EVALUATING THE IMPACT OF COMPONENT UNAVAILABILITY ON POWER DISTRIBUTION FEEDER RELIABILITY

By

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A project submitted to the Department of Electrical and Electronic Engineering in partial fulfillment of the requirements for the degree of
Master of Engineering in Electrical and Electronic Engineering

Department of Electrical and Electronic Engineering
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Declaration

It is hereby declared that

1. The project submitted is my own original work while completing degree at Brac University.
2. The project does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.
3. The project does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.
4. I have acknowledged all main sources of help.

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Approval

The project titled "Evaluating the Impact of Component Unavailability on Power Distribution Feeder Reliability" submitted by Bannay Roy on 06 March, 2025 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Engineering in Electrical and Electronic Engineering.

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Ethics Statement

This project entitled "Evaluating the Impact of Component Unavailability on Power Distribution Feeder Reliability" is the result of my study for partial fulfillment of the requirements for the degree of Master of Engineering in Electrical and Electronic Engineering under supervision of Dr. A. S. Nazmul Huda, Associate Professor, Department of Electrical and Electronic Engineering, BRAC University and the same work has not been submitted or published elsewhere for the award of any other degree. The research papers, journals, articles, etc. which were referred to during the project are properly acknowledged here in the reference section.

Abstract

The power distribution system reliability is the key driver for service quality as well as customer satisfaction. In this study, the impact of component unavailability on overhead as well as underground distribution feeder reliability is analyzed in terms of reliability metrics like SAIFI, ASAI, ENS, CAIDI, and SAIDI. Due to environmental conditions, overhead power distribution lines face many challenges, while underground power distribution cables are superior to this due to their resiliency and performance. The reliability of distribution feeders varies based on the analysis of different protective devices such as fuses, disconnecting switches, and alternative supplies as well as the restoration process of transformer failure. Using the analytical approach, this study evaluates the reliability of both feeder types such as overhead and underground in different unavailability cases. It is observed that the reliability level of feeders is greatly impacted by the absence of these devices. The results also show that the feeder reliability is improved when overhead power lines are replaced by underground power cables, resulting in a reduced number of outages and durations.

Keywords: Reliability; Distribution feeders; Component unavailability; Overhead power lines; Underground feeder; Outages.

Dedication

DEDICATED

TO MY

PARENTS

AND

FRIENDS

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List of Acronyms

AENS	Average Energy Not Supplied
AS	Alternative Supply
ASAI	Average Service Availability Index
ASUI	Average Service Unavailability Index
CAIDI	Customer Average Interruption Duration Index
DS	Disconnecting Switch
ENS	Energy Not Supplied
F	Fuse
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
FDR	Frequency Domain Reflectometry
OH	Overhead
T	Transformer
TC	Transformer Replacement
TDR	Time Domain Reflectometry
TR	Transformer Repair
UG	Underground

Chapter 1

Introduction

1.1 Background

Power distribution system stability is essential for ensuring a stable and uninterrupted electricity supply, which means the ability to deliver continuous power without noticeable interruptions. With this, it also includes the system's capability to tolerate disturbances, quickly recover from outages, and maintain continuous service under different conditions.

Overhead power lines have been used since the late 19th century. The installation cost of overline lines is low but overhead lines are highly exposed to weather events like storms, high winds, lightning, and ice accumulation, which may create interruptions in the power flow. These ultimately affect the power system stability and increase the maintenance cost as well [1]. The physical exposure of the overhead power cables also contributes to high failure rates [2]. The socio-economic impact of the power outage is also noticeably high. Businesses have to face high financial losses and low productivity because of this. Also, residents face difficulties in accomplishing the work because of long and frequent power outages. With the advancement in technology, using underground power cables offer greater resistance against environmental changes [3, 4].

Though the initial installation cost of underground power cables is high, however, in a long run they offer low maintenance cost, minimum power losses and enhanced reliability [5, 6]. To improve, grid resiliency against different weather changes, many countries in the world are implementing underground power cables [7]. The underground power cables are an attractive alternative for improving the reliability. As these cables are buried deep in the soil, they are protected from many of the environmental impacts that affect overhead power cables. So, the outages duration decreases in this case [8]. But due to high initial installation and maintenance costs, replacing overhead power cables by underground power cables is more challenging.

The power system reliability is always a main concern to the utilities, consumers and policymakers. By enhancing the power distribution feeder reliability, it benefits both the utilities and consumers reducing economic losses from outages, and by promoting continuous grid operation. This ultimately inspires future investors and policymakers to make decision on using underground power cables over overhead power cables [9].

In order to justify that the use of underground power cables increases the system reliability, we have to quantify the differences in reliability performance. The key stability metrics like SAIFI, SAIDI, CAIDI, ASAI, ASUI, ENS, and AENS, will be used to compare the stability of overhead and underground power systems.

1.2 Objectives and Scope of the Project

This project aims to study the impact of device absence on the power distribution stability, for both overhead power cables and underground power cables. By incorporating different component unavailability scenarios, it will find critical components that influence power system reliability. A complete analysis of six different reliability indices is conducted to differentiate the reliability of overhead and underground power cables. The outcomes of this project provide recommendations concerning the stability increase of the distribution system and outage reduction.

1.3 Project Outlines

The project outline is managed as follows:

Chapter 1 includes the background, challenges, and different aims and objectives set for the project.

Chapter 2 provides a comprehensive analysis of distribution systems, exploring their configurations, reliability metrics, and protection mechanisms.

Chapter 3 presents the methodology implemented for the analysis. Feeders taken under consideration and types of stability metrics are explained in this section.

Chapter 4 presents the various reliabilities obtained for the overhead and underground power cables taken under consideration. The analysis made is also included in this chapter.

Chapter 5 illustrates the main findings and conclusion of the project.

Chapter 2

Overview of Power Distribution Systems and Reliability

The distribution is the vital stage in the transmission of electrical power, responsible for delivering electricity from substations to end consumers, such as residential, commercial, and industrial users. Operating at lower voltage levels (typically below 33kV, depending on the country and utility), distribution includes types of devices like substations, transformers, distribution lines, circuit breakers, switchgear, feeder lines, and distribution panels. Substations step down high-voltage power from the transmission system to distribution voltage levels, while transformers adjust voltage levels as required. Distribution lines, either overhead or underground, carry electricity from substations to consumers, and circuit breakers and switchgear protect the system by isolating faults or failures. Feeder lines distribute power to different areas, and distribution panels directly connect to consumers' premises, ensuring reliable power delivery [10].

