Power System Quality and Reliability

ECEg-6312

WEEK 10

Generator System Reliability Analysis

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Topic Overview

- This lecture introduces analytical tools for reliability assessment of generation systems, focusing on:
  1. Probability models for generators unit and loads
  2. Reliability analysis of isolated and interconnected system
  3. Corporate model (Capacity Outage Probability Table – COPT)
  4. Generator system cost analysis
  5. Energy transfer and off peak loading

Learning Outcomes

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

- Model generator outages using probabilistic techniques
- Evaluate generation adequacy
- Analyze isolated vs interconnected system reliability
- Compute generation cost-reliability trade-offs
- Apply capacity outage probability methods

1. Introduction

- Electrical power systems are evolving into highly interconnected networks, Renewable-dominated generation mixes, and Demand-sensitive and stochastic systems [1].
- Ensuring reliable generation is now more complex and critical than ever
- Why Generator Reliability Matters? The generation subsystem must:
    - Continuously meet load demand,
    - Maintain system stability and security, and
    - Prevent loss of load and blackouts
- Generator failures directly impact system adequacy

Nature of Generator Behavior

- Generators are complex, repairable, and stochastic systems whose operational behavior is governed by:
  - **Random failures:** Generator outages occur unpredictably
  - **Maintenance and repair processes:** Generators are not permanently failed but Restored through corrective and preventive maintenance
  - **Operational constraints:** fuels and skilled man power
  - **Two-State Representation:** (State 0: Operating (Available) and State 1: Failed (Unavailable)
- Their behavior must be analyzed using probabilistic and Markov process reliability models.

2. Probabilistic Modeling of Generator Units

- Power system **generation adequacy analysis** requires probabilistic representation of both:
    - Generator behavior
    - Load demand uncertainty
- Since generation and load vary randomly with time, deterministic methods alone are insufficient.
- Generators are modeled using [1], [2]:
    - Failure probability
    - Repair probability
    - Availability states
- This allows realistic evaluation of generation adequacy and availability.

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1. Two-State Model:

- A generator is assumed to exist in one of two mutually exclusive states [2]:
  - **State 0 (Up State):** Generator is fully operational
  - **State 1 (Down State):** Generator is failed and unavailable
- State Transition Structure
  - **Up → Down:** Failure rate **λ**...............System or component fails due to fault or scheduled maintenance.
  - **Down → Up**: Repair rate **μ**................System or components are restored and fully functioned.
- Forms a continuous-time Markov process and it is the simplest model.

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2. Multi-State Model

- **Real generators** often operate in more than two states:
  - **State 0:** Full capacity operation (100%).........**Outage** → **Full** (repair and restoration)
  - **State 1:** Partial (derated) operation.................**Full** → **Partial** (degradation, maintenance, fuel issues)
  - **State 2:** Forced outage (0% output)................**Partial** → **Outage** (failure escalation)
- **Key Features:**
  - Captures performance degradation
  - Reflects real operational behavior
  - Supports more accurate reliability assessment

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- **Generator reliability modeling:** Evolves from a simple **binary representation** (Up/Down) to a **multi-state framework** that captures **real operational behavior** and performance degradation.
- **Two-state model:**
  - Good for system-level approximation
- **Multi-state model essential for:**
  - Renewable integration
  - Modern smart grids
  - High-precision adequacy studies

A. Reliability Function

- The reliability function represents the probability that a generator operates without failure over a specified time interval [1].

$$R(t) = e^{-\lambda t} = P(T > t)$$

- Where:
  - T = time to failure
  - t = operating time
- **Key Properties:** R(0)=1 (initially fully operational), R(t)→0 as t→∞, and decreases exponentially with time

B. Generator Availability

- Availability is the probability that a generator is operational and able to supply power at a given time, considering both failures and repairs.
- Steady-State Availability:

$$A = \frac{\mu}{\lambda + \mu}$$

- Where:
  - λ = failure rate
  - μ = repair rate

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- Alternative Form:

$$A = \frac{MTTF}{MTTF+MTTR}$$

- Unavailability:

$$U = 1 - A = \frac{\lambda}{\mu+\lambda}$$

- Key Properties:
  - $0 \leq A \leq 1$, High availability → high system reliability
- Depends on both: Failure frequency and Repair efficiency

3. Load Uncertainty Modeling

- Electrical load demand is inherently uncertain and time-varying due to [3]:
  - Consumer behavior
  - Weather conditions
  - Economic activity
  - Industrial operation patterns
- Therefore, load must be represented using probabilistic models rather than fixed deterministic values.
- The load demand is characterized by its dynamic, stochastic, time-dependant, and non-linear nature.

