Power Reliability

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Objectives

- Understand the concepts of Reliability, Availability and Unavailability
- Know the definition of reliability and the factors associated with it.
- Know the techniques for reliability analysis.
- Understand the failure and reliability curves as a factor of time.
- Understand Markov Reliability Model
- Understand Customer based Reliability Indies

Basic Reliability Terms

- Failure - A failure is an event when an item is not available to perform its function at specified conditions when scheduled or is not capable of performing functions to specification.
- Failure Rate - The number of failures per unit of gross operating period in terms of time, events, cycles.
- MTBF - Mean Time Between Failures - The average time between failure occurrences. The number of items and their operating time divided by the total number of failures.
- MTTF - Mean Time To Failure - The average time to failure occurrence. Used for repairable equipment.

Basic Reliability Terms

- MTTR - Mean Time To Repair - The average time to restore the item to specified conditions.
- Availability - A measure of the time that a system is actually operating versus the time that the system was planned to operate.

Basic Concept

- ***Reliability***
- Reliability is the analysis of failures, their causes and consequences.
- It is the most important characteristic of product quality as things have to be working satisfactorily before considering other quality attributes.

Basic Concept

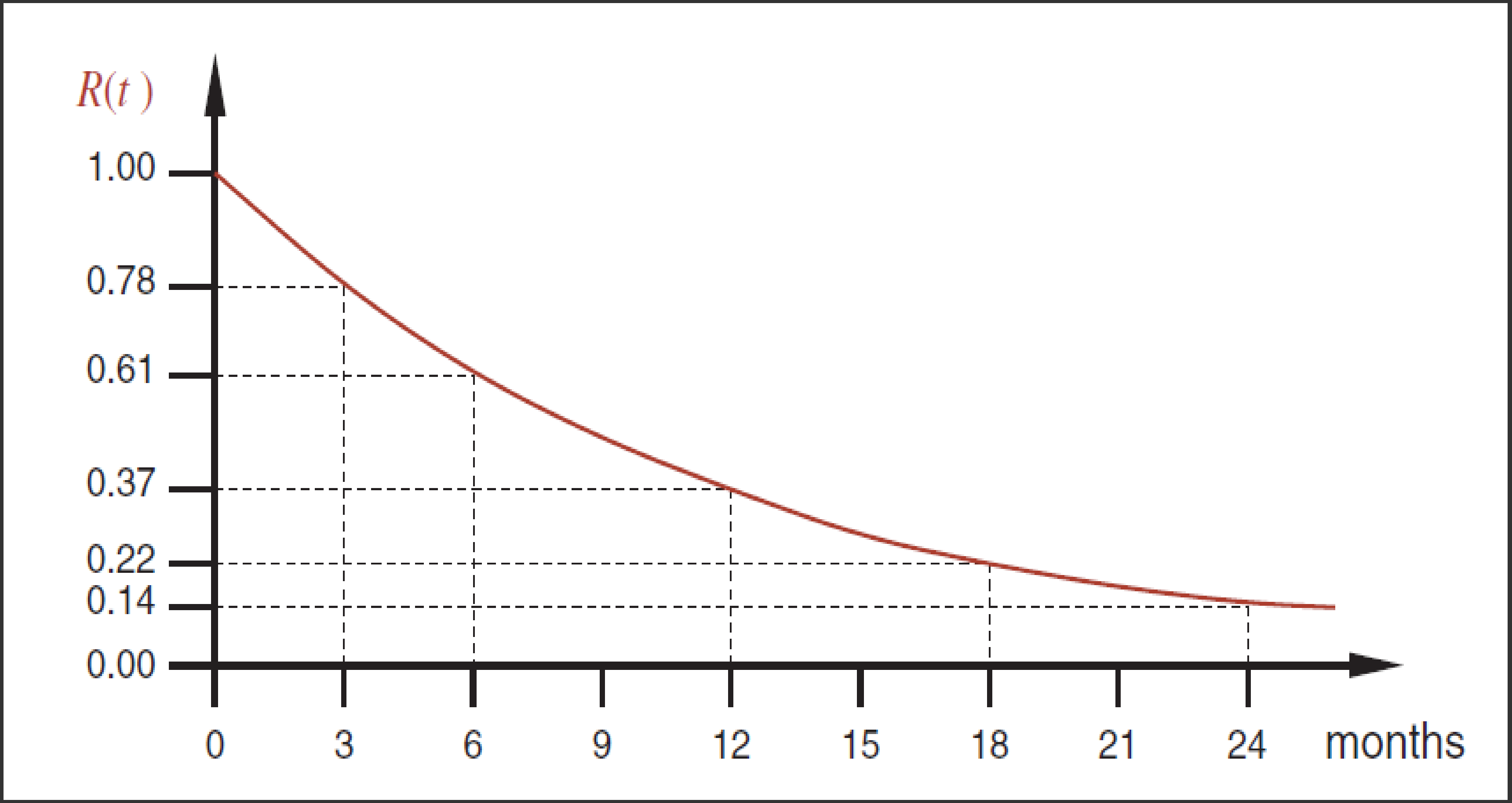
- **Definition** *Reliability:* is the probability that the system will perform its intended function under specified working condition for a specified period of time.