Distribution systems play a crucial role in delivering electrical power from generation sources to consumers, and their reliability has a significant impact on overall system performance. These systems can adopt various topologies, each offering distinct characteristics, advantages, and drawbacks. Simple, inexpensive, and often deployed in low-density regions, the radial distribution system has poor dependability since any malfunction effects all downstream customers [11]. The ring system's facilitation of re-routing electricity in the cyclone improves dependability and makes it suitable for urban areas at the cost of increased infrastructure costs [12]. The mesh system serves data centers and hospitals well due to the numerous power paths and superior dependability. However, its cost and maintenance problems are enormous [13].

2.1 Distribution System Configurations

The organization of the electrical network that delivers power from substations to users for consumption, both with attention to its physical appearance, which is the distribution system configuration. The design of distribution has an impact on the way power flows in it, its reliability, and how fast faults are detected and dealt with. Three main configurations of distribution system ring, meshed, and radial are differentiated by the characteristics, advantages, and disadvantages of each.

2.2.1 Radial Distribution Systems

The dominant type of low-voltage distribution system is called radial distribution topology. This type of system consists of a primary feeder and the lateral branches of each serving the transportation of electricity from the substation into connected load centers. With a straightforward design, this method is easiest to execute and frequently involves lower establishment costs. However, radial networks are predisposed to more frequent disruptions. If there is a problem with the feeder then it can interrupt power to downstream sites creating a wide spread disruption. Disconnect switches and sectionalizing devices are used to provide service to the service-free areas and to solve problems through utilizing protection measures like fuses and circuit breakers [14].

2.2.2 Ring Distribution Systems

A loop or ring distribution scheme defines a design of a network whereby distribution cables eventually loop back to source or substation in a contiguous loop. The direction of movement of power in the system is neither restricted, giving the users various opportunities for receiving power. Even though service gets interrupted power may be transferred along other paths thus limiting power outages and increasing the overall system reliability. Ring configurations are selected for areas under heavy power demands such as the city centers or regions where there are big continuous operations. Redundancy is the primary power of a ring system because it allows quick fault isolation and faster availability of the service. However, one need for maintaining safe operation is the installation of expensive, high-end protective systems and complex infrastructure [15].

2.2.3 Meshed Distribution Systems

In sub-transmission networks, meshed distribution systems with redundant power pathways are extensively applied. This networked structure means that there are other routes for routing powers in case there are outages, hence upgrades in reliability. Unlike radial systems, meshed systems can more effectively survive single-point failures and provide power to critical load points. The need to manage power flow and avoid chain reactions in meshed systems requires state-of-the-art safety and control measures despite the basic fact that such systems cost more and are more complicated to construct because of their advanced reliability. As reliability is a critical matter, such systems are normally adapted in industrial setting as well as in metropolitan areas with high population to provide a steady flow of power [16].

2.2 Power Distribution System Reliability

Reliability implies its ability to support stable distribution of electricity with no outages to its consumers thus supplying them with constant dependable and safe power supplies. As the industry developed, the reliability gauges changed from qualitative judgments to quantified, standardized tools that provide more reliable and comparable data for comparison purposes. As system availability and its financial implications are analyzed under the auspices of instruments such as ASAI, ASUI, ENS, and AENS, the classical metrics of SAIFI, SAIDI, and CAIDI are used for quantifying how closely outages occur and how long they last. By reviewing such data sets, utilities are able to monitor performance, increase customer satisfaction and drive improvements on how the grid is arranged and run.

2.3 Reliability Metrics for Power Distribution Systems

2.3.1 System Average Interruption Frequency Index (SAIFI)

The System Average Interruption Frequency Index is a useful instrument for measuring the amount of disruptions on the customers' side in the distribution network. It reflects the average number of interruptions that a customer can receive into his or her service within a year. SAIFI is calculated by dividing the sum of customers affected by blackouts over all customers. Through this metric; utilities can monitor their performance and estimate the outages that their customers experience. By numbers, increased system reliability corresponds to lower power breaks, evidenced by a decline in the SAIFI ratio. The utilities need to focus on investments in updated infrastructure, strict maintenance, and analytical approaches to SAIFI data that support the best operational outcomes while seeking to improve the efficiency of the system [17].

2.3.2 System Average Interruption Duration Index (SAIDI)

Later on, the SAIDI index, or system average interruption duration index, serves as the primary criterion of how long, on average, the consumers are in outage in the distribution networks. In order to find SAIDI, the overall outage time is divided by total system's customer population. SAIDI is able to measure both frequency and duration of outages and therefore offers relevant information on how interruptions affect how the customers are impacted. Reduced SAIDI shows that the customers are exposed to fewer disruption events per customer, meaning increased level of system reliability.

With SAIDI data, utilities can identify areas that are more likely to suffer outages, provide resources strategically, and then develop action plans to reduce the genset impact and improve reliability and customer satisfaction [18].

2.3.3 Customer Average Interruption Duration Index (CAIDI)

The Customer Average Interruption Duration Index (CAIDI) is used to measure the average length of disruptions of power to customers. As a primary indicator of system-resilience, CAIDI demonstrates the average time before the power restoration for the customers following a power outage. By tracking CAIDI, utilities have insight into the effectiveness of the processes they undertake for managing and restoring outages, can pinpoint areas that must be improved, and thus plan to reduce restoration periods, improving reliability and customer satisfaction [19].

2.3.4 Average Service Availability Index (ASAI)

We compute the availability of electricity over time using the Average Service Availability Index (ASAI), indicating how often a distribution system can provide electricity to its consumers. It is the proportion of the total period, normally a year, that the system is operational and supplies electricity to the customers. The ASAI is calculated as (total time — total interruption duration for the whole period) / total time. Utility firms may apply ASAI to identify the reliability of their power supply, identify vulnerabilities as well as design efforts to upgrade system performance and reduce downtime respectively, which ultimately enhances more robust customer service continuity [20].

2.3.5 Average Service Unavailability Index (ASUI)

ASUI is a measure of reliability that defines the number of hours the consumers fail to utilize as a power distribution system on account of disruptions. In its essence, it differs from the Average Service Availability Index (ASAI), which reflects the period over which consumers cannot access power. ASUI is calculated by dividing the total duration of a period by the duration spent by the system off-line during the same period, with the period often being a year. Using ASUI, utilities can analyze customer disruptions; identify infrastructure weaknesses; and adapt operations to reduce outage rate and enhance both reliability and customer satisfaction [20].

