

Power System Quality and Reliability

ECEg-6312

WEEK 13

Introduction to System Modes of Failure

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June 2026

Topic Overview

- This topic focuses on the analytical methods used to evaluate power system failure behavior and reliability performance under different operating conditions.
- This lecture covers:
 1. The loss of load approach
 2. Frequency & duration approach
 3. Spare value assessment
 4. Multiple bridge equivalents.

Learning Outcomes

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

- Explain different system modes of failure in power systems
- Apply loss of load techniques for reliability assessment
- Calculate failure frequency and outage duration indices
- Assess the value of reserve generation capacity
- Model complex reliability networks using bridge equivalent methods

1. Introduction

- Modern power systems are expected to supply electrical energy continuously with acceptable levels of quality, reliability, and security [1], [2].
- However, practical systems are subject to various disturbances and component failures such as:
 - Generator outages, Transmission line faults, Transformer failures,
 - Equipment aging, Maintenance activities, and unpredictable load variations.
- When one or more components fail, the system may experience operating conditions that lead to reduced service quality or complete interruption of power delivery [2].
- Therefore, understanding the modes of system failure is essential for planning, operation, and reliability evaluation of power systems.

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- System failure analysis aims to answer important questions regarding system failures and power system reliability analysis:
 - How often does failure occur?
 - How long does the interruption last?
 - What amount of load may be lost?
 - What economic impact results from outages?
 - How much reserve capacity is required?
- Power system reliability studies generally evaluate two major aspects:
 - Adequacy and Security

A. Adequacy

- Adequacy is the ability of a power system to supply the aggregate electrical demand and energy requirements of customers at all times while considering planned and unplanned outage [1], [3].
- It evaluates whether sufficient resources are available to meet the expected demand under normal operating conditions.
- Main Objectives of Adequacy Assessment
 - Ensure sufficient generation capacity and also maintain required reserve margins
 - Provide adequate transmission capability
 - Meet customer load demand continuously
 - Reduce the probability of power shortages

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- Components Considered in Adequacy Studies
 - **Generation System**
 - Generator availability, Unit outage rates, and Capacity reserve margins
 - **Transmission System**
 - Transmission line availability, Transformer capacity limits, Power transfer capability
 - **Load Characteristics**
 - Load forecasting uncertainty, Peak demand variation, Seasonal load behavior
- Adequacy condition: If $P_{Available} < P_{Demand}$, system is inadequate and **load curtailment** may occur.

$$P_{Available} \geq P_{Demand}$$

B. Security

- Security is the ability of a power system to withstand sudden disturbances or unexpected component failures while continuing to operate within acceptable stability and operating limits [1].
- Unlike adequacy, which focuses on whether sufficient resources exist, security focuses on the system's capability to survive disturbances without widespread interruption or instability.
- Objectives of Security Assessment [1], [3].
 - Maintain system stability during disturbances and preventing it from cascading failures
 - Minimize service interruptions
 - Keep voltage and frequency within allowable limits
 - Ensure continuous operation after component outages

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- Disturbances Affecting System Security
 - **Generation Disturbances**
 - Generator tripping, Sudden generation loss, Governor malfunction
 - **Transmission Disturbances**
 - Transmission line outages, Short-circuit faults, Transformer failures
 - **Load Disturbances**
 - Sudden large load increase, Rapid load shedding, Uncertain load behavior
- Security Criterion: A power system should continue operating satisfactorily even if one major component fails.

$$P_{Generation} - P_{outage} \geq P_{Load}$$

2. Loss of Load Approach

- The Loss of Load Approach is one of the most widely used probabilistic methods for evaluating generation system adequacy in power systems.
- It determines the likelihood that the available generation capacity will be insufficient to satisfy the system load demand.
- This approach is particularly important in generation planning, reserve assessment, and reliability evaluation of isolated and interconnected power systems.
- Loss of load condition occurs whenever [1]:

$$P_{\text{load}} > P_{\text{available}}$$

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- Under the condition $P_{\text{load}} > P_{\text{available}}$, the system may experience:
 - Load shedding
 - Customer interruption
 - Energy curtailment
 - Voltage reduction
 - System emergency operation
- Objectives of the Loss of Load Method
 - Estimate probability of supply shortages
 - Determine required reserve capacity
 - Evaluate generation adequacy
 - Support generation expansion planning
 - Quantify system reliability performance
- Main Reliability Indices:
 - Loss of Load Probability (LOLP)
 - Loss of Load Expectation (LOLE)
 - Expected Energy Not Supplied (EENS)

