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Integrated Reliability Evaluation of Distributed Power System

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Abstract— **This 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) Furthermore, This presents an example for optimization of distribution maintenance scheduling of a recloser. It applies a risk reduction technique associated with maintenance of the equipment. Given a large and complex plant to operate, a real-time understanding of the networks and their situational reliability is important to operational decision support.**

Index Terms—**reliability, distribution system, equipment**, **power quality, active power, reactive power.**

1INTRODUCTION

Reliability of a power system is generally designated as a measure of the ability of the system to provide customers with adequate supply. It is one of the primary performance criteria of power systems. Major outages can have a significant economic impact on utility providers as well as the end users who lose electric service. The power system has been significantly affected by a wide range of outage events caused by incorrect planning, operational error, equipment failures, environmental conditions, adverse weather effects, and load conditions. Large-scale blackouts emphasize the importance of reliability issues.

The reliability evaluation of transmission or composite systems analyzes the system failure events and estimates the chances of loss of load at major load points . The reliability of distribution systems is based on individual customer service interruptions. Since the reliability studies described in this dissertation are customer service oriented, one of the analysis zones of the study includes the whole distribution system with extension to the sub-transmission lines and substations.

For some of the networks analyzed here, the dominant causes of customer power interruptions are problems in secondary networks and faults in sub-transmission systems. Therefore, just considering the distribution system itself is not enough to accurately estimate customer outages.

2. CHALLENGES IN SYSTEM MODELING AND RELIABILITY ANALYSIS

The modeling and analysis studies associated with reliability evaluation are challenging, not only because of some of the system characteristics of the above proposed analysis zones, but also for persistent problems that have lingered in the energy industry for decades.

(i) Size. The reliability evaluation of large utility systems can be daunting due to the sheer size of the model. Modeling the underlying distribution system, including each customer's service point, can result in a model containing millions of objects. Relatively scant attention has been given to distribution systems as compared to generation and transmission systems. However, as the distribution system could be 80% larger than the transmission system, and occupies as much as 40% of the overall capital outlay of the total grid , it should receive adequate attention.

(ii) Data. The modeling and reliability analysis of distribution and/or transmission systems involves a large volume of various types of data and multiple system analysis algorithms. Examples of data include load, operation, planning, system design, system description, and reliability data. Examples of computer program algorithms include load flow, load forecast, network topology tracking and updating, and reliability analysis. Integrating the data into knowledge that is efficiently used by algorithms, and ensuring cooperation among algorithms are challenging tasks .

(iii) Load. The electrical load varies from hour to hour, day to day, and season to season. Each type of customer usually has different usage patterns. Residential, commercial, and industrial customers have different power demands and different peak demand times. This non-linear, time-varying characteristic has to be considered in order to obtain sound system evaluation results.

(iv) Uncertainty. The power system is vulnerable to many stochastic events. Random failures of control and protection devices, environmental disturbances such as high speed wind, lightning and severe storms, irregular load surges due to interruptions, and human errors all have impacts on customer outages.

3. INTEGRATED RELIABILITY EVALUATION OF POWER SYSTEMS

The reliability evaluation of hierarchical level I includes the generation system only. The generating capacity needs to be determined in order to satisfy the expected demand. The reliability evaluation of hierarchical level II includes generation and transmission systems, which is often referred to as the composite system or bulk power system. The transmission system has to be designed to ensure satisfactory energy transfer from generation plants to bulk load points. The reliability evaluation of hierarchical level III includes all the three systems, and is rarely done due to the enormity of the problem.

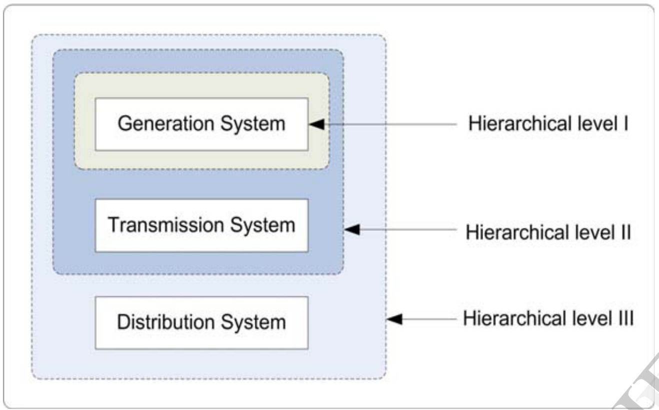


Figure1 Hierarchical levels of Power System for Reliability Analysis

During integrated system modeling, if transmission/sub-transmission systems are included, the boundaries of transmission systems are treated such that the generation capacity is not constrained. The reliability studies are then used to examine the energy delivery capability to bulk load points for a transmission system only study or, to end-customers if the study zones include distribution systems.