Basic Concepts

- Quantitatively, reliability is expressed as a mathematical function of time:
- $R(t)$ = Probability that the system still works correctly at time t.
- Reliability is a real number between 0 and 1; that is, at any time $0 \leq R(t) \leq 1$.

Basic Concepts

- ***A Typical Reliability Function***



Basic Concepts

- ***A Typical Reliability Function***

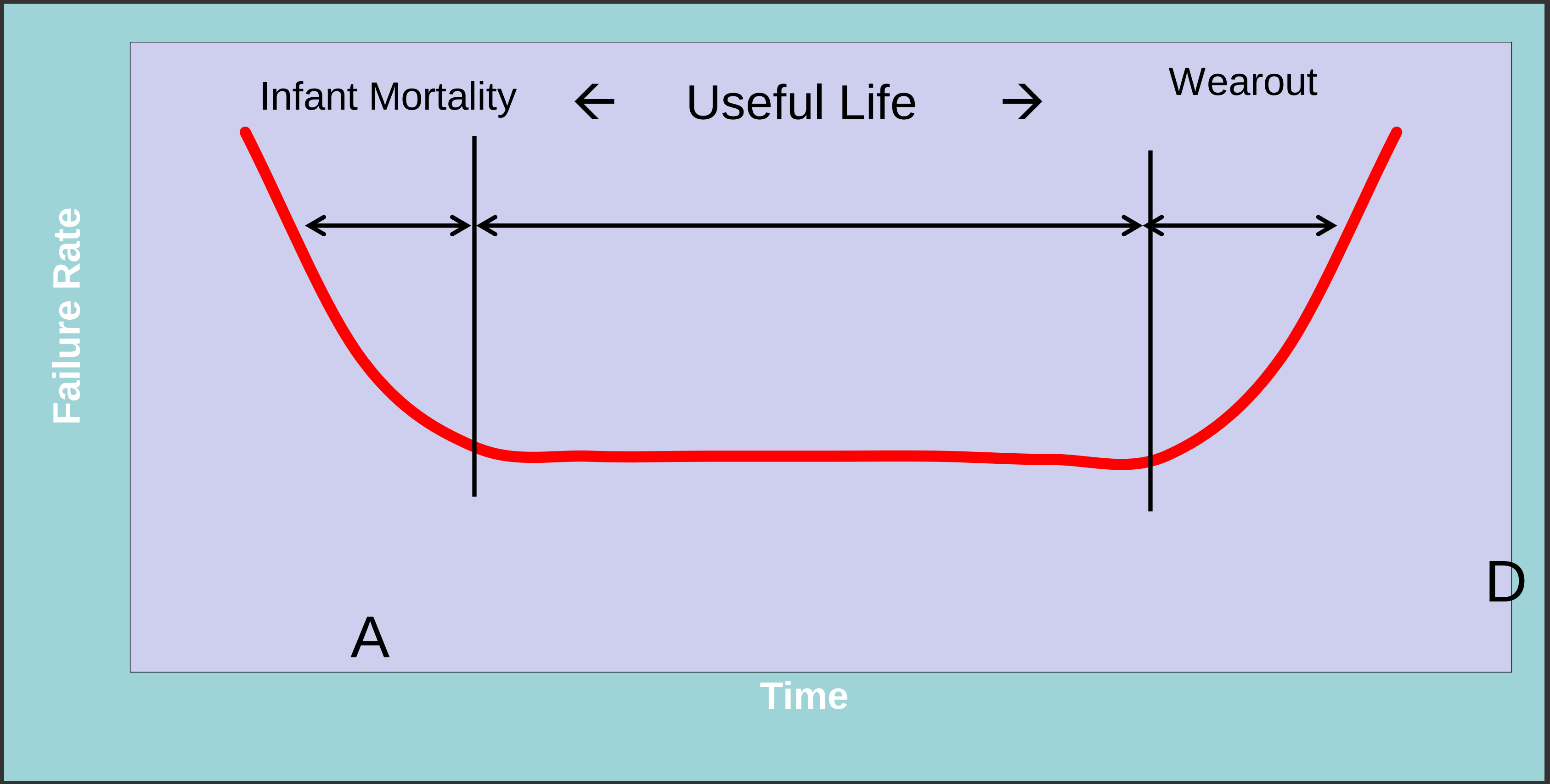
$$R = e^{-\lambda t}$$

Note: λ = failure rate (failures/second),