2.3.6 Energy Not Supplied (ENS)

The ENS model is used to find the amount of electricity lost to consumers via distribution system outages or disruptions. It measures the amount of energy lost during disturbances being commonly logged in MWh or kWh. To calculate ENS you multiply the time outages last, the number of people affected and the normal load encountered during the outage. Monitoring ENS enables utility companies to fine-tune their investments into infrastructure, identify areas of maximizing improvement of services through specific allocation of resources, and evaluate the macroeconomic impact of outages for both customers and the organization. In order to have a more efficient system and to reduce the effects of outages, the ENS has to be reduced [21].

2.3.7 Average Energy Not Supplied (AENS)

AENS is the abbreviation for Average Energy Not Supplied meaning average amount of energy not supplied to each customer due to outages during a period and is given in (MWh). or kilowatt hours (kWh). Offering a customer-oriented perspective on the effect of power outages, AENS sheds light into the average level of energy lost by each of the affected customers during outages. Monitoring AENS allows utilities to concentrate on maximizing system reliability, decrease the frequency and time of outages, as well as eventually minimize energy wastage in case of an outage in the future, thus improving the quality of customer service [22].

2.4 Protection and Sectionalizing in Distribution Systems

Closely designed protection and sectionalizing systems are high contributors to dependability for electricity distribution networks. To achieve constant and continuous power supply, it is a necessity to use important components like transformers, disconnect switches, fuses and circuit breakers [23]. All elements are required to help system security remain unassailable from errors and supply interruptions.

In overcurrent protection, the circuit breakers are provided at the main feeder and at important points throughout the distribution system. Anytime there is overcurrent, even a short circuit, these devices are to automatically interrupt power flow. Circuit breakers reduce excess agitation to the network by cutting out power to the affected sub duct thereby avoiding structural damages including possible fires and equipment defects.

Being able to isolate faults, fuses are usually located on lateral branches of the system of distribution. In the event of a surge in current, fuses trip automatically and the offending section is taken out of service, avoiding an overload of the main feeder. Despite the fact that fuses ensure that there are no short circuits, there is need to replace them manually, when they fail. Because of this they represent cost effective approach to protecting minor components of the system, thus strengthening the entire network.

Disconnect switches are used by operators to isolate trouble spots in the distribution system in order to make repairs. Disconnect switches are equally placed in such a way that trouble areas can be isolated in a rapid manner without interfering with the rest of the network. Disconnect switches are particularly helpful when it comes to the maintenance, or the repair of a disconnection, as they provide a possibility for de-energizing parts of the interconnection with the rest of the network remaining in operability.

Without transformers, it would be impossible to step-down transmission voltages to required consumer voltages. Using voltage control, these devices ensure that the energy delivered to homes, offices, and firms is steady and that it is within the acceptable range. One of the other functions of the transformers in maintaining power transmission efficiency is that they facilitate control of voltage losses and allow concurrent spreading at extending distances.

Working together, these devices form a united protective and sectionalizing system and reduce service interruptions, facilitate solving problems and maintain the integrity of the distribution network. These devices also provide rapid response for isolation and failure containment leaving behind a stable and uninterrupted power grid without further failure and reduces the negative impact that power outage has on the community and business.

2.5 Implications of System Configuration on Reliability

Radial systems that involve a single power line are also highly likely to fail, though they are a good budget alternative. Mesh systems, on the other hand, guarantee better service reliability and fault containment issues, but with increased operation difficulties and expenses. The recognition of these trade-offs is important to be able to reach an effective system cost and reliability balance.

Advancements toward enhancing power system reliability are demonstrated in the development of reliability measurements and modifications of the distribution network configurations. In locations where dependability need is not high, people prefer radial systems since they are economical in design and easy to use. At the same time, meshed systems have increased stability and dependability because of that reason, they perform well in high-demand areas and are indispensable in critical infrastructure.

This analysis demonstrates the absolute necessity of using reliability measures like SAIFI, SAIDI, CAIDI, ASAI and ENS for radial systems research. Their efficacy and improvement opportunities will be better understood by this study. The effective implementation of distribution systems improvement requires careful integration of these metrics.

Chapter 3

Methodology

This chapter contains procedures used for the assessment within the project. In the present chapter, a number of reliability assessments conducted include such analytical methods that are applied to test the overhead and underground cables' performance.

3.1 Reliability Indicators

For assessing the reliability of distribution feeder, following reliability assessment indicators are used in this project.

3.1.1 System Average Interruption Frequency Index (SAIFI)

SAIFI is defined as the average disturbances/interruptions that a customer faces in any particular duration.

System Average Interruption Frequency Index (SAIFI) =

$$\frac{Total\ number\ of\ interruptions\ in\ the\ feeder}{Total\ number\ of\ customers\ in\ the\ feeder} = \frac{\sum(\lambda_i \times N_i)}{\sum N_i}$$ (interruptions/feeder-customer/yr.) …. .. (i)

where

λ_i= Failure rate of each customer

N_i= Number of customers served in each feeder

3.1.2 System Average Interruption Duration Index (SAIDI)

SAIDI is defined as the net disturbances/interruptions durations for the average customer in any particular duration.

System Average Interruption Duration Index (SAIDI) =

$$\frac{Sum\ of\ customer\ interruption\ duration}{Total\ number\ of\ customers\ in\ the\ feeder} = \frac{\sum(U_i \times N_i)}{\sum N_i}$$ (hrs./feeder-customer/yr.) ………..… .. (ii)

where

U_i= Duration of each interruption event i (usually in hours)

3.1.3 Customer Average Interruption Duration Index (CAIDI)

CAIDI is defined as the mean time needed to restore the service to customers who have an interruption.

Customer Average Interruption Duration Index (CAIDI) =

$$\frac{Sum\ of\ customer\ interruption\ duration}{Total\ number\ of\ interruptions\ in\ the\ feeder}\ \frac{SAIDI}{SAIFI} = \frac{\sum(U_i \times N_i)}{\sum(\lambda_i \times N_i)}$$ (hrs./feeder-interruption) ……… (iii)

3.1.4 Average Service Availability Index (ASAI)

ASAI is defined as the rate of the availability of power system to the consumers in any specified duration.

