 hours then do not consider switching.  
100 Crews are available to work each outage.  
Time to find trouble is 0.00 hours.  
Travel Time is fixed at 0.17 hours per trip.  
If calculated travel distance is less than 0.25 miles then travel time is set to 0.0 hours.

---

Source Name	SAIFI	SAIDI	CAIDI	ASAI	ALIFI	ALIDI	Consumers	KVA
SRC1	0.3000	1.0500	3.5000	0.9999	0.0000	0.0000	50.0	0.0
Total System	0.3000	1.0500	3.5000	0.9999	0.0000	0.0000	50.0	0.0

From the above report, we can see that SAIFI is 0.3 and SAIDI is 1.05, which verifies that the prediction of SAIDI and SAIFI for examples 2.1 and example 2.2 is done properly.

### **3.3 Analysis and Results**

Reliability analysis is also done for the following distribution models, as shown in Figure 3.3 (a-p). Reliability indices SAIDI and SAIFI are calculated manually and verified by using reliability analysis software [3]. The results and comments for each model are provided in Table 3.2. All data required for calculation were provided previously in Table 2.1.

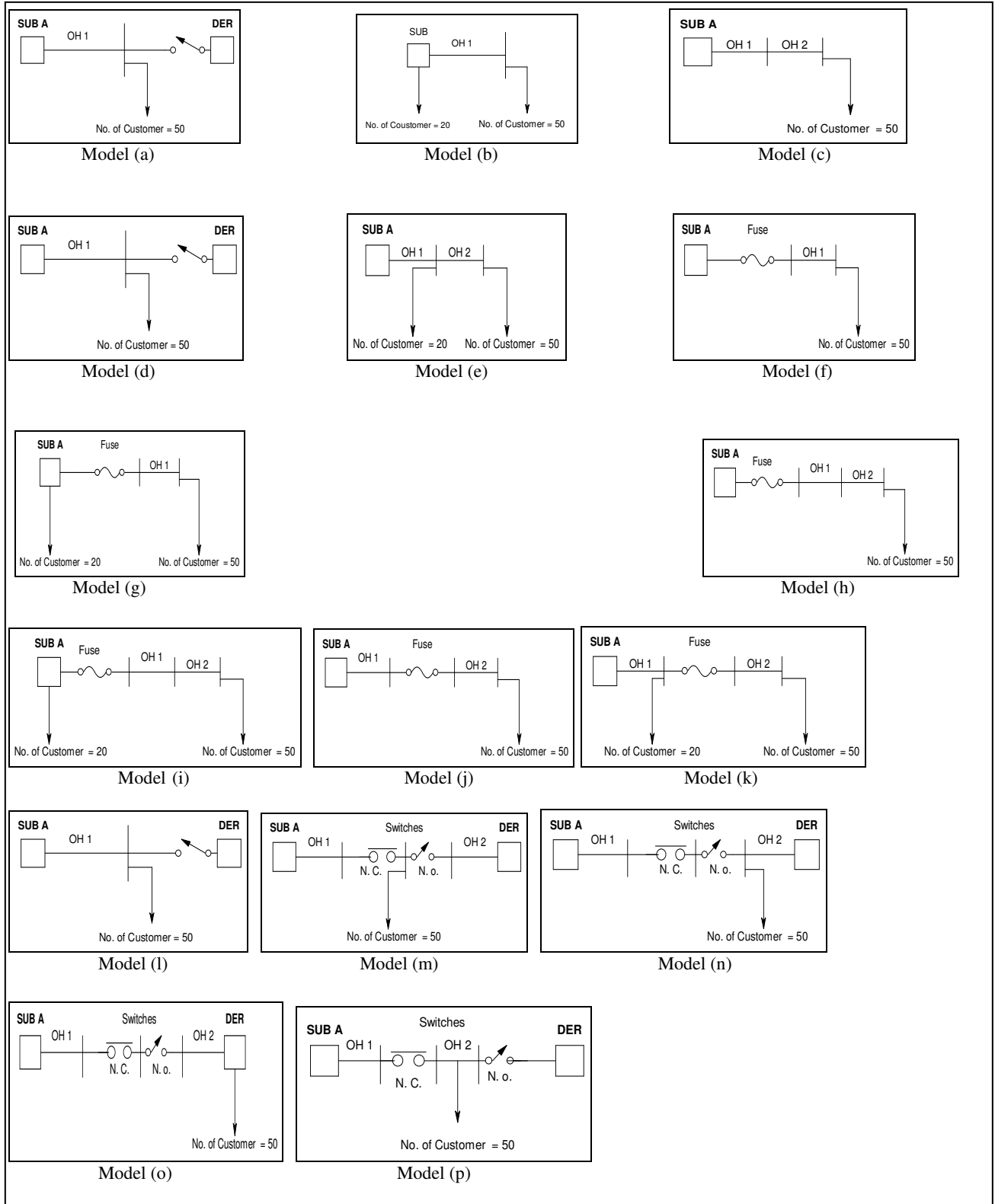


Figure 3.3: Different distribution models used in analysis.

TABLE 3.2

SUMMARY OF DISTRIBUTION MODELS USED IN ANALYSIS

Model No.	System Description	SAIFI	SAIDI	Result	Reason
(a)	Customers supplied with a source SUB A. Has a DER as a backup or alternative source. Model in Figure 2.1 has no DER.	0.3	1.05	Same value of indices as in Figure 2.1	No protecting device between SUB A and OH 1. DER cannot connect if line is still connected to failed substation.
(b)	Similar to model in Model 2.1 but with 20 additional customers.	0.3	1.05	Same value of indices as in Model (a)	Customers of SUB A added to OH 1 since no protection device to separate SUB A and OH 1. If OH1 fails, the substation must be disconnected from the entire system.
(c)	No DER. Customers supplied through two radial overhead lines by a substation.	0.5	1.55	Poorer reliability indices than in Model (b)	Addition of OH 2 adds another component that can fail.
(d)	Same as previous model with DER.	0.5	1.55	Same value of indices as in Model (c)	No protecting devices between SUB A and DER to OH 1 and OH 2.
(e)	No DER. Customers are in each OH line of a radial system.	0.5	1.55	Same value of indices as in Model (c)	Acts like 70 customers at OH 2 since no protective devices between OH 1 and OH 2.
(f)	Customers supplied through an OH line that has an over current protecting device.	0.3	0.95	Improvement in both reliability indices	Protecting device fuse used between SUB A and OH 1. Now, OH 1 can be connected to DER.