Failure Probability = 1 - R

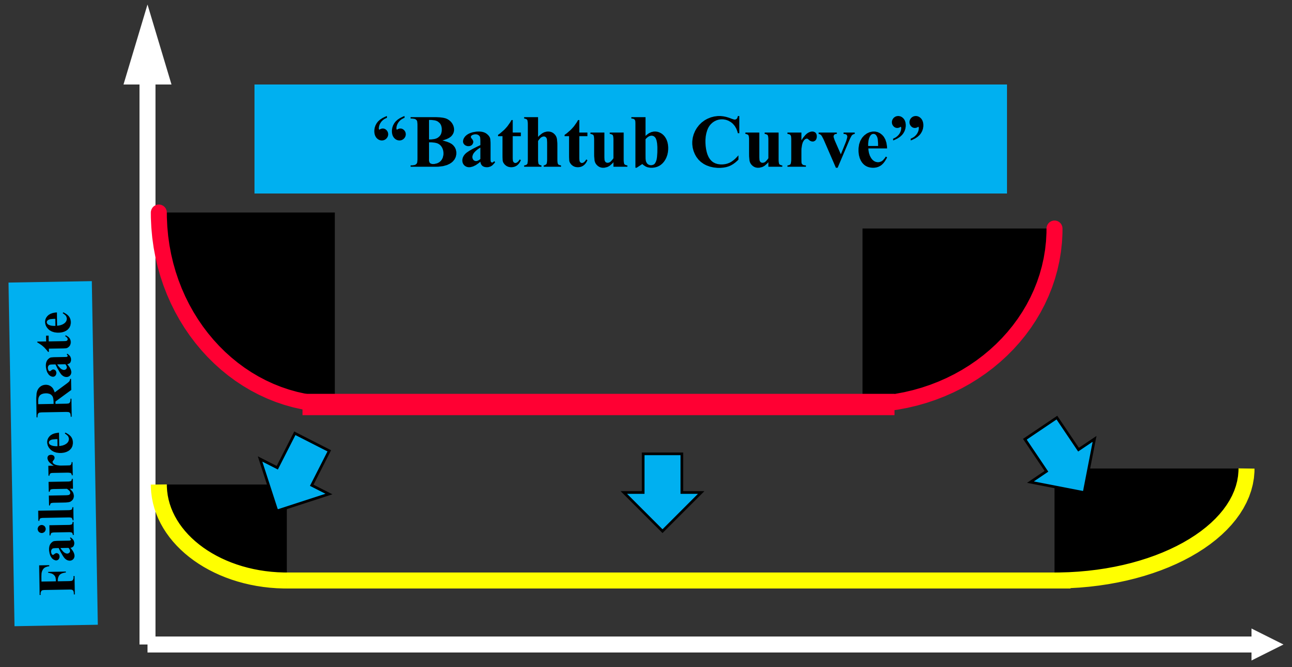
Basic Reliability Analysis

- ***Failure rate over the life of a product***
- **Bathtub Curve**



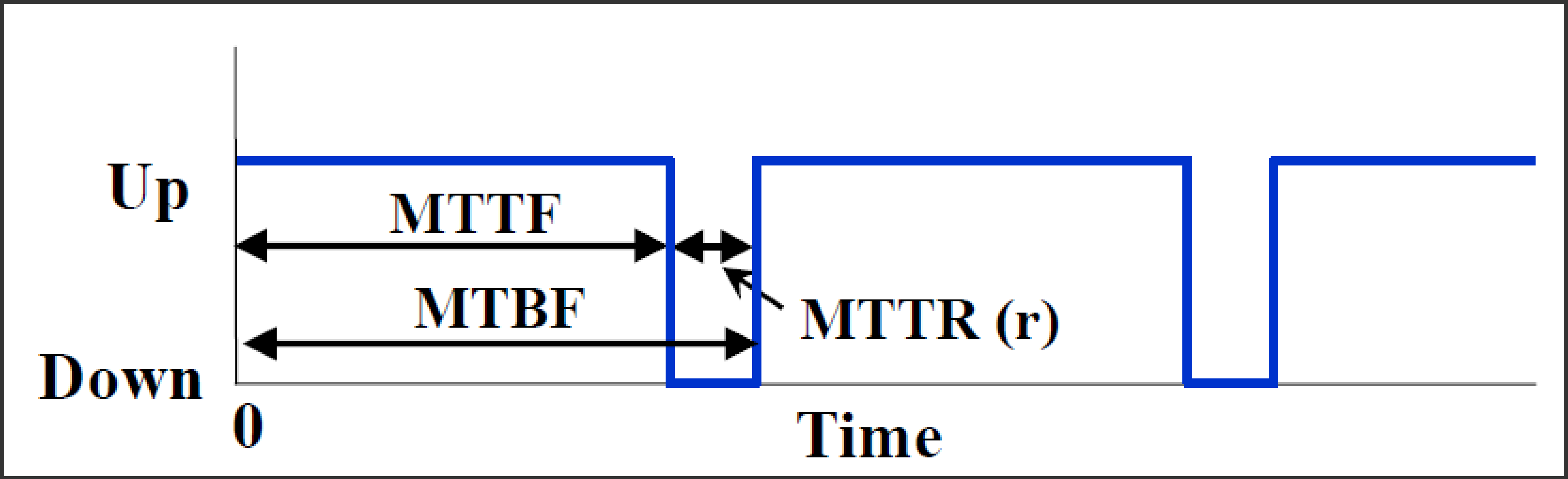
Basic Reliability Analysis

- ***Failure rate over the life of a product***



Basic Reliability Analysis

- ***System Reliability Evaluation***



$$U = \frac{\lambda}{\lambda + \mu} = \frac{1/m}{1/m + 1/r} = \frac{r}{m + r} = \frac{r}{T} = f.r \approx \lambda r$$

