Power System Quality and Reliability

ECEg-6312

WEEK 14

Reliability Case Study Project and Performance Evaluation

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Topic Overview

- This lecture presents a practical reliability assessment case study conducted on the Debre Markos Town Power Distribution System in Ethiopia based on Feeder 3 and Feeder 4.
- **This Lecture Covers:**
  - Reliability Assessment of an Ethiopian Distribution Grid
  - Distribution System Data Collection
  - Reliability Performance Evaluation
  - Calculation of Reliability Indices (SAIFI Analysis, SAIDI Analysis, CAIDI Analysis)
  - Interpretation of Results
  - Reliability Improvement Recommendations

Learning Outcomes

By the end of this lecture, students will be able to:

- Conduct reliability assessment of a distribution network
- Calculate SAIFI, SAIDI, and CAIDI
- Analyze utility performance using reliability indices
- Identify major causes of customer interruptions
- Recommend reliability improvement measures

1. Reliability Assessment of an Ethiopian Distribution Grid

- A reliability assessment of an Ethiopian distribution grid typically reveals that existing network performance falls significantly below the national regulatory benchmarks.
- Academic and utility case studies across major sub-networks—such as those managed by the Ethiopian Electric Utility (EEU) in:
  - Debre Markos,
  - Wolkite,
  - Haramaya,
  - Jimma, and Dangila—indicate that long radial overhead lines coupled with aging infrastructure lead to frequent and prolonged blackouts.

Current Reliability Baseline

- The baseline performance of the distribution grid frequently exceeds the threshold permitted by the Petroleum and Energy Authority (PEA), formerly the Ethiopian Electric Authority (EEA).
- **The National Benchmark Baseline:** The PEA targets a **SAIFI** of **20** interruptions per customer per year and a **SAIDI** of **25** hours per customer per year [1].
- **Actual Field Performance [1]-[3]:**
  - In the Wolkite City Grid (Line 1, 15 kV), assessments showed a SAIFI of 425.6 and a SAIDI of 144.0.
  - In the Dangila Grid (Feeder 7), baseline assessments reached a SAIFI of 636 and a SAIDI of 833.
  - In the Jimma Town Grid, research recorded an average SAIFI of 435.5 interruptions per customer per year and a SAIDI of 272.0 hours/year.

Root Causes of Grid Unreliability

- Previous research ssessments categorize the drivers of Ethiopian distribution system failure into structural, environmental, and operational challenges:
  - **Overhead Radial Topology:** Most rural and peri-urban networks utilize long radial lines. A single fault at the beginning of the feeder cuts off electricity to all downstream customers.
  - **Environmental Interferences:** Tree-branch contacts, high winds, and lightning strikes cause tripping.
  - **Infrastructure Age & Overloading:** Overloaded distribution transformers, decayed wooden poles, and brittle conductor components cause frequent mechanical and electrical failures.
  - **Operational Constraints:** A lack of automated switching infrastructure prolongs fault localization, requiring maintenance crews to manually patrol lines to find and fix damage

2. Case Study-System

- For reliability assessment, a case study project which was done at Debremarkos town from 2015 to 2016 is considered [4].
- The project is proposed to identify the towns reliability challenges and proposing the possible solution for reliability mitigation.
- The system consists of 23MVA, 230kV/15 kV transformer that feeds two 15 kV outgoing feeders at Debre Markos substation.
- It also goes further to include 139 low voltage 15kV/0.4 kV distribution transformers.
- The total load connected to the 15 kV feeders are varies between 0.333MW and 6.32 MW.

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- The case study distribution system modeled with **DigSielent** software is shown in Figure 1.
- The peak loading levels of the two feeders (feeder-3 and feeder-4) is **6.32MW** and the average load is **2.972MW [4]**.
- There is one 230kV main bus that corresponds to bus S1/D1_swab1 from Figure 1 which is connected to the 15KV supply point through substation transformer.
- There are four main feeders and each has 15kV voltage rating:
    - Amanuel line 1, Lumame line 2,
    - Debre Markos line 3, and Debre Markos line 4, and
    - All the feeders operate as radial system.