Average Service Availability Index (ASAI) =

$$\frac{Customers\ hours\ of\ available\ service}{Customers\ hours\ demanded} = \frac{\sum(Ni \times 8{,}760) - \sum(U_i \times N_i)}{\sum(N_i \times 8{,}760)}$$ …………………. (iv)

where

U_i= Duration of each interruption event i (usually in hours)

N_i = Number of interruptions for each event i

3.2 System Under Consideration

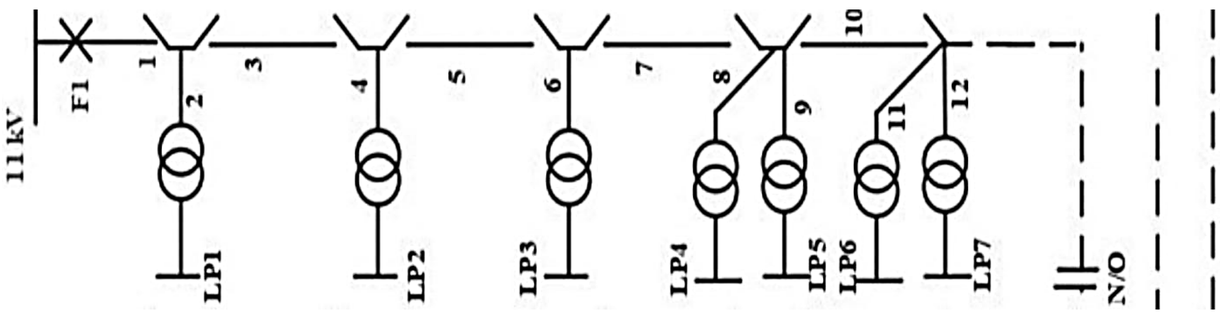

Figure 3.1 Single line diagram of the test feeder

Figure 3.1 shows the single line diagram of the test feeder taken under consideration [24]. The power from 11 kV bus is feed to the seven different feeders as shown in the single line diagram. Here, this feeder delivers power to the different seven load points as indicated. Also, disconnects, fuses, transformers, normally operated alternative supplies are as shown in figure above.

Table 3.1 depicts the data for feeder types and lengths. Twelve different types of feeder sections are categorized into three different types on the basis of their lengths. Feeder-1, feeder-2 and feeder-3 are of lengths 0.60 km, 0.75 km and 0.80 km respectively. There are 3, 5 and 4 sections respectively on these three feeders.

Table 3.1 Feeder types and lengths in km [24]

Feeder Type	Length (km)	Feeder Section Numbers
1	0.60	2, 6, 10
2	0.75	1, 4, 7, 9, 12
3	0.80	3, 5, 8, 11

Similarly, Table 3.2 illustrates the customer and load data based on different customer types and load points in MW. There are three different types of customers, namely residential, small user and commercial. There are two, two and one different kinds of load data for residential customer, small user and commercial customers respectively.

Table 3.2 Customer and load data in MW [24]

Number of Load Points	Load Points	Customer Type	Average Load Level per Load Point, MW	Number of Customers in each Load Point
6	1-4, 11-12	Residential	0.545	220
1	5	Residential	0.500	200
2	8, 10	Small User	1.000	1
1	9	Small User	1.500	1
2	6, 7	Commercial	0.415	10
Total			8.1	1,543

Likewise, Table 3.3 shows the line data depending upon the voltage level of the section. Here, the failure rate, repair time, replacement time and switching time for 11/0.415 kV transformer and 11 kV line are given.

Table 3.3 Line data [24]

Component	Failure Rate (f/yr. km)	Repair Time (hr.)	Replacement (hr.)	Switching (hr.)
11/0.415 Transformer	0.015	200	10	1
11 kV line	0.065	5		1

3.3 Different Cases Analyzed

Table 3.4 illustrates the sixteen different cases that are analyzed for both overhead and underground power cables. Here, eight cases each for transformer repair and replacement is done. The feeder design configurations are changed in different combinations to analyze the reliability indices. The feeder components: disconnect switch, fuse and alternative supply are varied as indicated.

Table 3.4 Different cases analyzed

Case	**Feeder Design Configurations**			**Transformer Restoration**
	Disconnect	**Fuse**	**Alternate Supply**	
A	√	√	√	Repair
B	×	×	×	Repair
C	×	√	×	Repair
D	√	×	√	Repair
E	√	√	√	Replacement
F	√	×	×	Repair
G	√	√	×	Repair
H	√	√	×	Replacement
I	×	×	×	Replacement
J	×	√	×	Replacement
K	√	×	√	Replacement
L	√	×	×	Replacement
M	×	√	√	Repair
N	×	×	√	Repair
O	×	√	√	Replacement
P	×	×	√	Replacement

These sixteen different cases are evaluated for analyzing the reliability of overhead and underground power cables. These cases are classified on the basis of the presence or absence of disconnects (i.e., isolators), fuses, alternative supply and repair/replacement of transformers at the different locations of the feeders.

Chapter 4

Results and Discussions

In this chapter, different reliability indices for overhead and underground lines are determined for the different cases of feeder-1 of standard RBTS. Then, the reliabilities are determined considering the unavailability of different components.

4.1 Overhead (OH) Lines

Here, table in Appendix A shows the calculation of different parameters of feeder-1 of overhead lines for the first case. Table 4.1 depicts the net reliability indices for Case-A. Here, SAIFI, SAIDI, CAIDI and ASAI are the important indices for reliability assessment and are obtained as 0.301, 3.47, 11.52 and 0.999604 respectively for the first case where all fuses, disconnect switch and alternative supply are connected.

Table 4.1 Different reliability indices of feeder (OH)

SAIFI (interruptions/ customer/yr.)	SAIDI (hours/customer/yr.)	CAIDI (hours/interruption)	ASAI	ASUI	ENS (MWh/ yr.)	AENS (MWh/customer/yr.)
0.301	3.47	11.52	0.999604	0.000396	12	0.01

Table 4.2 illustrates the values of reliability indices obtained considering the unavailability of zero component in different sections of feeder-1. Here, we can see the two different possible cases; where disconnect switch, fuse and alternative supply are available with transformer repair and transformer replacement. Here, SAIFI value is same for both cases; while SAIDI and CAIDI value decreases for transformer replacement case than in transformer repair case. ASAI is almost constant to unity in both the cases.

Table 4.2 Reliability indices considering no unavailability of component

Reliability indices considering unavailability of zero component					
Unavailable component	Available component	SAIFI (interruptions/ customer/yr.)	SAIDI (hours/customer /yr.)	CAIDI (hours/inter ruption)	ASAI
0	DS, F, AS, T(Repair)	0.301	3.47	11.52	0.999604
0	DS, F, AS, T(Replacement)	0.301	0.62	2.05	0.999929

Table 4.3 illustrates the values of reliability indices obtained considering the unavailability of one component in different sections of feeder-1. Here, we can see five different possible cases. Here, SAIFI, SAIDI and CAIDI value changes with the unavailability of the component. SAIFI/SAIDI and CAIDI are high for the unavailability of fuses and disconnect switches respectively.