Probabilistic Representation of Load

- **Probabilistic load modeling** is important for better generation planning, improved reliability analysis, an accurate reserve margin estimation, and risk-based operational decisions.

A. Probability Density Function (PDF)

  - The PDF $f(x)$ describes the probability of occurrence of different load levels and x is load demand level.
  - The high PDF value refers to highly probable load level while the low PDF value less likely load level.

B. Cumulative Distribution Function (CDF)

  - Represents the probability that load demand is less than or equal to x.

$$f(x) = P(X \leq x)$$

Load Duration Curve (LDC)

- A Load Duration Curve arranges load demand values in:
  - Descending order
  - Against duration of occurrence
- It has the **characteristics** of Peak load has short duration while Base load has long duration.
- **Applications:** Generation scheduling, Reliability studies, Capacity planning, and Economic dispatch

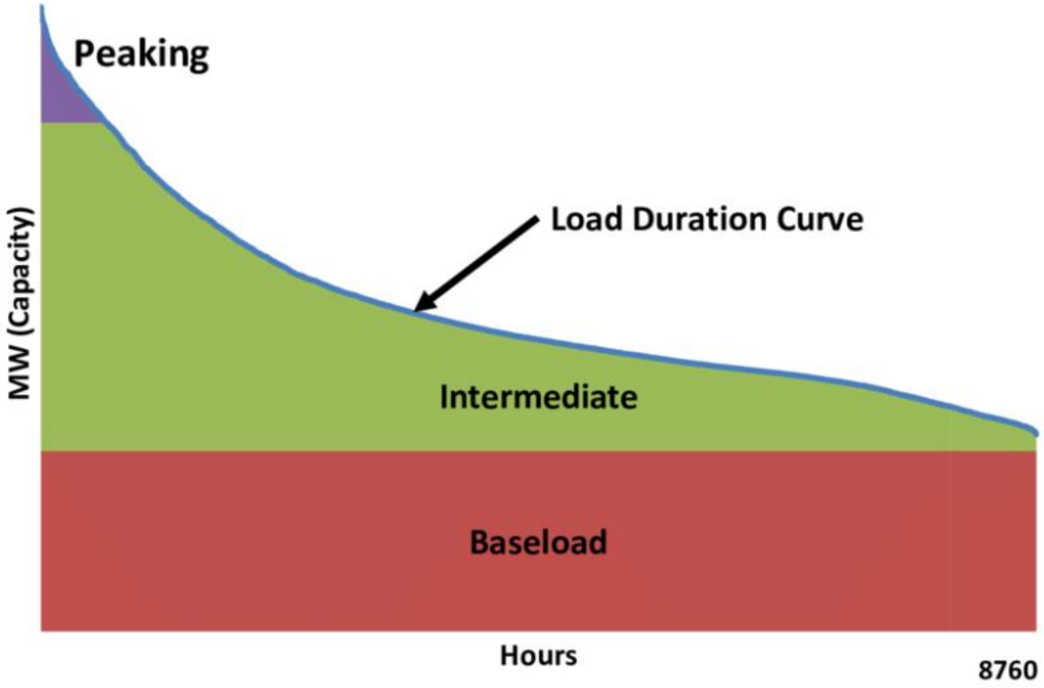

Figure 1: Load Duration Curve [1].

Reliability Impact of Load Uncertainty

- Load uncertainty significantly affects the reliability and operational security of power systems.
- Since electrical demand varies randomly with time, utilities must ensure that:
  - Available generation capacity can continuously meet demand
  - System reliability is maintained under varying operating conditions

1. Effect on Generation Adequacy

  - **Generation adequacy**: The ability of the power system to supply customer demand and maintain required reserve margin.
  - **Unexpected load increase may cause:** Generation deficiency, Reserve depletion, and also Supply interruption.