Basic Reliability Analysis

- ***Availability***

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

λ = Failure rate = 1/ MTBF

μ = Repair rate = 1/MTTR

Basic Reliability Analysis

- ***Availability***

λ = Failure rate = 1/ MTBF

μ = Repair rate = 1/MTTR

- ***Unavailability***

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

Basic Reliability Analysis

- ***For series system***

$$R_s = R_A * R_B * R_C$$

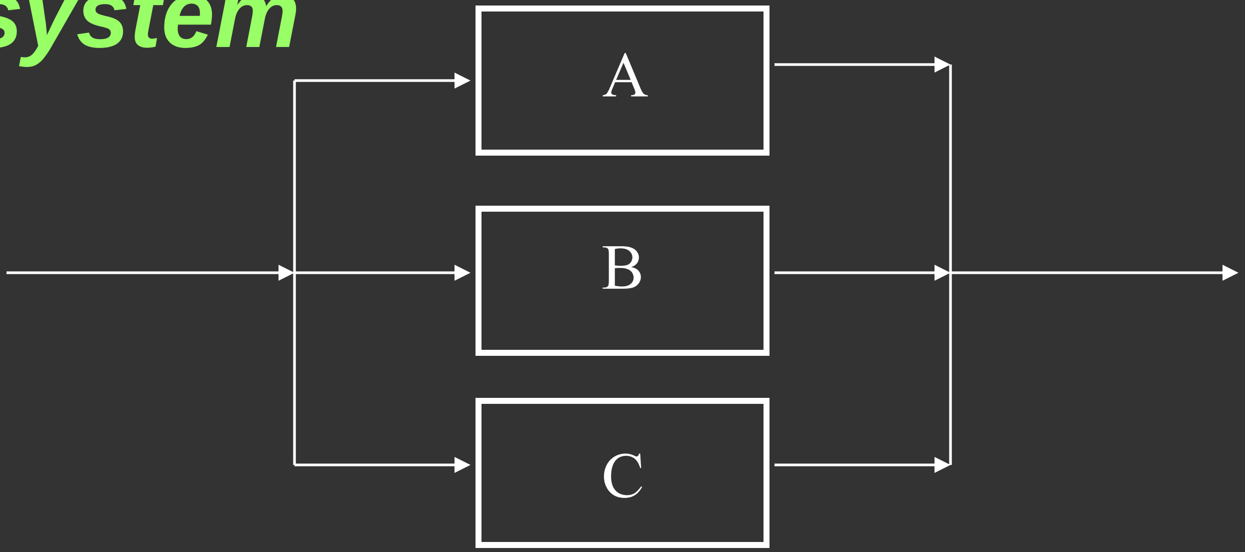
$$R_s = R_1 * R_2 * R_3 * \ldots \ldots R_n$$

$$= e^{-\lambda_1 t} * e^{-\lambda_2 t} * e^{-\lambda_3 t} * \cdots * e^{-\lambda_n t}$$

where λ_i is the failure rate of the i_{th} system

Basic Reliability Analysis

- ***For parallel system***



$$R_{tot} = 1 - (1 - R_A) * (1 - R_B) * (1 - R_C)$$

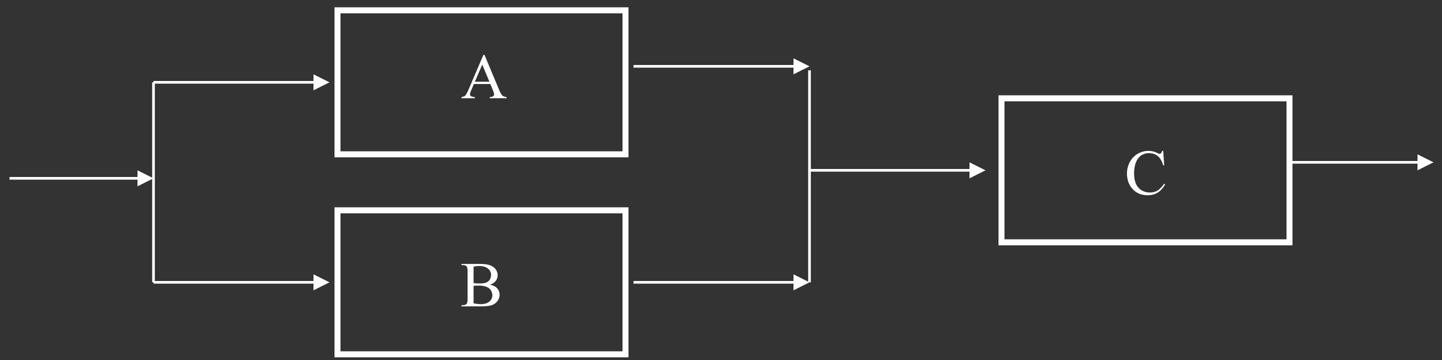
$$R_p = 1 - (1 - R_1) * (1 - R_2) * (1 - R_3) \ldots * \ldots (1 - R_n)$$