Table 4.3 Reliability indices considering unavailability of one component

Reliability indices considering unavailability of one component				
Unavailable component	SAIFI (interruptions/ customer/yr)	SAIDI (hours/customer/ yr.)	CAIDI (hours/interru ption)	ASAI
DS	0.602	6.01	19.97	1.999314
F	1.348	6.241	9.26	1.999288
AS	0.602	5.22	17.34	1.999404
T (Repair)	0.301	0.62	2.05	0.999929
T (Replacement)	0.301	3.47	11.52	0.999604

Table 4.4 depicts the values of reliability indices obtained considering the unavailability of two components in different sections of feeder-1. Here, we can see 9 different possible cases. Here, SAIFI is more when DS &F and F&AS are unavailable. Similarly, SAIDI and CAIDI are more when DS&F are unavailable in the feeder. The ASAI value does not change noticeably with the change in unavailable components.

Table 4.4 Reliability indices considering unavailability of two components

Reliability indices considering unavailability of two components				
Unavailable components	SAIFI (interruptions/ customer/yr.)	SAIDI (hours/customer /yr.)	CAIDI (hours /interruption)	ASAI
DS, F	1.348	27.74	41.17	1.996834
DS, AS	0.602	6.010	19.966	1.999314
DS, T (Repair)	0.301	1.58	5.25	0.999820
DS, T (Replacement)	0.301	4.43	14.72	0.999494
F, AS	1.348	13.73	20.37	1.998433
F, T (Repair)	0.674	1.13	1.67	0.999872
F, T (Replacement)	0.674	5.12	7.59	0.999416
AS, T (Repair)	0.301	1.19	3.94	0.999865
AS, T (Replacement)	0.301	4.04	13.40	0.999539

Table 4.5 illustrates the values of reliability indices obtained considering the unavailability of three components in different sections of feeder-1. Here, we can see five different possible cases. Here, SAIFI and ASAI are almost constant; except the first case when all components are unavailable except transformer. Also, SAIFI, SAIDI and CAIDI are high when DS+F+AS are unavailable.

Table 4.5 Reliability indices considering unavailability of three components

Reliability indices considering unavailability of three components				
Unavailable components	SAIFI (interruptions/ customer/yr.)	SAIDI (hours/customer/yr.)	CAIDI (hours/interruption)	ASAI
DS, F, AS	1.348	27.74	41.17	1.996834
DS, F, T (Repair)	0.674	3.89	5.78	0.999556
DS, F, T (Replacement)	0.674	23.84	35.39	0.997278
F, AS, T (Repair)	0.674	2.25	3.34	0.999743
F, AS, T (Replacement)	0.674	11.48	17.03	0.998690

Table 4.6 illustrates the values of reliability indices obtained considering the unavailability of all four components in different sections of feeder-1. Here, we can see two different possible cases. Here, SAIFI and ASAI values are almost same for both the cases while we can notice that SAIDI and CAIDI are more for the case when transformer is under replacement than that when the transformer is under repair.

Table 4.6 Reliability indices considering unavailability of four components

Reliability indices considering unavailability of four components				
Unavailable components	SAIFI (interruptions/ customer/yr.)	SAIDI (hours/customer /yr.)	CAIDI (hours/interrupt ion)	ASAI
DS, F, AS, T (Repair)	0.674	3.89	5.78	0.999556
DS, F, AS, T (Replacement)	0.674	23.84	35.39	0.997278

4.2 Underground (UG) Lines

Table 4.7 depicts the net reliability indices for Case-A. Here, SAIFI, SAIDI, CAIDI and ASAI are the important indices for reliability assessment and are obtained as 0.191, 4.28, 22.43 and 0.999511, respectively for the first case where all fuses, disconnect switch and alternative supply are connected.

Table 4.7 Different reliability indices of feeder (UG)

SAIFI (interruptions/cust omer/yr.)	SAIDI (hours/custo mer/yr.)	CAIDI (hours/interr uption)	ASAI	ASUI	ENS (MWh/ yr.)	AENS (MWh/custo mer/yr.)
0.191	4.28	22.43	0.999 511	0.000 489	15	0.01

Likewise, Table 4.8 illustrates the values of reliability indices obtained for UG lines considering the unavailability of zero component in different sections of feeder-1. Here, we can see the two different possible cases; where disconnect switch, fuse and alternative supply are available with transformer repair and transformer replacement. Here, SAIFI value is same for both cases; while SAIDI and CAIDI value decreases for transformer replacement case than in transformer repair case just like in case for OH line. ASAI is almost constant to unity in both the cases.

Table 4.8 Reliability indices considering no unavailability of component

Reliability indices considering unavailability of zero component					
Unavailable component	Available component	SAIFI (interruptions/ customer/yr.)	SAIDI (hours/customer/yr.)	CAIDI (hours/interruption)	ASAI
0	DS, F, AS, T (Repair)	0.191	4.28	22.43	0.999511
0	DS, F, AS, T (Replacement)	0.191	1.43	7.51	0.999836

Table 4.9 illustrates the values of reliability indices obtained for UG lines considering the unavailability of one component in different sections of feeder-1. Here, we can see the five different possible cases. Here, SAIFI, SAIDI and CAIDI value changes with the unavailability of the component. SAIFI and SAIDI/CAIDI are high for the unavailability of fuse and disconnect switches respectively.

Table 4.9 Reliability indices considering unavailability of one component in feeder

Reliability Indices Considering Unavailability of One Component				
Unavailable component	SAIFI (interruptions/ customer/yr.)	SAIDI (hours/customer /yr.)	CAIDI (hours/interruption)	ASAI
DS	0.382	13.71	71.78	1.998435
F	0.910	9.196	20.21	1.998950
AS	0.382	10.43	54.60	1.998809
T (Repair)	0.191	1.43	7.51	0.999836
T (Replacement)	0.191	4.28	22.43	0.999511

Table 4.10 illustrates the values of reliability indices obtained for UG lines considering the unavailability of two components in different sections of feeder-1. Here, we can see the nine different possible cases. Here, SAIFI is more when DS+F and F+AS are unavailable. Similarly, SAIDI and CAIDI are more when DS+F are unavailable in the feeder. The ASAI value does not change noticeably with the change in unavailable components.