4 RELIABILITY ASSESSMENT METHODS OF POWER SYSTEMS

The methods used in reliability assessments of power systems determine the accuracy of the results. Analytical and simulation approaches are the two types of techniques used in power system reliability analysis. Each approach has its merits and limitations. In this section, the concepts, assumptions, and typical applications of the commonly used methods in both techniques are reviewed. The limitations of analytical approaches are summarized as the reason to select the Monte Carlo simulation to perform the reliability analysis in this study.

1 Analytical Approach

The analytical analysis methods use mathematical models to provide solutions to a reliability problem. Specific calculation results are obtained for a given set of system topology and input values. Some widely used methods are block diagram, event tree, cut sets, fault tree, state enumeration, and Markov modeling. Using reliability sets in calculation is also proposed in recent years. Their common problem is the frequent need to make simplifying assumptions and approximations.

2 Simulation Approaches

Compared with analytical approaches, the simulation or Monte Carlo approach is more universal. It provides a solution for complex problems that is not feasible for analytical methods. The Monte Carlo method is widely used to simulate the stochastic behavior of systems and actual processes. The random number generator of the Monte Carlo simulation creates random variants that follow the distribution functions, even non constant hazard rates. The simulation convergence is a fluctuating process, with the estimated outcome closer to the true value as sample size increases. The convergence criterion usually uses the coefficient of variation of the output.

3. Performance indices

The study zones of this study include detailed modeling of end-customer information, and the system evaluation goal is also customer service oriented. SAIFI and SAIDI are the two most popular system level reliability indices used for customer service oriented studies [36]. SAIDI is an abbreviation of System Average Interruption Duration Index. It represents the average interruption duration per customer served per year. SAIFI denotes the System Average Interruption Frequency Index. It is the expected number of interruptions per customer per year. The calculation of SAIDI and SAIFI are shown in (1.1) and (1.2) respectively.

$$SAIDI_{SYS} = \frac{\text{Sum of customer interruption durations}}{\text{Total numbers of customers}} \quad (1.1)$$

$$SAIFI_{SYS} = \frac{\text{Total number of customer interruptions}}{\text{Total numbers of customers}} \quad (1.2)$$

The subscript sys in the above equations denotes that individual reliability indices can be calculated for each aggregated network, and only considers the customers served by the network. There are a total of 18 aggregate networks defined in the secondary distribution system containers. The whole secondary distribution system can be viewed as the largest aggregate network, with the 120V and 480V networks as individual aggregated networks.

Instead of selecting SAIFI and SAIDI, CAIDI and CAIFI are chosen as the reliability indicators for this study, because they give details of the interruption statistics of each customer. CAIDI is abbreviation of Customer Average Interruption Duration Index. It represents the average interruption duration for those customers served by the same load bus per year. CAIFI denotes for Customer Average Interruption Frequency Index. It is the expected number of interruptions of customers served by a load bus per year.

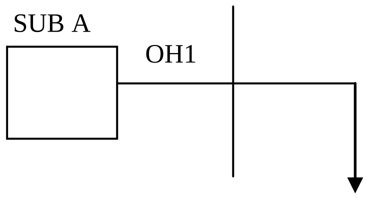
The calculation of CAIDI and CAIFI is shown in (1.3) and (1.4) respectively.

$$CAIDI = \frac{\text{Sum of Customer Interruption Durations}}{\text{Total Numbers of Customers Interruptions}} \qquad (1.3)$$

$$SAIDI = \frac{\text{Total number of customer interruption}}{\text{Total numbers of customers Affected}} \qquad (1.4)$$

5. CALCULATION AND RESULTS

5.1 Calculation of Reliability Indexes



NO.OF CUSTOMER=1500

Figure 2 Distribution model

The procedure and calculations to find SAIFI for a distributed model, as shown in Figure 2 , are provided in detail below. All required data to calculate SAIFI are given in Table 1.

In this example, it is assumed that the coordination failure rate of all over current devices (fuses and over current 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.

TABLE 1 RELIABILITY DATA TABLE

Substation Data	Overhead Line Data	Other
Failure Rate (PR) = 0.1	Failure Rate (PR) = 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, 1500 consumers are connected to a Substation (SUB A) through an overhead line (OH 1). In the Figure 2, there are no switches or over current 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

Calculation of System Average Interruption Frequency Index (SAIFI):

$$\begin{aligned} \text{MFR for OH 1} &= \text{FR of SUBA} + \text{FR of OH 1} \\ &= 0.1 + 0.2 \\ &= 0.3 \end{aligned}$$

TABLE 2 SAIFI CALCULATION TABLE

Element	FR	MFR	No. of customer Customer	Customer interruption Interruptions
SUB A	0.1	-	0	0
OH 1	0.2	0.3	1500	720
Total			1550	720

