RELIABILITY ASSESSMENT OF SECONDARY DISTRIBUTION CONFIGURATIONS

By

E. VIDYA SAGAR * P.V.N. PRASAD**

*Assistant Professor, Department of Electrical Engineering, Osmania University, Hyderabad.
**Associate Professor, Department of Electrical Engineering, Osmania University, Hyderabad.

ABSTRACT

In this paper a composite reliability evaluation of a practical distribution system is developed. The reliability of a substation is calculated using minimal cut-set technique. The interaction between distribution substation and primary distribution system is modeled according to the tripping behavior of feeder circuit breakers. Then, the contribution of reliability indices evaluated from the primary distribution system is added to the previous two effects. The primary indices (λ, r, U) and the secondary reliability indices such as customer oriented and load-energy oriented indices are calculated for four types of distribution configurations. The developed models reflect the effect of distribution substations, primary distribution systems, and the interaction between them. Comparisons of reliability indices are made.

Keywords: Distribution Substation, Distribution System, Minimal Cut-Set, Non-Radial, Reliability Indices.

INTRODUCTION

There are many types of distribution systems that can be used to supply customers. In this paper the following four types of distribution systems are considered i) Basic radial system ii) Link arrangement system iii) Open loop system iv) Primary network system [1].

It is necessary to select a proper type of distribution system to satisfy the requirements of reliability for a particular kind of load area or customers [2]. Hence, quantitative reliability assessment models are of considerable importance for various types of distribution system.

The reliability evaluation models for four commonly used distribution systems are developed according to their system configurations, the operating characteristics of protectors, and component reliability parameters. The reliability level of distribution substation configuration using minimal cut-set technique is evaluated [3]. Associated operating characteristics are also investigated. The model for the interaction between distribution substation and primary distribution system is developed according to the tripping behavior of feeder circuit breakers. The reliability models for the primary distribution systems are developed based on their topologies. Finally, the composite load point reliability evaluation models are developed by combining the three contributions [4] [5]. The most common system reliability indices such as SAIFI, SAIDI, etc. can be calculated using the load point indices. The developed models are demonstrated on four types of distribution system modified from a reliability test system and the reliability indices are compared among them [1].

1. Substation Reliability

The distribution substation is the source of the primary feeder system, and the failure of a substation may result in power interruption at all loads points. The reliability indices of a substation are average failure rate, average outage duration and annual outage time [5], [6]. The configuration of a distribution substation is composed of bus bars, circuit breakers, disconnect switches, and step down power transformers [1].

1.1. Substation Configuration

In this paper, the configuration of the distribution substation is determined by its bus schemes at the subtransmission voltage level. Figure 1 shows

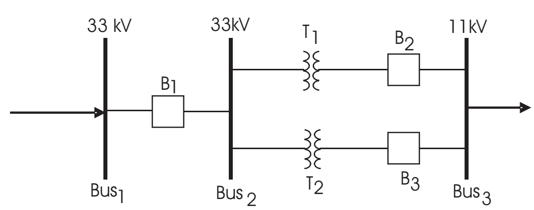

Figure 1. Practical substation Configuration

configuration of distribution substation. In this configuration, a low voltage bus is supplied by two subtransmission lines (L1 and L2) via two step down transformers T1 and T2. It is assumed that any one subtransmission line or transformer can serve all of the feeders connected at the same low voltage bus when another subtransmission line or transformer is out of service [7]. Feeder breakers located at the outlet of a substation are excluded here. Those circuit breakers will appear in the primary distribution systems.

1.2. Assessment Method

This paper uses MCSA (minimal cut-set approach) to evaluate distribution substation reliability based on the criterion of continuity of service [8] [9]. The minimal cut-sets of substation components are divided into several groups according to their failure modes. The failure modes of components can be divided into passive and active failures [10]. The various failure modes of the minimal cut-sets considered here are given below:

i) first order total failure (including both passive failure and active failure) ii) first order active failure iii) first order active failure with stuck condition of circuit breakers iv) second order overlapping failure event involving two substation components.