$$= 1 - Q_1 * Q_2 * Q_3 \ldots * \ldots Q_n$$

where $Q_i = (1 - R_i)$ is the failure probability of the i_{th} system

Basic Reliability Analysis

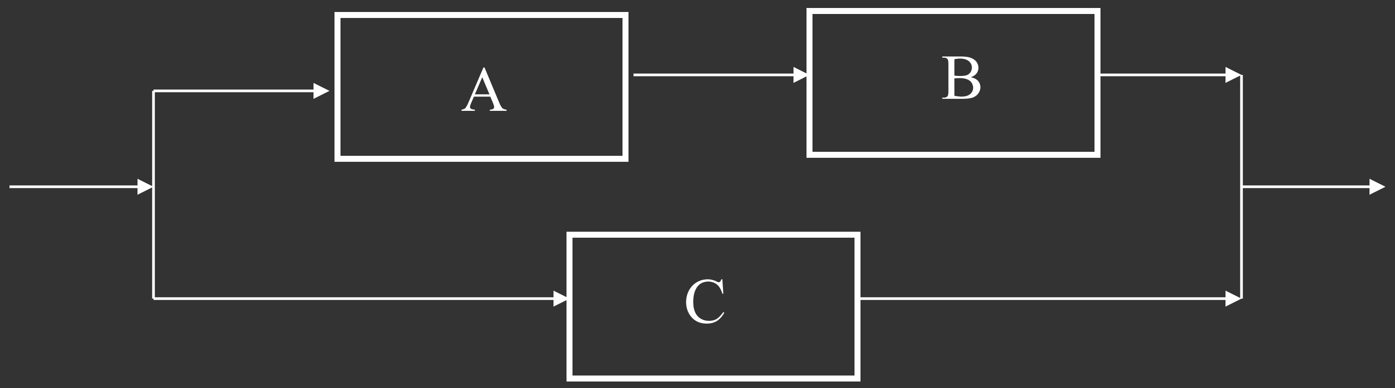
- ***For parallel series system***



$$R_{tot} = R_C * [\ 1 - (1 - R_A) * (1 - R_B)\ ]$$

Basic Reliability Analysis

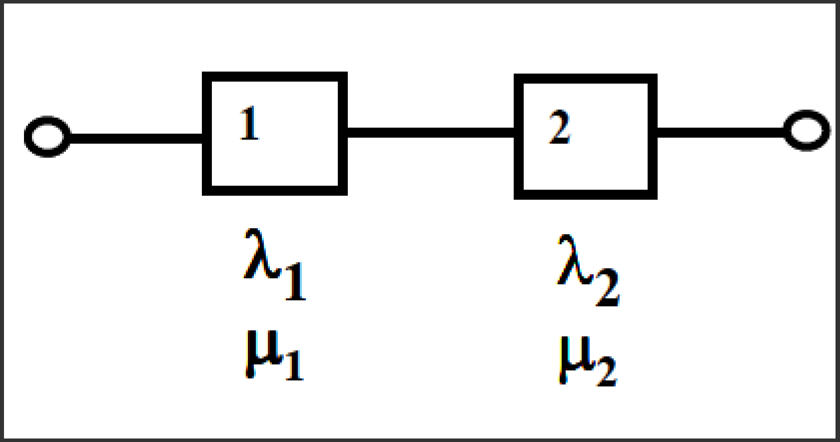
- ***For series parallel system***



$$R_{tot} = 1 - (1 - R_A * R_B) * (1 - R_C)$$

Basic Reliability Analysis

- ***For series system***



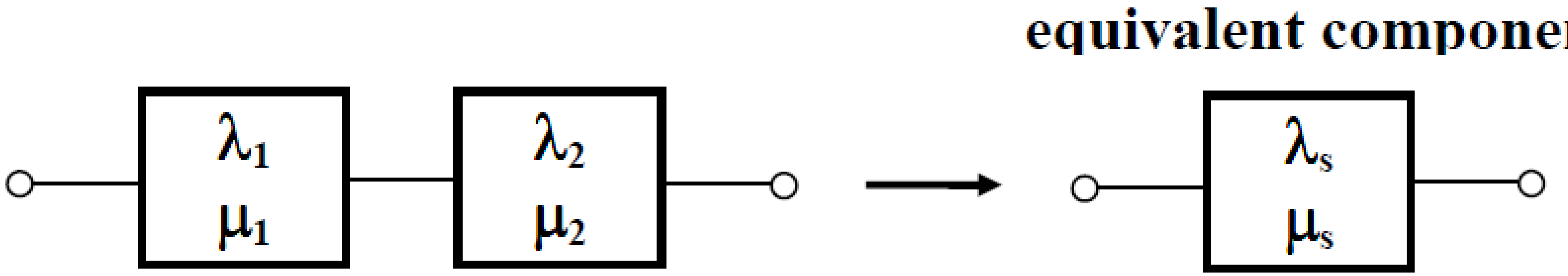
System Failure Frequency, $\lambda_s = \Sigma\, \lambda_i$