3. Frequency and Duration Approach

- The Frequency and Duration Approach is a reliability evaluation method used to determine [1]:
 - How often system failures occur
 - How long interruptions last
- Unlike the Loss of Load Approach, which mainly evaluates the probability of insufficient generation, this method provides additional information regarding the occurrence rate and restoration time of outages.
- It is widely used in generation, transmission, and distribution reliability assessment which is discussed in detail in our Week 12 lecture.

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- Procedure of Frequency and Duration Analysis

- Identify system components
- Obtain failure rates and repair times
- Develop system reliability model
- Calculate outage frequency
- Determine interruption duration
- Compute system reliability indices

- Requires detailed outage statistics.

- Common Reliability Indices of Frequency and Duration Method:

- **SAIFI:** System Average Interruption Frequency Index
- **SAIDI:** System Average Interruption Duration Index
- **CAIDI:** Customer Average Interruption Duration Index
- **ASAI:** Average Service Availability Index
- The Frequency and Duration Method is Complex for large interconnected systems and need computer tool and software assistance.

A. SAIFI

- **SAIFI (System Average Interruption Frequency Index):** is a widely used reliability index that measures the average number of interruptions experienced by a customer during a specified period, usually one year [4].
- It indicates how frequently customers experience power outages in a distribution or power system.
- **SAIFI represents:** The average interruption frequency per customer served **(Outages/customer/year)**.
- **A lower SAIFI value indicates:**
 - Better system reliability, fewer customer interruptions, and Improved continuity of service

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- The primary mathematical expression of **SAIFI** is formulated as [4]:

$$SAIFI = \frac{\sum N_i}{N_T}$$

- Where:
 - N_i : The number of customers interrupted by a specific power outage or failure event.
 - N_T : The total number of customers served by the utility system or target region.
- Alternative Formulations: SAIFI also formulated in two different alternative forms.
 - Failure Rate Formulation and
 - Relationship with Other Reliability Indices

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1. Failure Rate Formulation: When individual location-based failure rates (λ_i) are known, SAIFI can be modeled using individual component failure metrics [4]:

$$SAIFI = \frac{\sum \lambda_i N_i}{N_T}$$

- Where: λ_i is the failure rate (number of failures per year) at location or component (i).
- N_i : The number of customers affected by a failure at location (i).

2. Relationship with Other Reliability Indices: SAIFI can also be calculated if the system's total interruption duration (SAIDI) and customer average restoration time (CAIDI) are known:

$$SAIFI = \frac{SAIDI}{CAIDI}$$

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- The resulting value is expressed in units of interruptions per customer per year.
- According to IEEE Standard 1366, any momentary power drop lasting less than up to 5 minutes is strictly excluded from SAIFI calculations and tracked separately under momentary metrics.
- The Momentary Average Interruption Frequency Index (MAIFI) is an electrical reliability index that tracks brief power flickers.
- It measures the average number of momentary interruptions a customer experiences over a specific period (typically one year).

$$MAIFI = \frac{\sum I_m N_m}{N_T}$$

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- **Where:**

- I_m : The number of momentary interruption events (flickers) caused by a specific disturbance (m):
- N_m : The number of customers affected by that specific momentary event (m).
- N_T : The total number of customers served by the utility system.

- **Time Limit:** According to IEEE Standard 1366, a momentary interruption is an outage lasting less than 5 minutes.

- **The Threshold:** If power returns in under 5 minutes, it counts toward **MAIFI**.

- If it takes longer than 5 minutes, it becomes a sustained outage and counts toward **SAIFI**.