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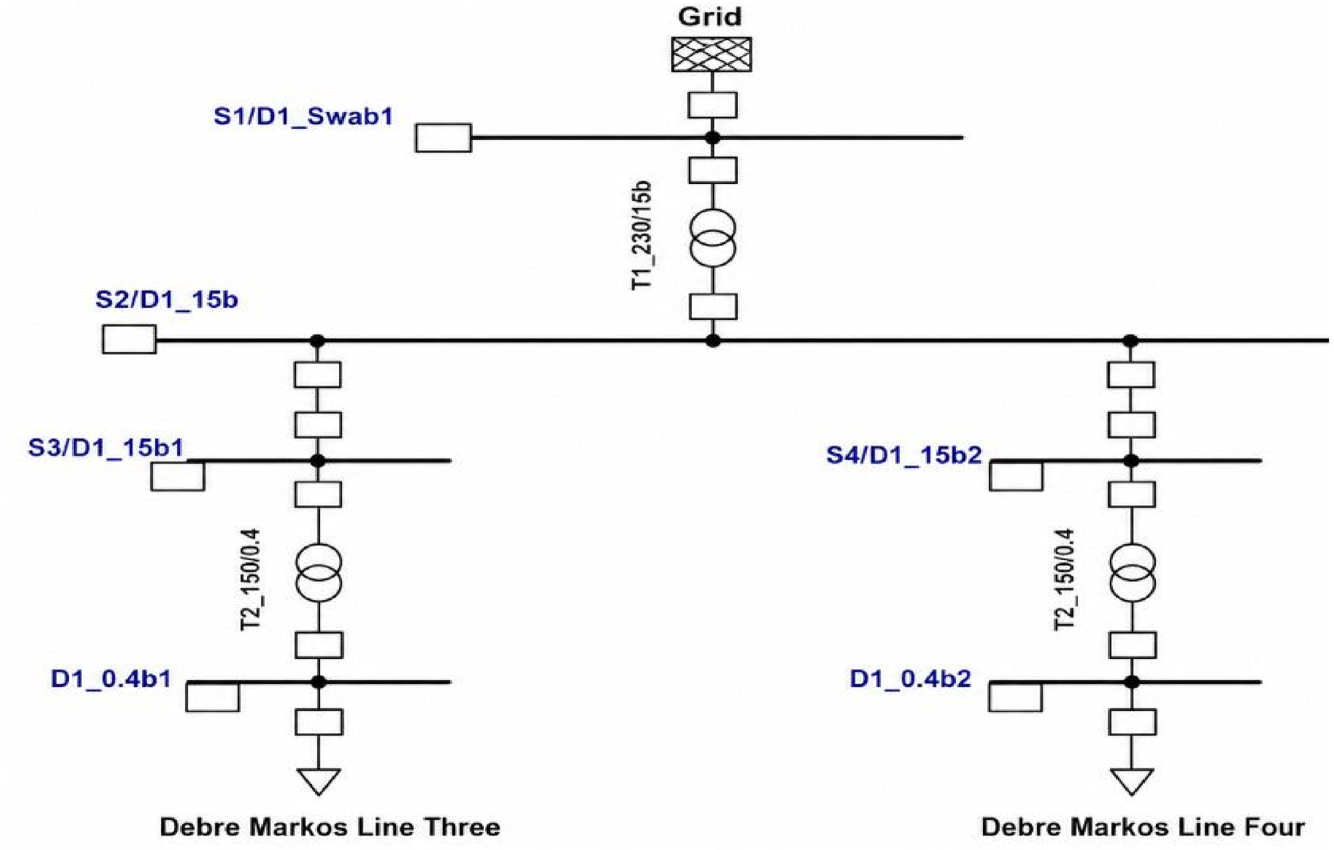

Figure 1: Debremarkos Town Power Supply Feeders (Feeder 3 and Feeder 4) [4].

3. Reliability Data Collection

- The following key data were collected directly from field measurements and utility records during the study period:
  - Major sources of power interruptions:
    - Feeder faults and equipment failures,
    - Weather-related events,
    - Scheduled maintenance, and external disturbances
  - Total number of interruptions recorded within a single calendar year
  - Total number of customers affected by each interruption event
  - Duration of each interruption event (restoration time and outage duration)

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- Based on the field data collected, the major causes of power interruptions recorded at the Debre Markos substation site are classified as follows:
  - Distribution permanent earth fault (DPEF)
  - Distribution permanent short circuits (DPSC)
  - Distribution transient earth fault (DTEF)
  - Distribution transient short circuit (DTSC)
  - Distribution Line Over Load (DLOL) and others like generation, transmission problems and operational or intentional isolation.