(g)	Similar to previous model (f) but 20 more customers added at the source.	0.2428571	0.8357143	More improved Reliability over Model (f)	Better reliability. In Model (f), 50/50 customers are interrupted but in model (g), 50/70 customers are interrupted.

TABLE 3.2 (continued)

SUMMARY OF DISTRIBUTION MODELS USED IN ANALYSIS

Model No.	System Description	SAIFI	SAIDI	Result	Reason
(h)	Similar to Model (f) but customers supplied through two overhead lines.	0.5	1.35	Poorer reliability than model (f)	No protecting device between OH 1 and OH 2, so DER cannot be connected if there is a substation or OH 1 failure.
(i)	Similar to model (h) but 20 more customers added at the source.	0.3857143	1.1214286	Improved reliability	Customers at SUB A do not interrupt with any faults on OH 1 or OH 2.
(j)	Same as model (h) but with different position of protecting device.	0.5	1.45	Poorer SAIDI than Model (h)	For a fault at OH 2, SUB A must shut down.
(k)	Same as model (j) but 20 more customers added at OH 1.	0.4428571	1.3357143	Improved Reliability over Model (j)	Fault on OH 2 will blow the fuse, so no interruption for the customers at OH 1.
(l)	Similar to model (k) but with DER.	0.4429	0.6214	Improved SAIDI over Model (k)	For a fault at OH 1 or SUB A, alternate source DER will supply customers at OH 2.
(m)	Customers supplied from substation through a normally closed switch and OH line and also connected to DER with normally open switch and OH line.	0.3	0	Best reliability	With ideal switches, customers will be supplied by alternate source DER if fault is in SUB A. Duration interruption is zero but counts the frequency interruption for switching time even the switches are ideal. So SAIFI is not zero.
(n)	Similar to Model (m) but position of the customers is different.	0.3	1.05	Poorer reliability than model (m)	Fault at OH 2 or at DER will interrupt customers.
(o)	Similar to model (n) but customers are connected to DER.	0.3	1.05	Same reliability as Model (n)	Fault at OH 2 or at DER will interrupt customers.
(p)	Customers connected to OH line, one side of which is connected to substation through a normally closed switch and OH line, and other side connected to DER with normally open switch.	0.5	0.6	Better reliability than Models (n) & (o)	Alternate source to supply. If fault at OH 2, both SUB A and DER will open for maintenance and close to resume supply.