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- According to **IEEE Standard 1366**, there are no specific, mandatory target values or strict limits for SAIFI and MAIFI.
- Instead, it serves strictly as a standardized math and methodology guide so that utilities across the globe define, measure, and calculate these indices identically.
- **Actual targets, thresholds**, or acceptable values are regulated and enforced by localized government entities—such as state Public Utility Commissions (PUCs).
- **Typical Benchmark Values:** SAIFI (0.50 to 1.50) interruptions per customer per year and MAIFI (1.00 to 5.00) interruptions per customer per year.

B. SAIDI

- **SAIDI (System Average Interruption Duration Index):** is a reliability index used to measure the average outage duration experienced by customers during a specified period, usually one year [4].
- It indicates the total time customers remain without electrical service due to system interruptions.
- **SAIDI represents:** The average total interruption duration for each customer served.
- A lower SAIDI value indicates:
 - Faster restoration of service
 - Better system reliability
 - Improved maintenance and operational efficiency

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- **Mathematical Expression:**

$$SAIDI = \frac{\sum N_i \times D_i}{N_T}$$

- **Where:**

- N_i = Number of interrupted customers for outage i
- D_i = Duration of outage i
- N_T = Total number of customers served
- **Units:** Hours/customer/year or Minutes/customer/year.
- Low SAIDI refers to short outage durations and SAIDI = 0 refers to no interruption duration.

C. CAIDI

- **CAIDI (Customer Average Interruption Duration Index):** is a reliability index used to measure the average time required to restore service to customers affected by interruptions.
- It indicates how quickly utility operators can repair faults and restore electrical service.
- CAIDI represents: The average outage duration experienced by interrupted customers.
- A lower CAIDI value indicates [1]:
 - Faster service restoration
 - Efficient maintenance operation
 - Improved fault management

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- **Mathematical Expression:**

$$CAIDI = \frac{\sum N_i \times D_i}{\sum N_i} = \frac{SAIDI}{SAIFI}$$

- **Where:**

- N_i = Number of interrupted customers for outage i
- D_i = Duration of outage i
- SAIFI = System Average Interruption Frequency Index

- **Units:** Hours/Interruption or Minutes/Interruption.

- Low CAIDI refers to Fast restoration and CAIDI = 0 refers to no interruption.

D. ASAI

- **ASAI (Average Service Availability Index):** is a reliability index used to measure the fraction of time that electrical service is available to customers during a specified period, usually one year.
- It represents the overall service continuity performance of a power system.
- **ASAI indicates:** The probability that the power system is available and capable of supplying customers when required [1], [4].
- **A higher ASAI value indicates:** Better system reliability,
 - Higher service continuity
 - Fewer customer outage hours

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- **Mathematical Expression:**

$$ASAI = \frac{\text{Customer Hours Available}}{\text{Customer Hours Demanded}} = \frac{N_T \times 8760 - \sum N_i D_i}{N_T \times 8760}$$

- **Where:**

- N_i = Number of sustained interrupted customers for outage i
- D_i = Duration of outage i
- N_T = Total number of customers served
- **Units:** ASAI is dimensionless and usually expressed as: Decimal value or Percentage (%)
- ASAI close to 1 refers to very high reliability, low ASAI mean poor service continuity.

Example

- A **municipal electric utility** operates a single radial distribution feeder that provides electricity to a residential suburb serving a total of 2,000 customers. Over a standard tracking period of one calendar year (consisting of 365 days), the utility's Supervisory Control and Data Acquisition (SCADA) system logged exactly three separate network disturbance events on this feeder:

Table 1: Customer Power Supply Information.

Event	Type	Affected Customers (N)	Duration (D)	Interruption Multiplier (I_i)
Event 1 (Jan 15)	Sustained	400 customers	2.0 hours	1 (Sustained)
Event 2 (May 22)	Momentary	600 customers	20 seconds	2 breaker operations (flickers)
Event 3 (Oct 09)	Sustained	200 customers	1.5 hours	1 (Sustained)

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- Using the definitions and guidelines established in IEEE Standard 1366, calculate the following system reliability performance indices for this evaluation year:
 1. **SAIFI** (System Average Interruption Frequency Index) in interruptions per customer.
 2. **SAIDI** (System Average Interruption Duration Index) in minutes per customer.
 3. **MAIFI** (Momentary Average Interruption Frequency Index) in flickers per customer.
 4. **CAIDI** (Customer Average Interruption Duration Index) in minutes per customer interruption.
 5. **ASAI** (Average Service Availability Index) as a percentage up to four decimal places.