System Unavailability, $U_s = \Sigma\, \lambda_i\, r_i$

System Average Down Time, $r_s = \dfrac{U_s}{\lambda_s}$

Basic Reliability Analysis

- *For series system*



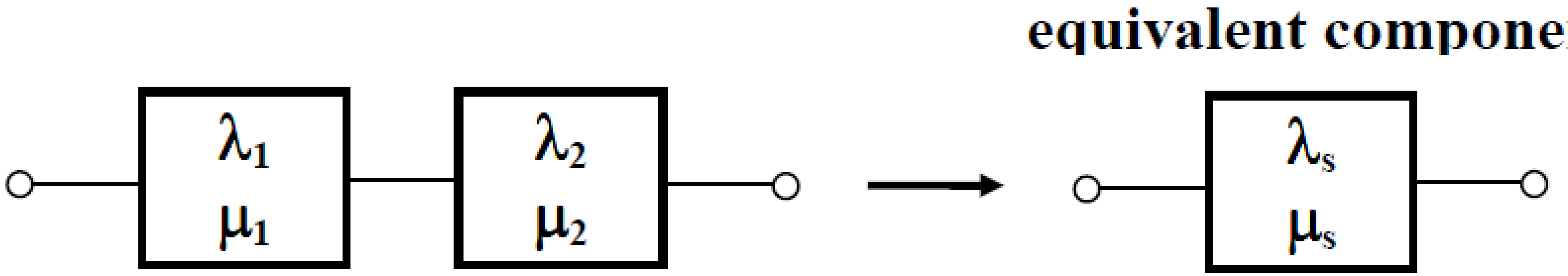
$$P_{up} = \frac{\mu_1 \mu_2}{(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} = P_{up} = \frac{\mu_s}{(\lambda_s + \mu_s)}$$

$$\lambda_s r_s = \lambda_1 r_1 + \lambda_2 r_2 + \lambda_1 \lambda_2 r_1 r_2$$

$$U_s \approx \lambda_1 r_1 + \lambda_2 r_2 \quad \text{for } \lambda_1 \lambda_2 r_1 r_2 << \lambda_1 r_1 \text{ and } \lambda_2 r_2$$

Basic Reliability Analysis

- ***For series system***



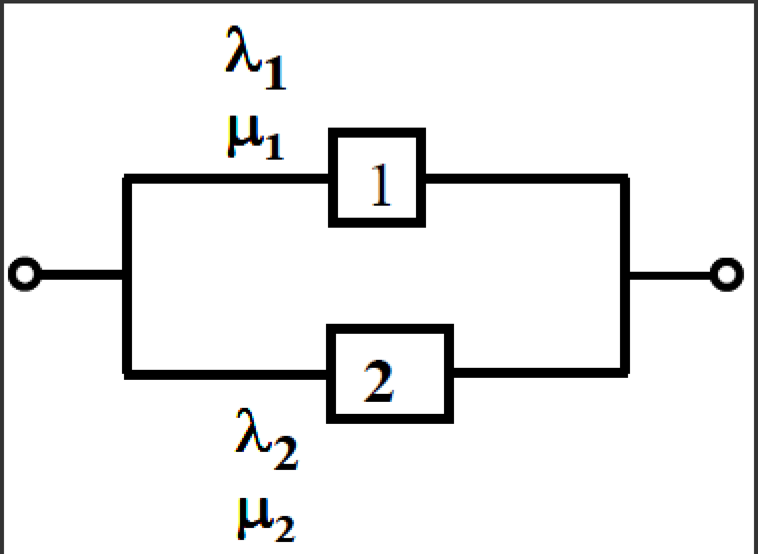
$$P_{up} = \frac{\mu_1 \mu_2}{(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} = P_{up} = \frac{\mu_s}{(\lambda_s + \mu_s)}$$

$$\lambda_s r_s = \lambda_1 r_1 + \lambda_2 r_2 + \lambda_1 \lambda_2 r_1 r_2$$

$$U_s \approx \lambda_1 r_1 + \lambda_2 r_2 \qquad \text{for } \lambda_1 \lambda_2 r_1 r_2 << \lambda_1 r_1 \text{ and } \lambda_2 r_2$$

Basic Reliability Analysis

- ***For parallel system***

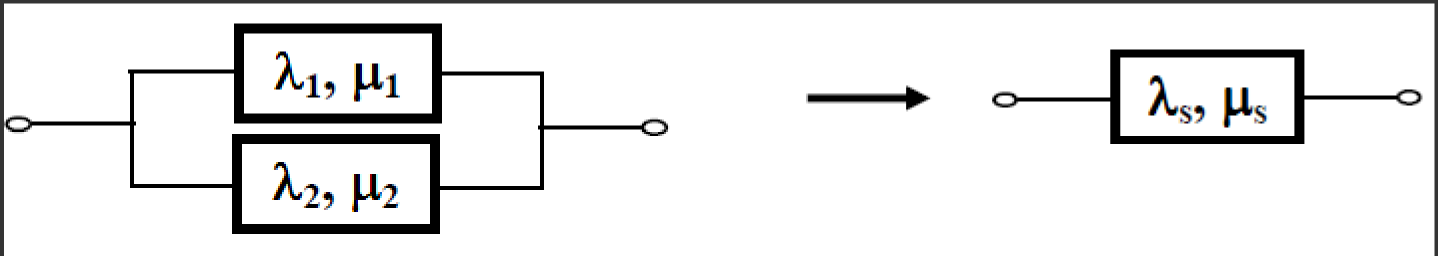


$$\lambda_s = \lambda_1 . \lambda_2 \,(r_1 + r_2) \qquad \text{for } \lambda_i . r_i << 1$$