The minimal cut-sets in which service can be restored by closing normally open connections and the malfunctions of the normally open circuit breakers are also considered in this study. Overlapping failure events include total failure or active failure overlapping the total failure or maintenance outage of another component [12]. When all of the minimal cut-sets have been recognized, the reliability indices of a distribution substation contributed to by individual minimal cut-set can be evaluated using equations that refer to [10], where each minimal cut-set is equivalently a set of parallel substation components and various minimal cut-sets are equivalently in series connection. The detailed procedure for the minimal cut-set method can be found in [12], [13]. For simplicity, it is assumed that L1 and L2 are completely reliable. When all of the above computations have been completed, the overall reliability indices of the distribution substation are evaluated by combining the contributions of all the minimal cutsets. The reliability indices can be determined as follows

$$\lambda = \lambda_t + \lambda_A + \lambda_S + \lambda_O \quad (1)$$

$$U = U_t + U_a + U_s + U_O \quad (2)$$

$$r = U/\lambda \quad (3)$$

1.3. Reliability Assessment of Substation

In this section, the reliability indices of a distribution substation have been evaluated for the configurations shown in Figure 1. It is assumed that the disconnect switches in Figure 1 are completely reliable for simplicity (i.e., the outage components considered in this study are subtransmission lines, circuit breakers, bus bars, and transformers). Here, all of the circuit breakers shown in Figure 1 can be assumed to be normally closed. The reliability data of these components include T, A, M,MTTR,and MTTM These values are taken from [3], and are shown in Table 1. Table 2 show the three reliability

Component Rating (kV)	P	A	r	"	r	rP	r"	rC	S
Transformers									
138/33	0.0100	0.0100	0.050	0.5	200	15	168	0.083	1
33/11	0.0150	0.0150	0.050	1.0		15	120	0.083	1
11/0.415	0.0150	0.0150	---	---		10	---	---	1 (line) 3 (cable)
Breaker									
138	0.0058	0.0035	0.05	0.2	8	---	108	0.083	1.0
33	0.0020	0.0015	0.02	0.5	4	---	96	0.083	1.0
11	0.0060	0.0040	0.06	1.0	4	---	72	0.083	1.0
Busbars									
33	0.0010	0.0010	0.010	0.5	2	---	8	0.083	1.0
11	0.0010	0.0010	0.010	1.0	2	---	8	0.083	1.0
Lines (single weather state)									
33	0.0460	0.0460	0.060	0.5	8	---	8	0.083	2.0
11	0.0650	0.0650	---	---	5	---	---	---	1.0
Lines (two weather state)									
33(normal)	0.0139	0.0139	0.018	0.5	8	---	8	0.083	2.0
(adverse)	5.860	5.860	7.60	---	---	---	---	---	---
Cables									
11	0.0400	0.0400	---	---	30	---	---	---	3.0

Weather data: average duration of normal weather = 724hr
Average duration of adverse weather = 4hr
Line failures occurring in adverse weather =70% of total.

Table 1. System Component Reliability Data

Configuration	(f/Year)	r (hours)	U (hours/year)
Practical Substation	0.0149	1.617	0.0242

Table 2. Reliability Indices for Substation Configuration

Feeder type	Length(km)	Feeder Section numbers
Bus 4		
1	0.60	02 06 10 14 17 21 25 28 30 34 38 41 43 46 49 51 55 58 61 64 67
2	0.75	01 04 07 09 12 16 19 22 24 27 29 32 35 37 40 42 45 48 50 53 56 60 63 65
3	0.80	03 05 08 11 13 15 18 20 23 26 31 33 36 39 44 47 52 54 57 59 62 66

Table 3. Feeder Types and Lengths of Bus 4

No. of load points	Load Points	Customer type	Load level per load point(MW)		No.of cust
			Avg	Peak	
Bus 4					
15	1-4, 11-13, 18-21, 32-35	Residential	0.545	0.8869	220
7	5,14,15,22,23,36,37	Residential	0.5	0.8237	200
7	8,10,26-30	Small user	1.00	1.63	1
2	9,31	Small user	1.50	2.445	1
7	6,7,16,17,24,25,38	Commercial	0.415	0.6714	10
Total			24.58	40.000	4779

Table 4. Customer and Load Data of Bus 4

indices of practical sub-station configuration. The reliability indices shown in Table 2 ignore sub transmission lines failure.