Total Customer Interruptions = 1440
Total Number of Customer served = 1500

Outage on Device	Number of Customers Customer Interruption	Interruption Duration (hour)	Failure Rate (per year)	Customer Hours Per Year
SUB A	750	5.5	0.1	1550
OH 1	750	2.5	0.2	1600
Total				3150
Total Customer Served: 1500				

Therefore SAIFI $= \frac{\text{Total Customer Interruption}}{\text{Total no. of Customers Served}}$

$= 1440/1500$

$= 0.90$

Calculation of System Average Interruption Duration Index (SAIDI):

TABLE 3 SAIDI CALCULATION TABLE

ID (SUBA) =5+0.5

Therefore

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

$= 3150/1500$

$=2.107$

Verification of SAIDI, and SAIFI Using Reliability Evaluation Software

This section presents verification of the calculation of SAIDI and SAIFI for using commercial reliability evaluation software.

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 tool bar button or select Analysis/Graphical Analysis from the menu bar, which shows the following options. Reliability Analysis, b. Travel Time Calculation, c. Element Reliability Data
4. Use the Reliability Analysis tab for the Reliability analysis settings.
5. Use the Travel Time Calculation tab for the time setting,.
6. Element Reliability Data tab provides a Reliability Data Quick Editor option, which allows setting reliability element data by element category.
7. After completing the model, click the Recalculate Analysis tab to run the reliability analysis.
8. After running the Reliability Analysis, click the DisplayCurrent Report tab for a summar report.

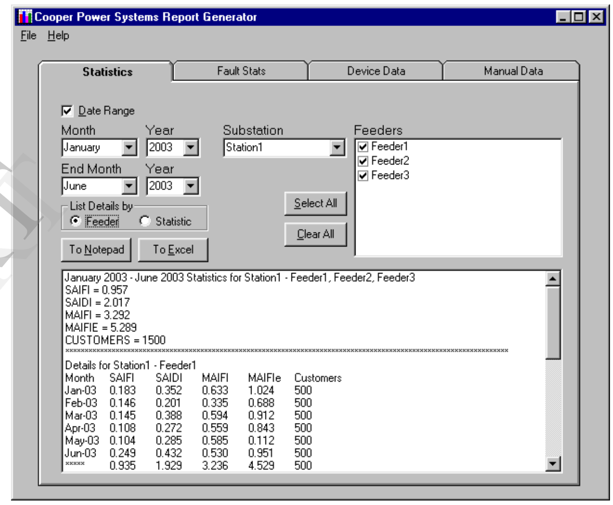
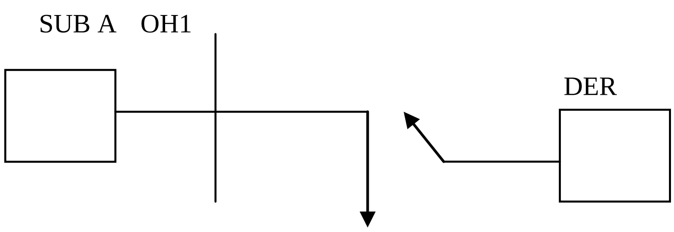


Figure 3 Result of analysis of SAIFI and SAIDI

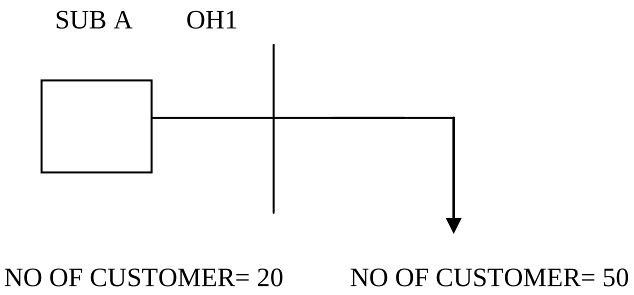
From the above report, we can see that SAIFI is 0.957 and SAIDI is 2.01, which verifies that the prediction of SAIDI and SAIFI for is done properly.

VARIOUS DISTRIBUTION MODELS USED IN ANALYSIS

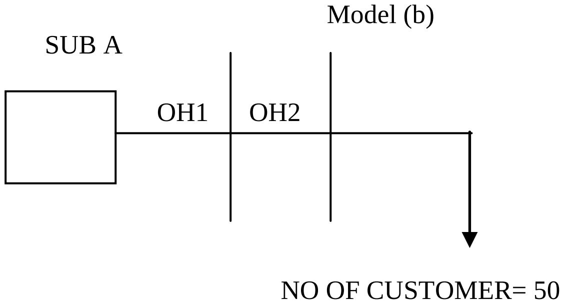


NO OF CUSTOMER= 20

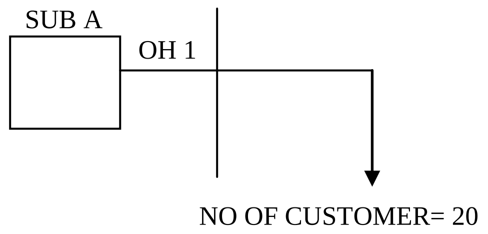
Model (a)