Table 4.10 Reliability indices considering unavailability of two components in feeder

Reliability indices considering unavailability of two components				
Unavailable components	SAIFI (interruptions/ customer/yr.)	SAIDI (hours/customer/yr.)	CAIDI (hours/interruption)	ASAI
DS, F	0.910	43.05	94.62	1.995086
DS, AS	0.382	13.711	71.779	1.998435
DS, T (Repair)	0.191	5.43	28.43	0.999380
DS, T (Replacement)	0.191	8.28	43.35	0.999055
F, AS	0.910	22.11	48.60	1.997476
F, T (Repair)	0.455	2.60	5.72	0.999703
F, T (Replacement)	0.455	6.59	14.49	0.999247
AS, T (Repair)	0.191	3.79	19.84	0.999567
AS, T (Replacement)	0.191	6.64	34.76	0.999242

Table 4.11 illustrates the values of reliability indices obtained for UG lines considering the unavailability of three components in different sections of feeder-1. Here, we can see five different possible cases. Here, SAIFI and ASAI are almost constant; except the first case when all components are unavailable except transformer. Also, SAIFI, SAIDI and CAIDI are high when DS, F, and AS are unavailable.

Table 4.11 Reliability indices considering unavailability of three components in feeder

Reliability indices considering unavailability of three components				
Unavailable components	SAIFI (interruptions/ customer/yr.)	SAIDI (hours/customer /yr.)	CAIDI (hours/interruption)	ASAI
DS, F, AS	0.910	43.05	94.62	1.995086
DS, F, T (Repair)	0.455	11.55	25.38	0.998682
DS, F, T (Replacement)	0.455	31.50	69.23	0.996404
F, AS, T (Repair)	0.455	6.45	14.16	0.999264
F, AS, T (Replacement)	0.455	15.67	34.44	0.998211

Table 4.12 illustrates the values of reliability indices obtained for UG lines considering the unavailability of all four components in different sections of feeder-1. Here, we can see two different possible cases. Here, SAIFI and ASAI values are almost same for both the cases while we can notice that SAIDI and CAIDI are more for the case when transformer under replacement than that when the transformer under repair.

Table 4.12 Reliability indices considering unavailability of four components in feeder

Reliability indices considering unavailability of four components				
Unavailable components	SAIFI (interruptions/ customer/yr.)	SAIDI (hours/cust omer/yr.)	CAIDI (hours/interr uption)	ASAI
DS, F, AS, T (Repair)	0.455	11.55	25.38	0.998682
DS, F, AS, T (Replacement)	0.455	31.50	69.23	0.996404

Tables 4.3 and 4.9 show the calculated reliability indices for the base case, which includes the use of disconnect switches, fuses, and an alternate supply. SAIFI values are noticeably lower for feeders with underground (UG) systems compared to overhead (OH) systems, primarily due to the lower failure rates in UG networks. However, SAIDI and CAIDI values are higher for UG systems because repairs typically take more time. Both transformer restoration methods repair and replacement with a spare are considered in the analysis. Since repairs generally require more time than replacements, SAIDI and CAIDI are higher in repair scenarios. The ASAI values remain close to unity across all cases.

Tables 4.4 and 4.10 illustrate how the unavailability of individual components, such as a disconnect switch, fuse, or alternate supply affects the reliability indices in both overhead (OH) and underground (UG) systems. In cases where a single component is unavailable, UG systems show lower SAIFI values than OH systems, mainly due to their reduced failure rates. However, SAIDI and CAIDI values tend to be higher in UG systems under these conditions when compared to both OH systems and the base scenario.

Analyzing all sixteen cases (data obtained of remaining fifteen cases are included in Appendix A and Appendix B) and the unavailability of components in similar sequence, we can observe that the reliability of the underground power cables is higher than that of overhead lines.

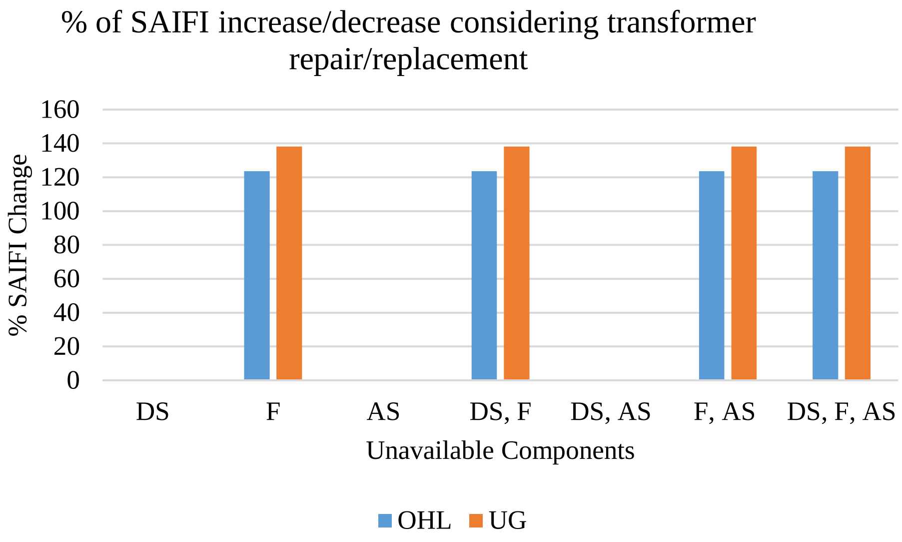

Figure 4.1 SAIFI for unavailability of different components with transformer repair/replacement

Figure 4.1 illustrates the percentage change in SAIFI relative to the base value under different component unavailability scenarios, specifically during transformer repair or replacement. The highest increases in SAIFI were observed at 123% for overhead (OH) systems and 138% for underground (UG) systems across both transformer restoration methods.