## CHAPTER 4

### CUSTOMER INTERRUPTION DUE TO LINE OR SYSTEM RATING

#### 4.1 Methodology

The Chapter 3 analysis only included how a second source can improve reliability during a component outage. If a feeder's capacity is not sufficient for the total load connected, the load may have to be curtailed during periods of heavy load. This reduces reliability, but distributed resources can improve this by reducing total line loading while still supplying all loads. Previous examples are calculated based on failure rate or protection reliability of elements in that system. In this way, the interruption by overloading due to system or line ratings is neglected. Therefore, to calculate the actual indices, the interruption due to line rating should not be neglected. An example of actual calculation of SAIDI including interruption due to line rating is shown below.

#### **Example 4.1:**

To calculate the interruption due to line rating, a 24 hrs feeder load profile is considered. A load profile is shown in Figure 4.1. For the given load profile, if line rating is assumed to be 11 MW, it could be viewed from the graph that this is not enough supply for an entire load demand. Some of the consumers are going to be interrupted for two periods of approximately four hours each. Considering Figure 2.1 and Example 2.2, the actual SAIDI would be higher than it was without considering line rating.

### Load Profile

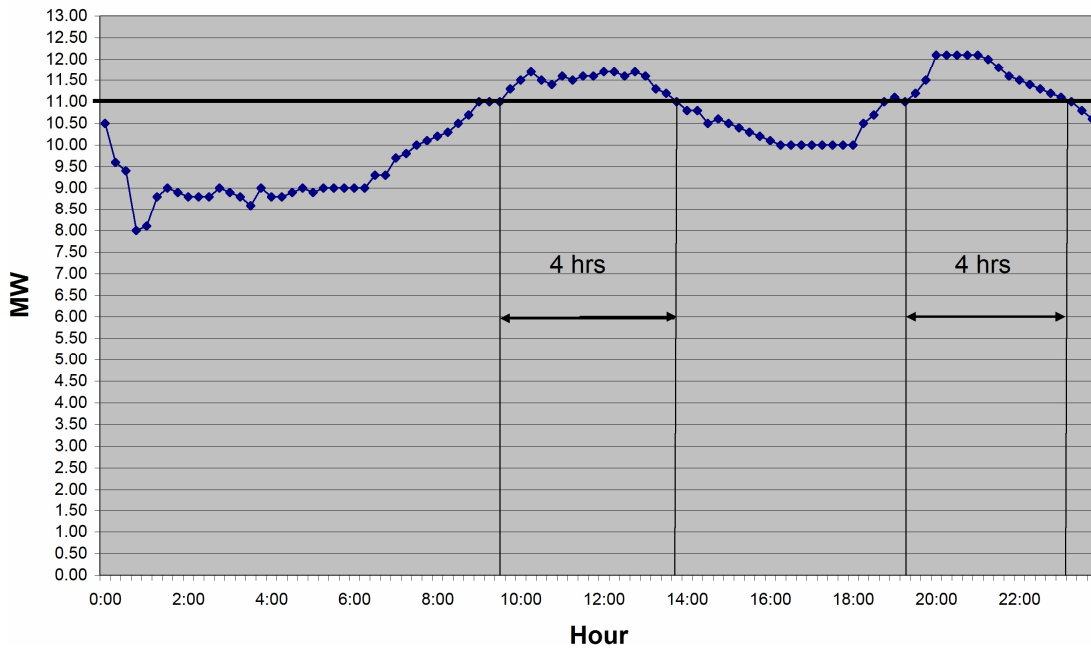


Figure 4.1: Load profile [7].