2.Distribution System Reliability Model

In this section, four types of distribution systems, which are basic radial, link arrangement, open loop and primary network system are described. Then, the composite reliability evaluation models for the four distribution networks are developed. The models include the impact of distribution substations, primary distribution systems, and the interaction between them.

2.1. Description of the Four Types of Distribution Systems

A primary distribution system is that portion of a power system between the distribution substation and the distribution transformers [1].

The distribution networks as shown in Figure 2- Figure 5 can be used to illustrate the above description for the four types of distribution systems. Figure 2 shows a link arrangement system, which is the RBTS BUS4 developed by [3]. It consists of seven primary feeders supplied by three low-voltage buses of three different distribution substations. The dash lines and the N/O shown in Figure 2 denote tie lines and normally open tie disconnect switches respectively. The alternative emergency feeders are supplied by a different distribution substation. If one of

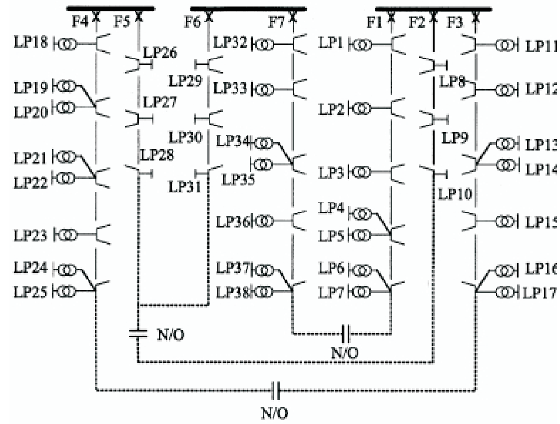

Figure 2. Link arrangement system

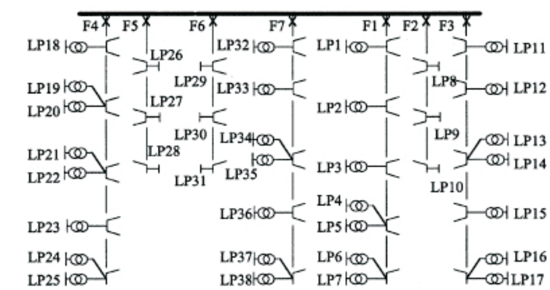

Figure 3. Basic radial system.

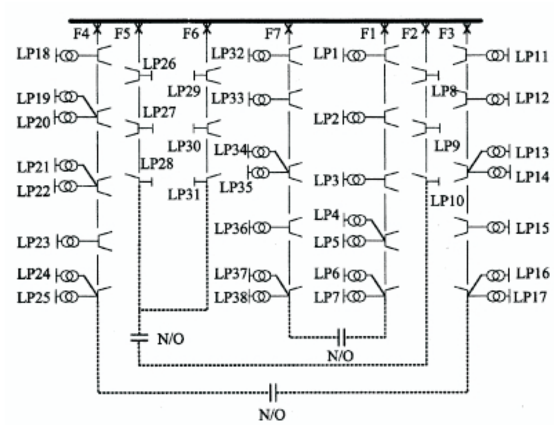

Figure 4. Open loop system.