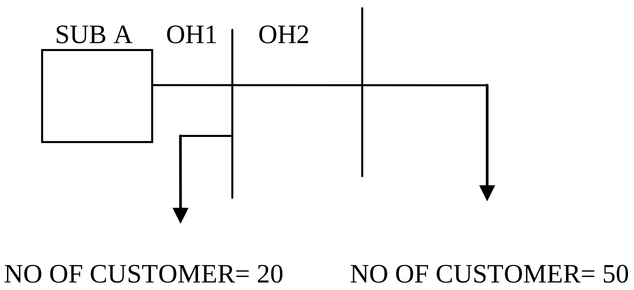
Model (b)



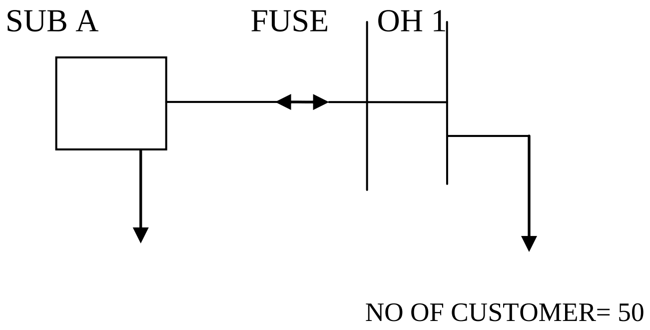
Model (c)



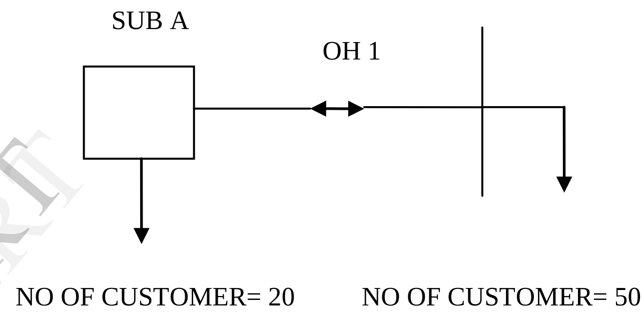
Model (d)



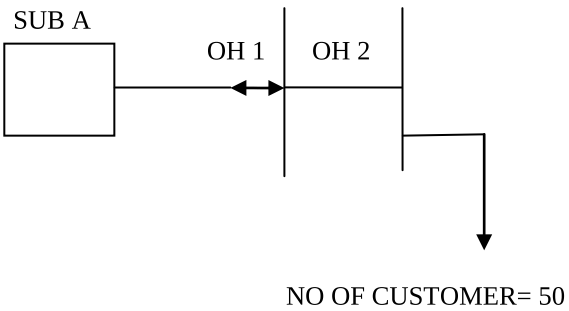
Model (e)



Model (f)



Model (g)



Model (h)

Model No.	System Description	SAIFI	SAI DI	Result	Reason
(a)	Customers supplied with a source SUB A. Has a DER as a backup or alternative source. Model in Figure 5.1 has no DER.	0.3	1.05	Same value indices as in Figure 1	No protecting device between SUB A and OH 1. DER cannot connect if line is still connected to failed substation.
(b)	S i m i l i a r to model in Model 5.1 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. 11 OH1 fails, the substation must be disconnected from the entire system.
(c)	No DER. Customer 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	Improve-ment in both reliability indices	Protecting device fuse used between SUB A and OH 1. Now, OH 1 can be connected to DER.
(g)	s i m i l a r to previous model (f) but 20 more customer added d a the source.	0.242857 1	0.8357 143	More improved Reliability over Model (f)	Better reliability. In Model (0, 50/50 customers are interrupted but in model (g),50/70 customer are interrupted.

TABLE 4 SUMMARIES OF DISTRIBUTION MODELS USED IN ANALYSIS

6. CONCLUSION

Although much research has been performed on the reliability evaluation of power systems, how large-scale realistic systems should be analyzed is still under investigation. Various values of reliability models and analysis are described in Table 4.

This research makes efforts to move forward the past works towards the direction of addressing reliability needs directly from the consumer point of view. Previously, electric utilities use contingency and margin criteria for indirect reliability measures during planning and design. Generally, consumer oriented reliability evaluation indices such as SAIDI and SAIFI are not directly used in the design stage. However, given the complexity of the realistic system with constant facility additions and operating changes, directly use reliability values as numeric criterion on selecting a solution among potential alternative designs is expected to be a trend. In this research, the expected reliability behaviors of realistic systems are computed by utilizing detailed analysis of their configurations and equipment information.

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