Actual SAIDI = SAIDI due to Failure Rate (or SAIDI calculated using commercial software) +  
SAIDI due to Line Rating

SAIDI due to Failure Rate (calculated in Example: 2.1) = 1.05

$$\begin{aligned} \text{SAIDI due to Line Rating} &= \frac{(\text{Outage 1} + \text{Outage 2}) * \text{No. of Customer Interruption}}{\text{Total Customer}} \\ &= \frac{(4 + 4) * 50}{50} \\ &= 8 \end{aligned}$$

Therefore, the Actual SAIDI = 1.05 + 8  
= 9.05

## 4.2 Summary

From the example presented in this chapter, it can be seen that SAIDI value of 8 is added because of interruption due to line rating or system rating. That value of SAIDI can be improved by using distributed energy resources, generation, or storage. Whenever there is an excess demand or the system rating is not enough to supply peak load demand, DER could be the alternative source of energy to avoid the interruption for that period. In this example, interruption is approximately from the 10<sup>th</sup> hour to 14<sup>th</sup> hour and again approximately from the 19<sup>th</sup> to 23<sup>rd</sup> hour. For the period from the 10<sup>th</sup> to 14<sup>th</sup> hour, the peak load demand is approximately 11.75 MW, and for the period from the 19<sup>th</sup> to 23<sup>rd</sup> hour approximately 12.20 MW. For those durations, a single DER of capacity of 2.0 MW or two DERs of 1 MW each could be added to the system [8]. Then the system capacity will be increased from 11 MW to 13 MW for that peak load demand period, which is enough to avoid the interruption for the given load profile.

## CHAPTER 5

### CONCLUSIONS AND FUTURE RESEARCH

#### 5.1 Conclusions

Chapter 2 of this thesis is a part of a larger project that focuses on distribution system maintenance scheduling. It requires a large amount of data and work before it can be used. The example for maintenance scheduling of the recloser allows a utility to apply the technique to any equipment in the distribution system and to as few as two pieces of equipment to determine which should be maintained first. This allows results as soon as the utility begins collecting data for the optimizer. Accuracy of the results requires actual detailed information about the equipment's condition obtained from inspection, monitoring, and maintenance records. This technique does not indicate what kind of maintenance is required for that recloser but explains the priority of maintenance on the basis of reliability indices. However, this method will help the utility to maintain the specific level of reliability and a high level of customer satisfaction with a limited maintenance budget by identifying poor-performing equipment and allocating the budget in the best way for their maintenance.

The next part of this thesis again applies the reliability evaluation technique used in Chapter 2 to evaluate the effect of equipment failure rate in distribution system reliability. Furthermore, analysis is done for distribution model with DER to improve the distribution system reliability. SAIDI and SAIFI are two important indices to understand the distribution system reliability, so the concepts and methods to calculate reliability indices SAIDI and SAIFI of some distribution system models are presented. The example presented here shows that the location of the protecting device plays the main role in changing the reliability indices. An

important conclusion of this research is that the line rating forces SAIDI to go higher than with failure rate of the device alone. So, to decrease the interruption due to line rating, especially at the peak load demand period, DER can be used; a single or a combination of more than one generator could be connected, depending upon the amount of required energy and the available DER in the market.

## **5.2 Future Research**

For better optimization of maintenance scheduling, the gathering of actual system data is important. For the accuracy of results, all the historical data and detailed information about the equipment's condition obtained from inspection, monitoring, and maintenance record should be provided by the utility. Any missing parameters that can affect system reliability must be included in the optimization method. For the calculation of reliability indices, it is assumed that the coordination failure rate of all overcurrent devices (fuses and OCRs) is 0.0. So, this could be done with the coordination failure rate. Further research could be done on calculating optimal capacity and the location of the distributed generator to improve system reliability.

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