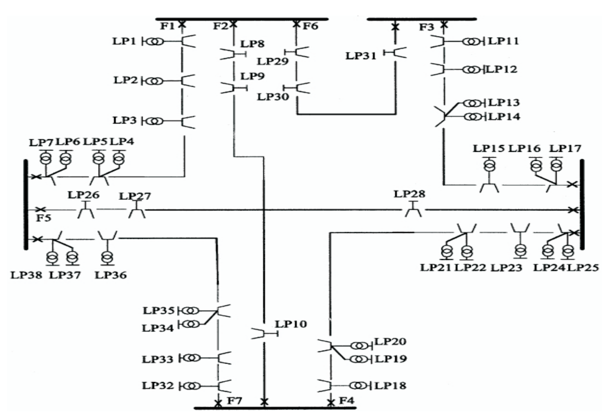

Figure 5. Primary network system.

the substations fails, service can be supplied by another substation after the fault has been isolated. The other three types of distribution network are modified from Figure 2. Figure 3 is a basic radial system. All of the primary feeders are supplied by the same low voltage bus. All the N/O and the tie lines shown in Figure 2 are removed. A fault at any location on a main feeder will cause an outage for every customer on the feeder sections located downstream of the faulted section after the fault has been isolated. Figure 4 is an open loop system. All of the primary feeders are also supplied by the same low voltage bus. If a fault occurs on any portion of the main feeder, the N/O between the end of the faulted feeder and the adjacent feeders can be closed after the fault has been isolated. The unfaulted feeder sections that were cut off from their supply source are then restored to service. Figure 5 is a primary network system; it is a system of interconnected primary feeders that are supplied by a number of distribution substations. A substation failure does not have an impact on any customer of primary feeders

2.2. Interaction between Distribution Substation and Primary Distribution System

The interaction between distribution substation and primary distribution system can be examined from two aspects of feeder circuit breakers [5].

(1) Primary Protection: If a short circuit active failure occurs on a feeder circuit breaker, all the feeder breakers that are connected at the same low voltage bus must trip. The low voltage bus then loses continuity of supply and the load points supplied by the bus suffer an outage event except for the load points on the primary network. As for the primary network, only the breakers located at the two ends of a primary feeder can interrupt the load points supplied by the feeder. The reliability indices of load points i contributed to by the factor can be formulated as follows:

$$ {}^{a}_{CB\,i,} \quad \begin{cases} 2\;{}^{a}_{cb}, & \text{for primary network type} \\ N_{cb}\;{}^{a}_{cb} & \text{for other three types} \end{cases} \qquad (4)$$

$$ U^{a}_{CB,i} = \begin{cases} 2\;{}^{a}_{cb}ts & \text{for primary network type} \\ {}^{a}_{cb}[r_{cb} \quad (N_{cb} \quad 1)t_s] & \text{for basic radial} \\ N_{cb}\;{}^{a}_{cb}t_s & \text{for other two types} \end{cases} \qquad (5)$$

2) Backup Protection: When a feeder breaker fails to clear the fault on its associated main section, the backup protection of the feeder breakers connected at the same low voltage bus need to operate. This action may result in power interruption of load points supplied by the de-energizing bus for every type except the primary network. The reliability indices of load point i contributed to by the factor can be formulated as follows:

$$ {}_{stuck.i} \quad \begin{cases} 0 & \text{for primary network type} \\ P_C * \sum_{m\;1,m\;f_i}^{N_m} {}_{m} & \text{for other three types} \end{cases} \qquad (6)$$

$$ U_{stuck,i} \quad \begin{cases} 0 & \text{for primary network type} \\ P_c * \sum_{m\;1,m\;fi}^{N_m} {}_{m} * t_s & \text{for other three types} \end{cases} \qquad (7)$$

m f_i denotes that the main feeder that serves load point is excluded. The reliability indices of load point contributed to by f_i are considered in the next subsection.

2.3. Reliability Model for Primary Distribution System

According to the primary feeder configuration of the primary distribution system, the average failure rate ${}_{Fi}$ and U_{Fi} the annual outage time of load point i contributed to by this portion can be expressed as follows: In the Eq (8) & Eq (9), $m=m_i$ denotes the m^{th} main section located upstream of load point i , and $m_{i+1} = m=F_{m,i}$ is downstream of load point i .