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2. Impact on Reliability Indices

- Load uncertainty directly affects major reliability indices:

A. Loss of Load Probability (LOLP)

- Probability that: Load Demand > Available Generation
- Higher load uncertainty: Increases LOLP and Raises blackout risk

B. Loss of Load Expectation (LOLE)

- Expected duration during which: System demand exceeds available capacity
- Uncertain load patterns increase: Frequency of inadequacy events and Expected outage duration

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C. Expected Energy Not Supplied (EENS)

- Expected amount of energy curtailed due to insufficient generation.
- Load uncertainty may increase: Unserved energy and Economic losses

3. Operational Reliability Challenges:

- **Peak Demand Stress:** During peak loading, generator reserve margin decreases and system operates near stability limits which results reliability becomes more vulnerable.
- **Off-Peak Period:** During low demand, reliability risk decreases and excess generation may exist

4. Impact on System Stability: Sudden load variation may causes frequency deviation, Voltage fluctuation, and transmission congestion

4. Reliability of Isolated and Interconnected Systems

- Power system reliability depends strongly on the system configuration and the availability of external support.
- Power systems are generally categorized into:
  - **Isolated systems:** An independent system configuration with no connection from the neighbourhood network through transmission network.
  - **Interconnected systems:** A group of two or more electric power systems or networks that are electrically linked together through transmission lines and operate in coordination.
- Their reliability characteristics differ significantly.

A. Isolated Power System

- A power system that operates independently without electrical connection to other power systems or external grids [1], [4].
- It generates, transmits, and distributes electrical energy within its own local network only.
- Typical Examples of Isolated Power Systems:
    - **Remote Rural Microgrids:** Small local grids supplying villages far from the national grid (Solar PV, Wind turbine, Battery Energy Storage System (BESS), and Diesel generator backup).
    - **Standalone Diesel Generator Systems**
    - **Industrial Captive Power Plants:** Large industries generating their own electricity independently.
    - **Shipboard Power Systems:** Electrical systems inside ships or naval vessels operate independently at sea.

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Key Characteristics of Isolated Power System:

  - No interconnection with neighboring grids
  - Local generation must satisfy local demand
  - Limited reserve capacity
  - Independent frequency and voltage control
  - Usually smaller in size

- In an isolated system, generation must continuously equal demand plus losses:

$$P_{\text{Generation}}=P_{\text{Load}}+P_{\text{Loss}}$$

- Since there is no external support, any imbalance directly affects system frequency and stability.

Reliability Evaluation Procedure

Step 1: Collect System Data

- Generator ratings
- Failure rates
- Repair times
- Load demand
- Reserve capacity

Step 2: Model Component States

- Operating state
- Failed state

This is commonly represented using a two-state model.

Step 3: Determine System Configuration

- Single generator system
- Parallel generating units
- Microgrid with renewable energy and storage

Step 4: Compute Reliability Indices:

- LOLP (Loss of Load Probability)
- LOLE (Loss of Load Expectation)
- ENS/EENS (Expected Energy Not Supplied)
- Availability

Example

- A remote rural community is supplied by an isolated microgrid consisting of two diesel generators operating independently without connection to the national grid:
  - **Generator G1:** 100 kW, **Failure rate:** $\lambda 1=0.015$ failures/year and **Repair rate:** $\mu 1=3$ repairs/year
  - **Generator G2:** 80 kW, **Failure rate:** $\lambda 2=0.020$ failures/year and **Repair rate:** $\mu 2=4$ repairs/year
  - The peak load demand of the isolated system is: $\mathbf{P_{Load}=120\ kW}$
- Assume:
  - Generators operate independently
  - The load is fully supplied if available generation ≥ 120 kW
  - Otherwise, loss of load occurs

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Determine:

- Availability of each generator
- Unavailability of each generator
- Possible operating states
- Capacity outage probability table (COPT)
- Loss of Load Probability (LOLP)
- System reliability assessment

Solution:

Step 1: Compute Generator Availability

- **Availability formula:**

$$\mathrm{A} = \frac{\mu}{\lambda+\mu}$$

- **Generator G1:** λ1=0.015 and μ1=3

$$A_1 = \frac{3}{0.015 + 3} = 0.9950$$

$$U_1 = 1 - A_1 = 0.0050$$

.

Solution:

- **Generator G2:** λ1=0.020 and μ1=4

$$A_2 = \frac{4}{0.020 + 4} = 0.9950$$

$$U_2 = 1 - A_2 = 0.0050$$

Step 2: Determine System Operating States

- A two generator isolated system has four states (S1, S2, S3, and S4)

Table 1: Operating States of a Two Generators Isolated Power system.