$$r_s = r_1 . r_2 \,/\, (r_1 + r_2)$$

$$U_s = \lambda_s . r_s$$

- ***For parallel system***

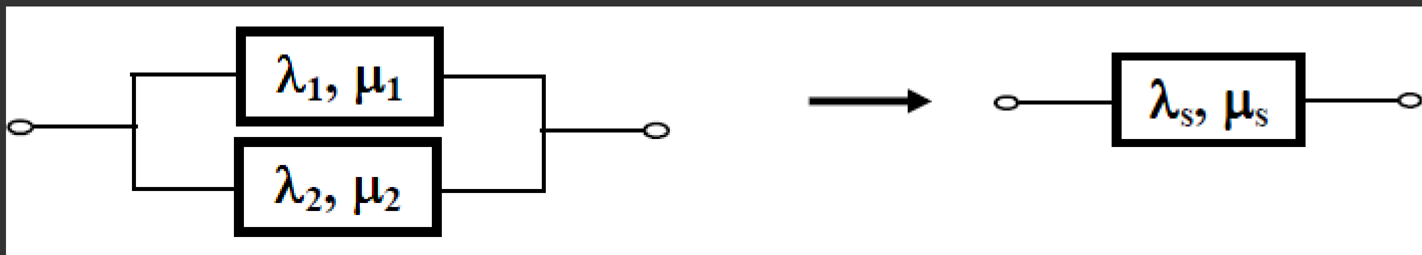


$$P_{down} = \frac{\lambda_1 \lambda_2}{(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} = \frac{\lambda_s}{(\lambda_s + \mu_s)}$$

$$\lambda_s = \frac{\lambda_1 \lambda_2 (r_1 + r_2)}{1 + \lambda_1 r_1 + \lambda_2 r_2} \approx \lambda_1 . \lambda_2 \, (r_1 + r_2) \qquad \text{for } \lambda_i . r_i << 1$$

Basic Reliability Analysis

- ***For parallel system***



$$\lambda_s = \lambda_1.\lambda_2\,(r_1 + r_2)$$

$$\mu_s = \mu_1 + \mu_2 \qquad \text{(departure rate from State 4)}$$

$$\text{i.e. } r_s = r_1.r_2 / (r_1 + r_2)$$

$$U_s = \lambda_s\,.r_s$$

Basic Reliability Analysis

- ***For parallel system***

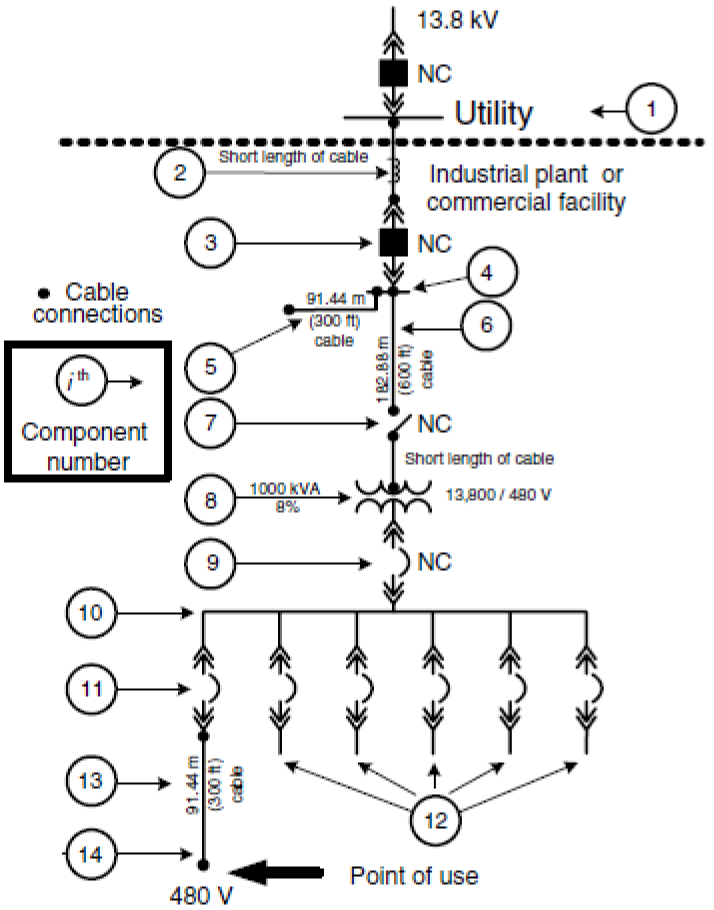
$$\lambda_s = \lambda_A \lambda_B \lambda_C \, (r_A + r_B + r_C)$$