Solution

1. SAIFI (System Average Interruption Frequency Index):

$$SAIFI = \frac{\sum N_{sustained}}{N_T} = \frac{400+200}{2000} = 0.3 \text{ interruptions/customer/year}$$

- **Meaning:** The average customer on this system experienced **0.3 sustained** power outages this year.

2. SAIDI (System Average Interruption Duration Index):

$$SAIDI = \frac{\sum N_{sustained} \times D}{N_T} = \frac{400 \times 2 + 200 \times 1.5}{2000} = 0.55 \text{ hours/year}$$

- **Meaning:** The average customer spent **33 minutes** without power over the course of the year.

3. MAIFI (Momentary Average Interruption Frequency Index):

$$MAIFI = \frac{\sum N_{mom} \times I_m}{N_T} = \frac{2 \times 600}{2000} = 0.6 \text{ momentary interruption per customer per year}$$

Solution

- **Meaning:** The average customer experienced 0.6 power "flickers" (lasting under 5 minutes) this year.

4. CAIDI (Customer Average Interruption Duration Index):

$$CAIDI = \frac{\sum N_{sustained} \times D}{\sum N_{sustained}} = \frac{400 \times 2 + 200 \times 1.5}{400 + 200} = 1.833 \text{ hours/interruptions}$$

- **Meaning:** When an outage actually occurred, it took the utility an average of 1 hour and 50 minutes to restore power to those affected.

5. ASAI (Average Service Availability Index):

$$ASAI = \frac{\text{Customer Hours Available}}{\text{Customer Hours Demanded}} = \frac{N_T \times 8760 - (N_{sustained} \times D)}{N_T \times 8760} = \frac{2000 \times 8760 - (400 \times 2 + 200 \times 1.5)}{2000 \times 8760} = 0.999937$$

- **Meaning:** The grid successfully delivered electricity **99.9937%** of the time it was demanded over the year.

4. Spare Value Assessment

- **Spare Value Assessment** is a reliability and economic evaluation method used to determine the importance and economic benefit of maintaining additional reserve capacity in a power system.
- The **spare capacity**, also called reserve margin or standby generation, improves system reliability by ensuring that sufficient power remains available during component outages, maintenance conditions, or sudden load increases.
- A power system must maintain **reserve generation capacity** above the expected load demand to ensure reliable operation.

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- **The spare capacity is defined as:**

$$\text{Spare Capacity} = (\text{Installed Capacity} - \text{Peak Load})$$

- **Where:**

- Installed Capacity = Total available generation capacity
- Peak Load = Maximum system demand

- **Spare generation capacity helps to:**

- Improve system reliability, Reduce loss of load probability,
- Support emergency operation, Handle sudden load increases,
- Compensate for generator outages, and Maintain system frequency stability

Reserve Margin

- Reserve margin is one of the most important indices in spare value assessment.

$$RM(\%) = \frac{\text{Installed Capacity} - \text{Peak Load}}{\text{Peak Load}}$$

- **Example:** Suppose a power system has an installed generation capacity of 1200 MW and a peak load demand of 1000 MW. Determine the spare capacity and the reserve margin.
- Spare Capacity = 1200 – 1000 = 200MW.
- Reserve Margin = $\frac{200}{1000} \times 100 = 20\%$.
- Thus, the system has a Spare capacity of **200 MW** and a Reserve margin of **20%**.

Economic Evaluation of Spare Capacity

- The economic evaluation of spare capacity is based on achieving a balance between:
 - Reliability improvement
 - Economic efficiency
- As reserve capacity increases:
 - Reliability improves
 - Loss of load probability decreases
 - Customer interruption cost decreases
 - However, Investment and operating costs increase
- Therefore, the optimal reserve margin is selected at the minimum total cost point.