State	G1	G2	Available Capacity (kW)
S1	ON	ON	180
S2	ON	OFF	100
S3	OFF	ON	80
S4	OFF	OFF	0

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Step 3: Compute State Probabilities/Corporate Model

- Because generators are independent:
- **State S1: Both Operating:**

$$P(S1) = A_1A_2 = 0.995 \times 0.995$$

$$P(S1) = 0.990025$$

- **State S2: G1 ON, G2 OFF:**

$$P(S2) = A_1U_2 = 0.995 \times 0.0050$$

$$P(S2) = 0.004975$$

- **State S3: G1 OFF, G2 ON:**

$$P(S3) = U_1A_2 = 0.0050 \times 0.995$$

$$P(S3) = 0.004975$$

- **State S4: G1 OFF, G2 OFF:**

$$P(S3) = U_1A_2 = 0.0050 \times 0.0050$$

$$P(S3) = 0.000025$$

The above values computed refers to the **Capacity Outage Probability (COP)** or **Corporate model**, the probability where the generators are serving the load.

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Step 4: Construct Capacity Outage Probability Table (COPT)

Table 2: Capacity Outage Probability Table.

State	Available Capacity (kW)	Load Served?	Probability
S1	180	Yes	0.990025
S2	100	No	0.004975
S3	80	No	0.004975
S4	0	No	0.000025

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Step 5: Compute Loss of Load Probability (LOLP)

- Loss of load occurs when:

$$P_{Avaliable} < P_{Load}$$

- Since load demand is 120 kW:
- States causing loss of load: S2, S3, and S4.
- Therefore the loss of load probability, LOLP is calculated as:

$$LOLP = P(S2) + P(S3) + P(S4)$$

$$LOLP = 0.004975 + 0.004975 + 0.000025 = 0.009975$$

- Therefore: The loss of load probability due to generation and load unbalance is 1%.

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Step 6: Compute System Reliability

  - System reliability is:

$$R = 1 - LOLP = 1 - 0.009975 = 0.990025$$

  - Thus: the system has a reliability of R=99%.

- Although the system reliability appears high:
  - The isolated system still faces risk when one generator fails.
  - Neither generator alone can supply the 120 kW load.
  - Loss of load occurs immediately after a single outage.

B. Interconnected Power System

- An **interconnected power system** consists of two or more electrical power systems linked through transmission ties, allowing continuous exchange of electrical energy between regions or utilities [1].
- **System Structure**
  - Multiple generating stations connected via transmission network
  - Loads supplied from local and external sources
  - Coordinated operation through control centers
- **Power flow is governed by:**
  - System demand balance, Transmission line constraints, and
  - Economic dispatch and reliability requirements

Reliability Advantages

A. Reserve Sharing

- Generators in one area support another during outages
- Reduces required spinning reserve in each subsystem

B. Improved Adequacy

- Deficit in one area is compensated by surplus generation elsewhere
- Enhances system reliability indices (LOLP, LOLE)

C. Fault Support

- Neighboring systems supply power during generator or line outages
- Reduces probability of load shedding

Example

- Two neighboring power systems, Area A and Area B, are interconnected through a tie-line.
  - **Area A** (Ethiopia-like system segment)
    - Installed capacity: P1=200 MW
    - Peak load: P_{L1}=180 MW
    - Generation unit outage probability: U1=0.08
  - **Area B** (neighboring system)
    - Installed capacity: P2=150 MW
    - Peak load: P_{L2}=140 MW
    - Generation unit outage probability: U2=0.10
- Tie-line capacity: 50 MW (The tie-line can transfer power in either direction depending on surplus)

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Required:

- Identify reliability states of each area
- Determine surplus/deficit conditions
- Compute probability of each operating state
- Evaluate Loss of Load Probability (LOLP) for:
    - Area A alone (isolated case)
    - Interconnected system case
- Quantify reliability improvement due to interconnection

Solution

Step 1: Define Area States, Determining the avaliability and unavaliability of each unit.

- Each area has two states:
- **Area A**
  - Normal: probability of Avaliability, A1 = 0.92
  - Failed: probability of Unavaliability, U1= 0.08
- **Area B**
  - Normal: probability of Avaliability, A2 = 0.90
  - Failed: probability of Unavaliability, U2= 0.10

Step 2: System State Combinations

Table 3: State Probabilities of an Interconnected System.