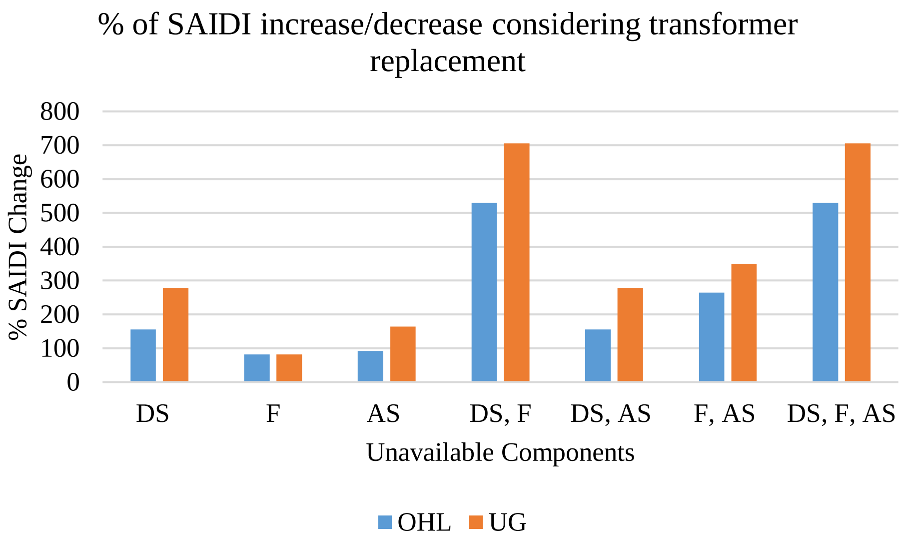

Figure 4.2 SAIDI for unavailability of components with transformer replacement

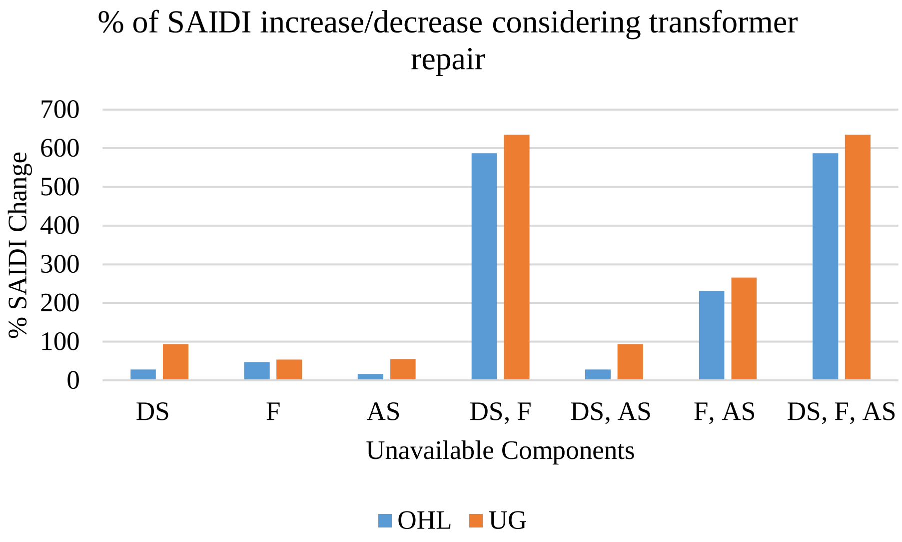

Figure 4.3 SAIDI for unavailability of components with transformer repair

Figures 4.2 and 4.3 depict the percentage variation in SAIDI relative to the base value under different component unavailability scenarios during transformer replacement and repair, respectively. For transformer replacement, the highest SAIDI increases were 529% in overhead (OH) systems and 705% in underground (UG) systems, while the lowest increases were 82% and 81% for OH and UG, respectively. In contrast, during transformer repair (Figure 4.3), the maximum SAIDI changes reached 587% for OH and 635% for UG, with minimum changes of 16% and 53%, respectively. The unavailability impact of components on SAIDI can be arranged as:

- For transformer replacement in both OH and UG systems, the impact of component unavailability on SAIDI follows the order: [DS, F & AS] = [DS & F] > [F & AS] > [DS & AS] = [DS] > [AS] > [F] > Base value.
- For transformer repair in OH systems, the SAIDI impact due to component unavailability follows this order: [DS, F & AS] = [DS & F] > [F & AS] > [F] > [DS & AS] = [DS] > [AS] > Base value.

- For transformer repair in UG systems, the impact of component unavailability on SAIDI is ranked as follows: [DS, F & AS] = [DS & F] > [F & AS] > [DS & AS] = [DS] > [AS] = [F] > Base value.

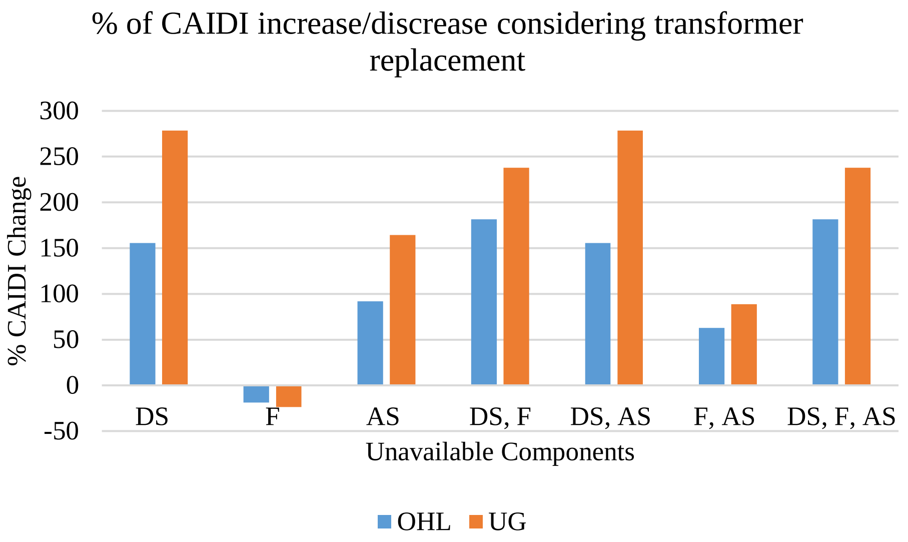

Figure 4.4 CAIDI for unavailability of components with transformer replacement

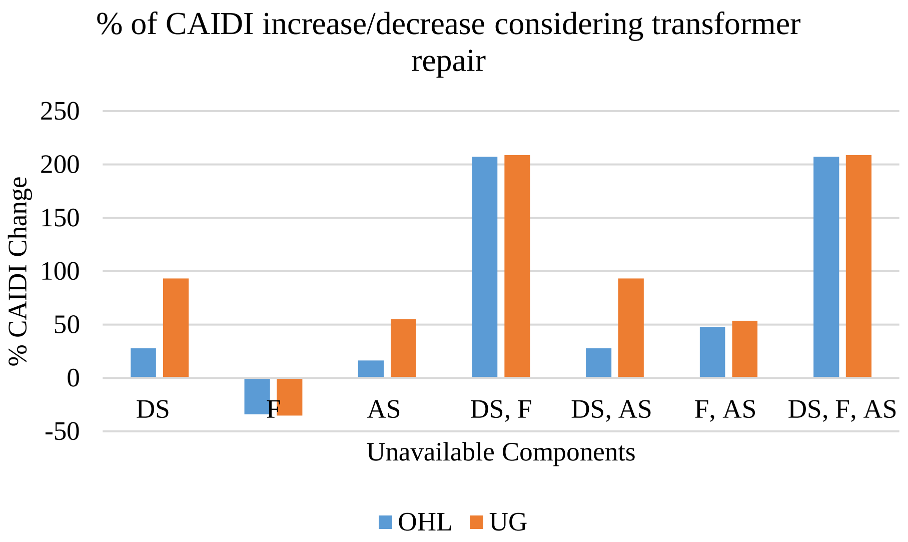

Figure 4.5 CAIDI for unavailability of components with transformer repair

Figures 4.4 and 4.5 illustrate the percentage change in CAIDI relative to the base value under different component unavailability scenarios during transformer replacement and repair, respectively. For transformer replacement, the highest CAIDI increases were observed at 181%

for overhead (OH) and 238% for underground (UG) systems, while the lowest changes were -18% and -23%, respectively. During transformer repair, as shown in Figure 4.5, the maximum increases in CAIDI were 207% for OH and 208% for UG, with the minimum changes recorded at -34% and -35%, respectively.