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- From historical data of the past years, major cause of outages, occurrences, and durations in the system is being evaluated and presented in **Table 1** and **Table 2**.

Table 1: Causes of outage and number of occurrences in Debre Markos line-3 and 4 [4].

System	Total Number of Customers	Number of Interuption					
		DPEF	DPSC	DTEF	DTSC	DLOL	**Total**
Feeder 3	6541	116	74	116	64	320	690
Feeder 4	4129	57	45	53	49	242	446
Total	**10670**	173	119	169	113	562	1136

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- The interruption durations, expressed in hours for each previously recorded outage occurrence shown in **Table 1**, are presented in **Table 2**.

Table 2: Causes of outage and interruption duration in Debre Markos line-3 and 4 [4].

System	**Interuption Duration in Hours**					
	DPEF	DPSC	DTEF	DTSC	DLOL	**Total**
Feeder 3	134.92	178.45	4.467	3.167	298	619.001
Feeder 4	142.43	118.10	2.717	2.033	260.08	525.366
Total	277.35	296.55	7.184	5.20	558.08	1144.37

4. Reliability Performance Evaluation

- Reliability performance evaluation is the process of assessing how effectively a power distribution system delivers continuous electrical service to customers with minimum interruptions.
- The objective is to quantify the quality of service provided by the utility and identify areas requiring improvement.
- For the Debre Markos distribution system, reliability performance is evaluated using:
  - SAIFI (System Average Interruption Frequency Index)
  - SAIDI (System Average Interruption Duration Index)
  - CAIDI (Customer Average Interruption Duration Index)
  - ASAI (Average Service Availability Index)

Quantifying Reliability Indices

1. **Feeder 3**

A. Failure Rate: From the data in Table 1, the failure rate is:

$$\lambda_3 = \underline{\mathbf{690}} \text{ failures/year}$$

B. Annual Outage Time: Similarly from Table 2, the total outage duration is:

$$U_3 = \underline{\mathbf{619.001}} \text{ hr/year}$$

C. Average Repair Time: The average time for every outage recorded is:

$$r_3 = \frac{U_3}{\lambda_3} = \frac{619.001}{690} = \mathbf{0.8971}\ hour/failurs/year$$

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D. Availability Index:

$$ASAI_3 = \frac{Total\ hours\ in\ a\ year - Anual\ Outage\ duration}{Total\ hours\ in\ a\ year}$$

$$ASAI_3 = \frac{8760 - 619.001}{8760} = 0.9293 \text{ or } ASAI_3 = 92.93\%$$

E. Unavailability Index:

$$ASUI_3 = 1 - ASAI_3$$

$$ASUI_3 = 1 - 0.9293 = 0.0707$$

$$ASUI_3 = 7.07\%$$

- Feeder 3 is unavaliable in 7.07% of the year.

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F. SAIFI: For Feeder 3the system average interruption frequency index is:

$$SAIFI_3 = \frac{\lambda_3 \times N_i}{N_i} = \frac{690 \times 6541}{6541} = \mathbf{690}\ \text{interruptions/customer/year}$$

G. SAIDI: The system average interruption duration index is:

$$SAIDI_3 = \frac{U_3 \times N_i}{N_i} = \frac{619.001 \times 6541}{6541} = \mathbf{619}\ hours/\text{customer/year}$$

H. CAIDI: The customer average interruption duration index is:

$$CAIDI_3 = \frac{SAIDI_3}{SAIFI_3} = \frac{619.001}{690} = \mathbf{0.897}\ hours/interruption$$

- Since the feeder is radial all the customers are affected by feeder 3 interruption.

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2. **Feeder 4**

A. Failure Rate: From the data in **Table 1**, the failure rate of feeder 4 is:

λ_4 = **446** failures/year

B. Annual Outage Time: Similarly from **Table 2**, the total outage duration is:

U_4 = **525.37** hr/year

C. Average Repair Time: The average time for every outage recorded is:

$$r_4 = \frac{U4}{\lambda 4} = \frac{525.37}{446} = \mathbf{1.1780}\ hour/failurs/year$$

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D. Availability Index:

$$ASAI_4 = \frac{Total\ hours\ in\ a\ year - Anual\ Outage\ duration}{Total\ hours\ in\ a\ year}$$

$$ASAI_4 = \frac{8760-525.37}{8760} = 0.94003 \text{ or } ASAI_4 = \mathbf{94.003}\%$$

E. Unavailability Index:

$$ASUI_4 = 1 - ASAI_4$$

$$ASUI_4 = 1 - 0.94003 = \mathbf{0.05997}$$

$$ASUI_4 = \mathbf{5.997}\%$$

- Feeder 4 is unavaliable in **5.997%** of the year.