$$ {}_{F,i} \quad \begin{cases} \sum_{m\;1}^{F_{m,i}} {}_{m} \quad {}_{ti} \quad {}_{li} & \text{for primary network} \\ P\;{}_{cb} \quad \sum_{m\;1}^{F_{m,i}} {}_{m} \quad {}_{ti} \quad {}_{li} & \text{for other two types} \end{cases} \qquad (8)$$

$$ U_{Fi} = \begin{cases} P\;{}_{cb}r_{cb} + \sum_{m=1}^{m,i} {}_{m}r_{m} + \left(\sum_{m=m_i+1}^{Fm,i} {}_{m}t_s \right) + {}_{ti}r_{ti} + {}_{li}r_{li} \\ \sum_{m=1}^{Fm,i} {}_{m}t_s + {}_{ti}r_{ti} + {}_{li}r_{li} \\ P\;{}_{cb}t_s + \left(\sum_{m=1}^{Fm,i} {}_{m}t_s \right) + {}_{ti}r_{ti} + {}_{li}r_{li} \end{cases} \qquad (9)$$

2.4. Composite Load Point Reliability Evaluation Model

In this section, the three basic composite load point reliability indices ${}_{LP,i}\,r_{LP,i}$ and $U_{LP,i}$ can be evaluated by using Eq(10) –(15).

$$ {}_{LP,i} = {}_{S,i} + {}_{CB,i} + {}_{stuck,i} + {}_{F,i} \qquad (10)$$

$$ U_{LP,i} + U_{S,i} + U_{CB,i} + U_{stuck,i} + U_{Fi} \qquad (11)$$

$$ r_{LP,i} = \frac{U_{LP,i}}{{}_{lp,i}} \qquad (12)$$

$$SAIFI \quad \frac{\overset{NL}{i\ 1}\ _{C,i}N_i}{N_i} \text{ int/cust} \qquad (13)$$

$$SAIFI \quad \frac{U_{C,i}N_i}{N_i} \ hrs\ /\ cust.yr \qquad (14)$$

$$ENS \quad L_{av,i}\ U_{C,i}\ kwh \qquad (15)$$

3. Results

Applying the reliability assessment model developed in the previous section, comparisons of reliability levels are made for the four distribution networks shown in Figures 2-5. The relevant reliability parameters and load point data are given in [3]. It is assumed in all the case studies in this paper that there are two 100% reliable disconnect switches at the two ends of each main section, a 100% reliable fuse cutout in each lateral, a failed distribution transformer is replaced rather than repaired, and all of the lines of the primary distribution system are overhead lines. Table 5 shows the basic load point indices of feeder F2 for four types of primary distribution system considering four configurations of distribution substation.

1) It is observed that the primary network has better reliability indices such as low failure rate, high system availability index and low average energy not supplied to the customers etc.

2) Table 6 shows that the load point average failure rate for open loop is identical to the basic radial type, but its corresponding annual outage time is significantly lower than basic radial type. Thus, it can be concluded that an alternative supply has no impact on the load point average failure rate but has a significant impact on annual outage time.

3) Both the link arrangement and the open loop have alternative emergency sources by closing the associated tie switch. However, there are three different substations supplying the former, and the effect of each substation on load point indices is insignificant.

4) The annual outage time of load point for basic radial type continually increases as it gets farther from the substation. The phenomenon is not apparent for the other four types

Configuration	Load points		U
Basic radial	LP8	0.2132	3.752436
	LP9	0.2748	3.93718
	LP10	0.3172	4.116731
Link arrangement	LP8	0.1584	3.30876
	LP9	0.2202	3.4095
	LP10	0.2495	3.4647
Open Loop	LP8	0.02132	3.36343
	LP9	0.27489	3.464231
	LP10	0.31714	3.517437
Primary n/w	LP8	0.1289	3.2792
	LP9	0.19065	3.4352
	LP10	0.2329	3.3702

Table 5. Load Point Reliability Indices of f2.