The unavailability impact of components on CAIDI can be arranged as:

- For transformer replacement in OHL systems, the impact of component unavailability on reliability indices follows the order: [DS, F & AS] = [DS & F] > [DS & AS] = [DS] > [AS] > [F & AS] > [F] > Base value.
- For transformer replacement in UC systems, the impact of component unavailability on reliability indices follows this order: [DS & AS] = [DS] > [DS, F & AS] = [DS & F] > [AS] > [F & AS] > Base value > [F]
- For transformer repair in OHL systems, the impact of component unavailability on reliability indices follows this order: [DS, F & AS] = [DS & F] > [F & AS] > [DS & AS] = [DS] > [AS] > Base value > [F]
- For transformer repair in UC systems, the impact of component unavailability on reliability indices follows this order: [DS, F & AS] = [DS & F] > [DS & AS] = [DS] > [AS] = [F & AS] > Base value > [F]

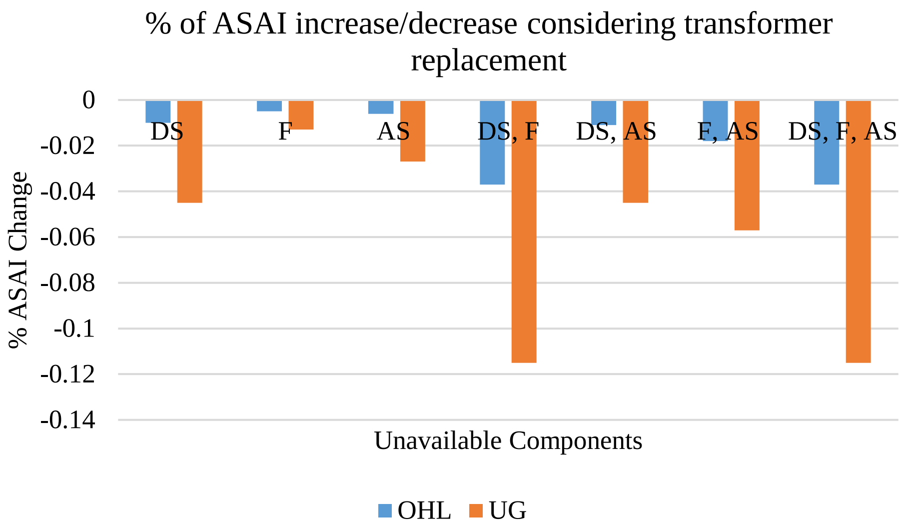

Figure 4.6 ASAI for unavailability of components with transformer replacement

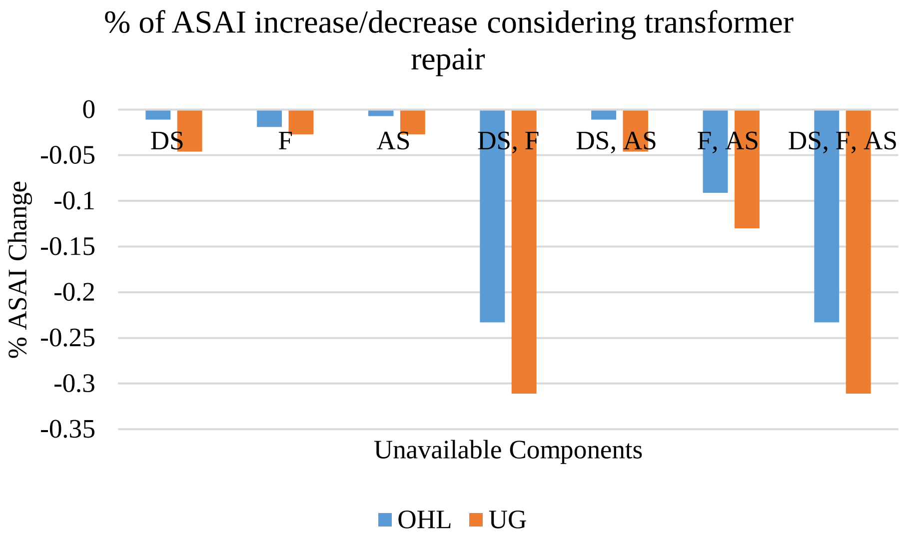

Figure 4.7 ASAI for unavailability of components with transformer repair

Figures 4.6 and 4.7 illustrate the percentage change in ASAI relative to the base value under scenarios involving the unavailability of various components, considering both transformer replacement and repair.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

The replacement of overhead lines with underground power cables in power system grids has demonstrated significant improvements in system reliability. By analyzing these indices, it is found that the power interruptions are less while using underground power cables. SAIFI and CAIFI were reduced, indicating a smaller number of interruptions while using underground power cables. Similarly, SAIDI and CAIDI suggests that when interruptions occur, they are cleared more smoothly in systems with underground power cables. The ASAI indicates better availability and higher reliability than in overhead lines.

With this, by analyzing ENS and AENS we can see the additional advantages of underground power cables. The reduced value of ENS and AENS indicates that low wastage of energy, contributing to increase the overall efficiency and reliability of the system. This assists on making the service quality better.

In conclusion, use of underground power cables creates noticeable improvements in the reliability of power system than by using overhead power cables. The huge decrement in interruption frequency and duration makes underground cables a viable and most economical option for modern power distribution.

5.2 Future Work

The projects can be extended by performing following future works.

1. Cost-benefit analysis can be conducted to evaluate the economic feasibility on implementing the underground power cables over overhead power cables.

2. Investigating and integrating advanced materials and technologies like cable insulation, cooling systems, and fault detection mechanisms can be performed for enhancing the efficiency and reliability of underground power cables.
3. Collaboration with policymakers and other regulatory bodies can be done to make a supportive framework for the effective implementation of using underground power cables.
4. Implementing underground power cables with smart grid technologies can be done for real-time monitoring, automated fault detection and grid management systems.
5. Environment impact assessment can be conducted for assessing the impact made by underground power cables on soil, water tables and so on.

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