State	G1	G2	State Probability
S1	Ok	Ok	0.92*0.90=0.8280
S2	Ok	Failed	0.92*0.10=0.0920
S3	Failed	Ok	0.08*0.90=0.0720
S4	Failed	Failed	0.08*0.10=0.0080

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Step 3: Power Balance Logic

- **Case S1:** Both Areas Healthy
  - Area A surplus = 200 − 180 = 20 MW
  - Area B surplus = 150 − 140 = 10 MW
  - No problem → system secure
- **Case S2:** Area A OK, Area B deficit
  - B deficit = 140 MW load
  - B generation insufficient= 140-20=120MW

Case S3: Area A Failed, Area B OK

- A cannot meet 180 MW load
- B surplus = 10 MW
- Tie-line Capacity = 50 MW
- A generation insufficient= 180-10=170MW

Case S4: Both Failed

- Severe system condition
- No adequate generation → total blackout risk

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Step 4: Loss of Load Probability (LOLP)

- Loss occurs in S2, S3, S4:

$$LOLP = P(S2) + P(S3) + P(S4)$$

$$LOLP = 0.092 + 0.072 + 0.008 = 0.172$$

Step 5: Isolated System Comparison

- If systems were NOT interconnected: G1 and G2 are operated independantly and each has 2 states (Ok and Failed).

$$LOLP_A = P(A\,failed) = 0.08$$

$$LOLP_B = P(B\,failed) = 0.1$$

- When generator A and B operated as an isolated system the system LOLP is:

$$LOLP = LOLP_A\; + \; LOLP_B = 0.18$$

Step 6: Reliability Improvement

Improvement = 0.18−0.172 = 0.008

- Interconnection reduces LOLP from 18% to 17.2%.

5. Generator System Cost Analysis

- Generator system reliability improvement is associated with significant economic considerations.
- Power utilities must achieve an optimal balance between:
  - Reliability
  - Operational cost
  - Investment cost
- Reliability **enhancement** always involves economic trade-offs.
- The **main objective** is to minimize total system cost, maintain acceptable reliability level, and to ensure secure and economic operation.

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- **Major Cost Components** for Generator System Cost Analysis:
  1. **Capital Cost:** Generator installation and Infrastructure investment
  2. **Operating Cost:** Fuel cost, Labor and operation expenses
  3. **Maintenance Cost:** Preventive maintenance and Corrective maintenance expenses
  4. **Outage Cost:** Cost due to power interruption and Economic loss from unserved energy
- **Reliability-Cost Trade-off**
  1. High reliability → high investment **cost** but reduces **outage probability**
  2. Low reliability → high outage cost
- **Utilities seek** the minimum total expected cost.

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- The **economic objectives** of generator system cost analysis is to determine the reliability level where:

Marginal Reliability Benefit = Marginal Reliability Cost

- The **reliability improvement worth evaluation is justified by comparing:**
  - Reliability improvement cost
  - Reduction in outage cost
- **Excessive reliability** may become economically inefficient because it requires **additional investment**.

Example

- A **utility** is considering installing a standby generator to improve system reliability.
- **Given**
  - Installation cost = $1,500,000 and Annual operating cost = $100,000
  - Current annual outage cost before generator installation= $600,000
  - Expected outage cost after installation = $200,000
- **Questions**
  - Determine the annual outage cost reduction
  - Compute the total annual savings
  - Determine the payback period

Solution

Step 1: Outage Cost Reduction

- Savings=600,000−200,000 = $400,000

Step 2: Net Annual Benefit

- $Annual\ Cash\ Inflow = 400{,}000 - 100{,}000$

$$= \$300{,}000/year$$

Step 3: Payback Period

- $Payback = \frac{Initial\ Investment}{Annual\ Cash\ Inflow} = \frac{1500000}{300000}$

$$= 5\ years$$

Conclusion

- Reliability improvement reduces outage cost significantly
- Investment becomes economically viable after 5 years
- Reliability-cost analysis supports utility decision-making
- The optimal reliability level is achieved when the reduction in outage cost economically justifies the additional investment.

6. Energy Transfer and Off-Peak Loading

- Modern interconnected power systems improve reliability and economic performance through **Energy transfe**r and **Off-peak load** management
- These strategies help utilities to **balance** generation and demand, to **improve** system utilization, **reduce** operational cost, and to **enhance** reliability.
- **Energy Transfer:** is the exchange of electrical power between interconnected power systems through transmission tie-lines.
- **Purpose of Energy Transfer** is to: support deficient areas during shortages, share reserve generation, improve system reliability, and reduce operating cost

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- **Off-Peak Loading:** refers to the utilization of electrical energy during periods of low demand.
- **Typical Off-Peak Periods include:** Nighttime hours, Low industrial activity periods, and Weekends and holidays.
- **Objectives:** Improve load factor, Reduce peak demand stress, and Increase generation utilization
- **Applications:**
  - Electric vehicle charging and Battery charging systems
  - Pumped-storage systems
  - Industrial load scheduling

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Thank You!