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F. SAIFI: For Feeder 4, the system average interruption frequency index is:

$$SAIFI_4 = \frac{\lambda_4 \times N_i}{N_i} = \frac{446 \times 4129}{4129} = \mathbf{446}\ \text{interruptions/customer/year}$$

G. SAIDI: The system average interruption duration index is:

$$SAIDI_4 = \frac{U_4 \times N_i}{N_i} = \frac{525.37 \times 4129}{4129} = \mathbf{525.37}\ hours/\text{customer/year}$$

H. CAIDI: The customer average interruption duration index is:

$$CAIDI_4 = \frac{SAIDI_4}{SAIFI_4} = \frac{525.37}{446} = \mathbf{1.178}\ hours/interruption$$

- Since feeder-4 is radial all the customers are affected by the feeder interruption.

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3. **Overall System Reliability Indices**

   A. **System SAIFI:**

$$SAIFI = \frac{\sum \lambda_i N_i}{N_T} = \frac{(690\times6541)+(4129\times446)}{6541+4129} = \mathbf{595.6}\ \text{interruptions/customer/year}$$

   B. **System SAIDI:**

$$SAIDI = \frac{\sum N_i \times D_i}{N_T} = \frac{(619.001\times6541)+(4129\times525.37)}{6541+4129} = \mathbf{582.88}\ hours/\text{customer/year}$$

   C. **System CAIDI:**

$$CAIDI = \frac{SAIDI}{SAIFI} = \frac{582.88}{595.6} = \mathbf{0.979}\ hours/interruption$$

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D. System ASAI

$$ASAI = \frac{N_T \times 8760 - \sum N_i D_i}{N_T \times 8760} = 1 - \frac{(619.001 \times 6541) + (4129 \times 525.37)}{10670} = 0.93346$$

$$\boldsymbol{ASAI = 93.346\%}$$

E. System ASUI

$$ASUI = 1 - ASAI$$

$$ASUI = 1 - 0.93346 = 0.0665$$

$$\boldsymbol{ASUI = 6.65\%}$$

- The system is unavailable **6.65%** of the year.

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4. Outage Frequency Contribution

- For Feeder 3: $\%Contribution = \frac{\lambda_3}{\lambda_3+\lambda_4} \times 100 = \frac{690}{690+446} \times 100 = \mathbf{60.74\%}$

- For Feeder 4: $\%Contribution = \frac{\lambda_4}{\lambda_3+\lambda_4} \times 100 = \frac{446}{690+446} \times 100 = \mathbf{39.26\%}$

5. Outage Duration Contribution

- For Feeder 3: $\%Contribution = \frac{U_3}{U_3+U_4} \times 100 = \frac{619}{619+525.37} \times 100 = \mathbf{54.09\%}$

- For Feeder 4: $\%Contribution = \frac{U_4}{U_3+U_4} \times 100 = \frac{525.37}{619+525.37} \times 100 = \mathbf{45.91\%}$

- More than half of the total annual outage duration originates from Feeder 3.

Result Summary

Table 3: Reliability Evaluation Summary.

No.	Index	Feeder 3	Feeder 4	System
1.	Number of Customers	6541	4129	10670
2.	Failure Rate, λ (failures/year)	690	446	1136
3.	Repair Time, r (hr/failure)	0.897	1.178	0.979
4.	Outage Time, U (hr/year)	619	525.37	1144.37
5.	SAIFI (int./cust./yr)	690	446	595.58
6.	SAIDI (hr/cust./yr)	619	525.37	582.88
7.	CAIDI (hr/int.)	0.897	1.178	0.979
8.	ASAI (%)	92.93	94.003	93.37
9.	ASUI (%)	7.07	5.997	6.65

5. Interpretation of Results

- **Feeder 3** is the least reliable feeder because it has the highest outage frequency (690 outages/year) and the lowest availability (92.93%).
- **Feeder 4** experiences fewer outages but longer restoration times.
- **The system-wide** SAIFI (595.58 interruptions/customer/year) and SAIDI (582.88 hr/customer/year) are extremely high compared with typical utility standards since the outage records many switching, operational, or momentary events in addition to sustained interruptions.
- **Feeder 3** should be prioritized for reliability improvement through maintenance, feeder automation, sectionalizing switches, and operational practice improvements.