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- Main Cost Components of Spare Capacity Includes:

1. Reserve Capacity Cost (C_R)

- This cost increases with additional reserve generation.
- Includes: Capital investment, Fuel cost, Maintenance cost, and Operating reserve cost

2. Outage Cost (C_O)

- This cost decreases as reserve capacity increases.
- Includes: Customer interruption losses, Industrial production loss, Commercial losses, and Unsupplied energy cost

Cont'd...

- The total system cost becomes:

$$C_T = C_R + C_O$$

Where:

- C_T = Total cost
- C_R = Reserve capacity cost
- C_O = Outage cost and R = Reserve capacity
- The optimum reserve occurs where:

$$\frac{dC_R}{dR} = \frac{dC_O}{dR}$$

- Marginal reserve investment equals marginal reliability benefit.

Exercise

- A utility company is planning the reserve capacity requirement of a power system in order to improve reliability while minimizing the total annual operating cost. The system peak load demand is 1000MW, study period 1 year, and additional reserve generation costs \$15,000/MW-year.
 1. Calculate Spare Capacity, Reserve Capacity Cost, and Total Annual Cost for each cases.
 2. Analyze and interpret the results under each scenario and your final engineering conclusion.

Table 2: Reserve margin, installed capacity, and outage cost information of a utility company.

Cases	Reserve Margin	Installed Capacity	Expected Outage Cost
Case 1	10%	1100MW	\$8 million
Case 2	20%	1200MW	\$3 million
Case 3	30%	1300MW	\$1 million

5. Multiple Bridge Equivalents

- The Multiple Bridge Equivalent Method is a reliability evaluation technique used to simplify complex interconnected system networks into equivalent reliability models for easier analysis [1].
- Large power systems contain many interconnected components such as: Generators, Transmission lines, Transformers, Switching stations, and Tie-lines
- Direct reliability evaluation of such systems can become mathematically complex.
- Therefore, bridge equivalent methods are used to reduce the network into simpler equivalent structures while preserving the overall reliability characteristics.

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- A bridge network is a system configuration in which power can flow through multiple alternative paths between the source and the load as in **Figure 1**.
- These alternative paths improve system reliability because failure of one component may not completely interrupt supply [5].

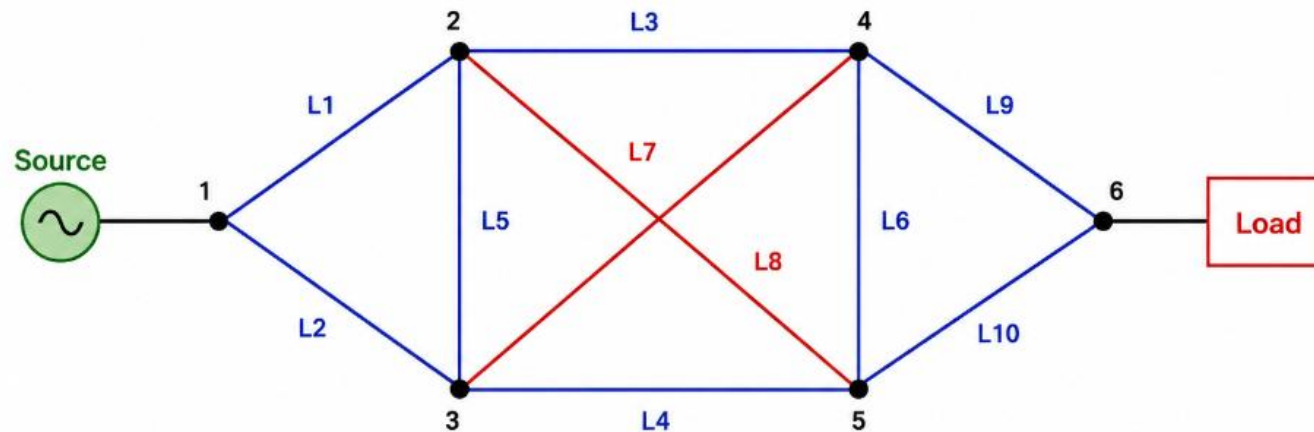


Figure 1: Bridge Network.

Example

- Reliability Evaluation of a Simple Bridge Network: Consider the following bridge network connecting a source to a load. The system contains five transmission components: R1, R2, R3, R4, AND R5 as shown in **Figure 2**. Please compute the system reliability.