Configuration	SAIFI	SAIDI	CAIDI	ASAI	ASUI	ENS	AENS
Basic radial	0.26872	3.93545	14.6452	0.99955	0.00045	13.7749	4.5916
Link arrangement	0.2094	3.39432	16.2097	0.99961	0.00038	11.88769	3.9625
Open loop	0.26842	3.4484	12.847	0.99961	0.00039	12.07721	4.025
Primary n/w	0.18415	3.36153	18.25432	0.99962	0.00038	11.8022	3.934

Table 6. System Indices for Four Configurations

Conclusion

In this paper a set of load point reliability indices have been that include the impact of distribution substations, primary distribution systems, and the interaction between them for four types of distribution system. Distribution substation reliability assessment and their associated operating characteristics have been undertaken. The

degree order of the reliability level for the four types of distribution system is primary network, link arrangement, open loop, and basic radial type.

Nomenclature

- U — Annual outage time of a distribution substation.
- λ_T — Total failure rate of a distribution component.
- λ_A — Active failure rate of a distribution component.
- λ_M — Maintenance rate of a distribution component.
- Pc — Probability of a circuit breaker failing to open when called upon to open.
- $^{a}_{CB,i}$ — Average failure rate of load point contributed to by active failure of feeder circuit breakers.
- $U^{a}_{CB,I}$ — Annual outage time of load point contributed to by active failure of feeder circuit breakers.
- N_{cb} — Number of feeder circuit breakers connected at the same low voltage bus.
- $^{a}_{cb}$ — Active failure rate of a feeder circuit breaker.
- r_{cb} — Repair time for a feeder circuit breaker.

t_s Time required to perform the required isolation,switching, and load transfer actions.

$_{stuck,i}$ Average failure rate of load point contributed to by Active failures of main feeder sections in combination with an associated stuck circuit breaker

$U_{stuck,i}$ Annual outage time of load point contributed to by Active failures of main feeder sections in combination with an associated stuck circuit breaker.

$_m$ Failure rate of the m^{th} main section of a primary feeder.

N_m Total number of main feeder sections connected at the same low voltage bus.

$F_{m,i}$ Number of main sections of a primary feeder which Services load point i.

$_{ti}$ Failure rate of a distribution transformer that services load point i.

$_{li}$ Failure rate of a lateral that services load point i.

r_m Repair time for a main feeder section.

r_{ti} Repair time for the distribution transformer that Services load point i.

r_{li} Repair time for the lateral that services load point

$^p_{cb}$ Passive failure rate of a circuit breaker.

$_{s,i}$ Average failure rate of load point contributed to by the distribution substation itself.

$U_{s,i}$ Annual outage time of load point contributed to by the distribution substation itself.

MTTR Mean time to repair.

MTTM Mean time to maintenance.

SAIFI System Average Interruption Frequency Index

SAIDI System Average Interruption Duration Index

CAIDI Customer Average Interruption Frequency Index

ASAI Average System Availability Index

ASUI Average System Unavailability Index

ENS Energy Not Supplied

AENS Average Energy Not Supplied

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ABOUT THE AUTHORS

E. Vidya Sagar is currently working as an Assistant Professor in the Department of Electrical Engineering, Osmania University. He graduated in Electrical & Electronics Engineering from Jawaharlal Nehru Technological University, Hyderabad in 1998 and received M.E in Power Systems from Jawaharlal Nehru Technological University, Hyderabad in 2004. His areas of interest are Computer Simulation of Power Systems and Reliability Engineering. He has presented three National and International Paper and presented a technical paper in Hong-Kong in 2008.

Dr. P.V.N. Prasad is currently working as an Associate Professor in the Department of Electrical Engineering, Osmania University. He graduated in Electrical & Electronics Engineering from Jawaharlal Nehru Technological University, Hyderabad in 1983 and received M.E in Industrial Drives & Control from Osmania University, Hyderabad in 1986. He received his Ph.D in Electrical Engineering in 2002. His areas of interest are Simulation of Electrical Machines & Power Electronic Drives and Reliability Engineering. He is a member of Institution of Engineers India) and Indian Society for Technical Education. He is recipient of Dr. Rajendra Prasad Memorial Prize, Institution of Engineers (India), 1993 - 94 for best paper. He has published more than 40 papers in National and International Journals, Magazines, Conferences & Symposia and, also presented technical papers in Thailand, Italy and U.S.A.