6. Reliability Benchmarks

- The values below are representative ranges reported by utilities and regulatory agencies.

Table 4: Worldwide Reliability Performance Benchmarks.

Countries	SAIFI	SAIDI	CAIDI	ASAI(%)	Availability
Japan	0.10-0.20	0.1-0.3	0.5-1.5	99.97-99.99	>99.99
France	0.30-0.80	0.50-1.50	1.0-2.0	99.98-99.99	>99.98
USA	1.00-1.50	1.50-4.00	1.0-3.0	99.95-99.99	99.95-99.99
South Africa	5.00-20.0	20.0-100-0	2.0-8.0	98.0-99.5	98.0-99.5
Ethiopia	20.0-200.0	50.0-1000	2.0-10.0	85.0-98.0	85.0-98.0
Debremarkos Feeder 3	690.00	619.00	0.897	92.93	92.93
Debremarkos Feeder 4	446.00	525.37	1.178	94.00	94.00
Debre Markos System	595.58	582.88	0.979	93.35	93.35

Final Remarks

- **According to the international reliability Benchmarks:**
  - The Debre Markos system exhibits a significantly higher interruption frequency than international benchmarks and even exceeds the typical range observed in Ethiopian distribution systems.
  - The annual outage duration is substantially higher than those of developed countries and falls within the higher end of the range commonly reported for developing distribution networks
  - Despite the high outage frequency, the restoration time per interruption is relatively short and comparable to that of developed countries.
  - This suggests that the major reliability issue is outage frequency rather than repair efficiency.
  - The overall availability of the Debre Markos system is considerably below international utility standards.

7. Reliability Improvement Recommendations

- **Recommended Reliability Improvements**
  - Install sectionalizing switches along Feeder 3 and Feeder 4.
  - Implement feeder automation and SCADA systems.
  - Strengthen preventive maintenance programs.
  - Improve operational procedures and switching practices.
  - Enhance vegetation management.
  - Upgrade aging distribution equipment.
  - Introduce fault indicators for faster fault location.

Course Summary (Weeks 1–14)

- This course provided a comprehensive understanding of Power Quality and Reliability, focusing on the analysis, assessment, mitigation, and improvement of power system performance.
- The course is structured into two major parts:
  - **Part I - Power System Quality (Weeks 1–8):** This part focuses on power quality phenomena, disturbances, standards, analysis techniques, and mitigation methods used to ensure the delivery of high-quality electrical power..
  - **Part II - Power System Reliability (Weeks 9–14):** This part focuses on reliability concepts, reliability assessment methodologies, system adequacy and security, reliability indices, and practical techniques for evaluating and improving power system reliability.

Course Assessment and Evaluation

- The overall course grade is determined based on continuous assessment and final examination components as follows:

Table 5: Assessment Breakdown.

No.	Assesment Type	Weight (%)
1.	Individual Assignment	10
2.	Project Work	15
3.	Presentation	5
4.	Mid-Term Examination	20
5.	Final Examination	50
	Total	**100**

References

[1]. Ethiopian Power Sector Authority (PEA), Distribution System Reliability Performance Standards and Benchmark Guidelines, Addis Ababa, Ethiopia, 2023.

[2]. T. T. Tadesse and A. A. Alemu, "Reliability assessment of Wolkite City distribution network using customer-oriented reliability indices," International Journal of Engineering Research and Technology, vol. 11, no. 12, pp. 243–251, 2022.

[3]. M. A. Mekonnen and B. G. Assefa, "Reliability assessment and enhancement of Dangila distribution system with distribution generation," Cogent Engineering, vol. 10, no. 1, pp. 1–15, 2023.

[4]. D. M. Teferra and A. J. Godebo, "Reliability assessment of Debremarkos distribution system found in Ethiopia," International Journal of Science, Technology and Society, vol. 4, no. 2, pp. 34–41, 2016.

Thank You!