Table 2: Network Reliability Values.

Line	Reliability	Line	Reliability
R1	0.90	R4	0.92
R2	0.85	R5	0.80
R3	0.88	R _{sym}	??

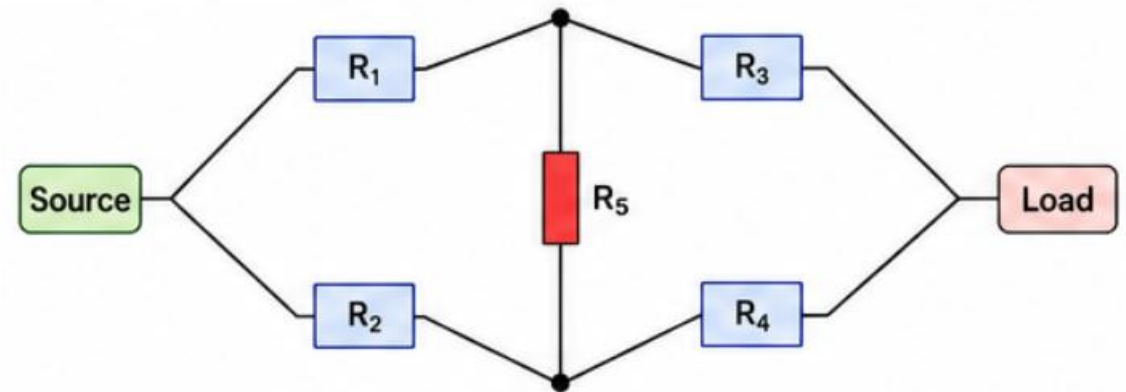


Figure 2: Sample Bridge Network.

Solution

- Apply Decomposition (Total Probability Theorem): To eliminate a bridge component B, evaluate the system under two mutually exclusive conditions:

1. **Case 1:** The bridge component works perfectly ($R_5 = 1$). In this state, the node before the bridge and the node after the bridge are combined into a single, perfectly connected node.

- R_1 & R_2 are connected in parallel and also R_3 & R_4 .
- Their final equivalent circuit is connected in series

$$R_{A_1} = 1 - (1 - R_1)(1 - R_2) = 0.985 \text{ and } R_{A_2} = 1 - (1 - R_3)(1 - R_4) = 0.9904$$

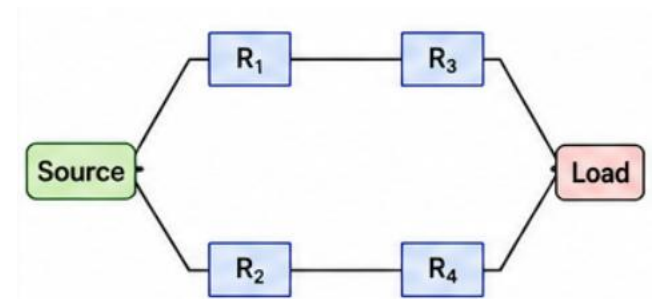
- Since their equivalent is connected in series and the final reliability value under this case is:

$$\mathbf{R_A = R_{A_1} \times R_{A_2} = 0.9755}$$

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2. **Case 2:** The bridge component fails ($R_5 = 0$). In this state, the bridge component is removed entirely from the network (open circuit).

- R_1 & R_3 are connected in series and also R_2 & R_4 .
- Their final equivalent circuit is connected in parallel



$$R_{B_1} = R_1 R_3 = 0.792 \text{ and } R_{B_2} = R_2 R_4 = 0.782$$

- Since their equivalent is connected in parallel and the final reliability value under case 2 is:

$$R_B = 1 - (1 - R_{B_1}) \times (1 - R_{B_2}) = 0.9547$$

- The overall system reliability (R_{sys}) is calculated using the Total Probability Theorem [1], [5]:

$$R_{sys} = R_5 R_{A(works)} + (1 - R_5) R_{B(fails)} = 0.8 \times 0.9755 + (1 - 0.8) \times 0.9547 = 0.971$$

References

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Thank You!