$$\mu_s = \sum \mu_i$$

$$U_s = \lambda_s \, . r_s$$

Basic Reliability Analysis

Simple radial system



Component Number	Component	λ (failures/year)	λr (forced hours of downtime per year)
1	13.8 kV power source from electric utility	1.956000	2.582000
2	Primary protection and control system	0.000600	0.003000
3	13.8 kV metalclad circuit breaker	0.001850	0.000925
4	13.8 kV switchgear bus—insulated	0.004100	0.153053
5	Cable (13.8 kV); 900 ft, conduit below ground	0.002124	0.033347
6	Cable terminations (8) at 13.8 kV	0.002960	0.002220
7	Disconnect switch (enclosed)	0.001740	0.001740
8	Transformer	0.010800	1.430244
9	480 V metalclad circuit breaker	0.000210	0.001260
10	480 V switchgear bus—bare	0.009490	0.069182
11	480 V metalclad circuit breaker	0.000210	0.001260
12	480 V metalclad circuit breakers (5) (failed while opening)	0.000095	0.000378
13	Cable (480 V); 300 ft, conduit aboveground	0.000021	0.000168
14	Cable terminations (2) at 480 V	0.000740	0.000555
	Total at 480 V point of use	1.990940	4.279332

Note: λ*r* is the product of the failure rate multiplied by the repair duration "*r*."

Distribution System Reliability

- ***Design for reliability***

  - **Keep It Simple!**

  - **Design Margin** - Assure adequate strength of all mechanical and electrical parts, including allowance for unusual loads due to environmental extremes.

  - **Redundancy** - Provide alternative means of accomplishing required functions where design for excess strength is not suitable / reasonable.

POWER SYSTEM RELIABILITY

- The basic function of an electric power system is to supply consumers with electricity.
- Modern society demands that electrical energy should be as economical as possible with reasonable degree of continuity and quality.

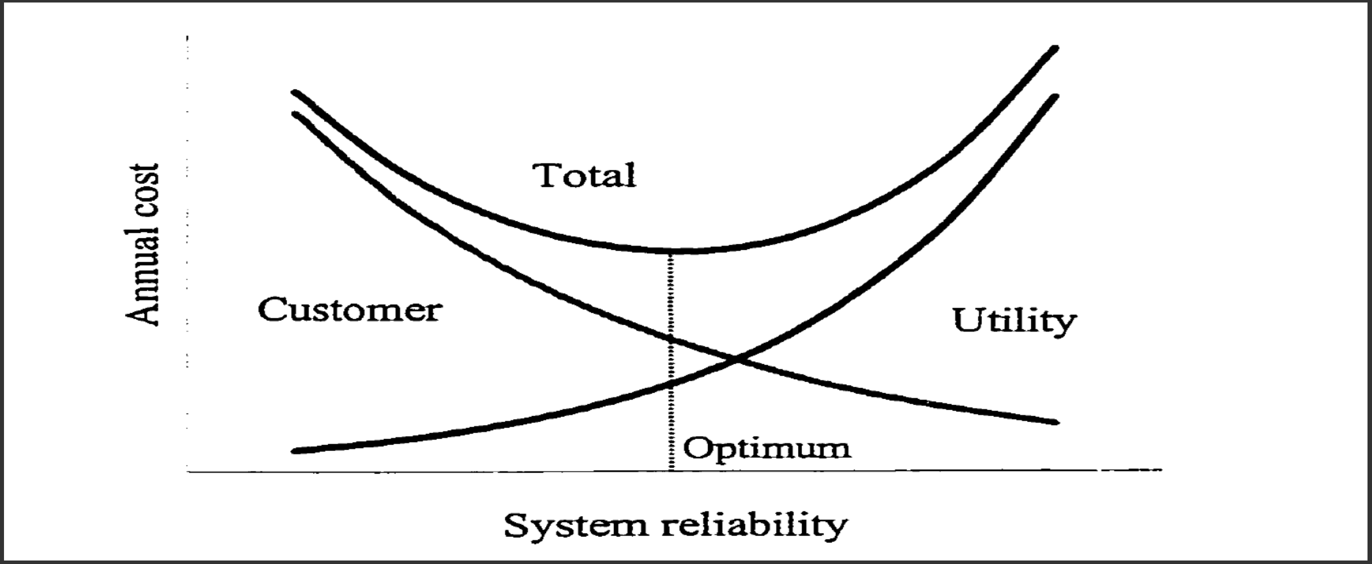
POWER SYSTEM RELIABILITY

- The continuity of energy supply can be increased by
  - improved system structure,
  - Effective and efficient Operation.

It is evident therefore that the reliability and economic constraints are related.

Distribution System Reliability

- The Fig. shows that the system cost will generally increase with higher investment cost in equipment & facilities which provide higher reliability. On the other hand, the customer interruption costs due to higher reliability will decrease. The total cost to society is the sum of these two costs. There is a minimum point in the resulting total cost curve which indicates the optimal target level of reliability.



Distribution System Reliability

The majority of customer reliability problems stem from distribution systems.

- 85% of power interruption is due to distribution system outages (poles and wires, cables, switchgear, etc.);
- 9% from substations;
- 4% from transmission; and
- 2% is caused by generation.

Distribution System Reliability

Outages can be:

- Momentary interruption-when a customer is deenergized for less than 5 minutes (IEEE).
- Sustained interruption-when a customer is deenergized for more than a few minutes.

Reliability Analysis of Fault Tree

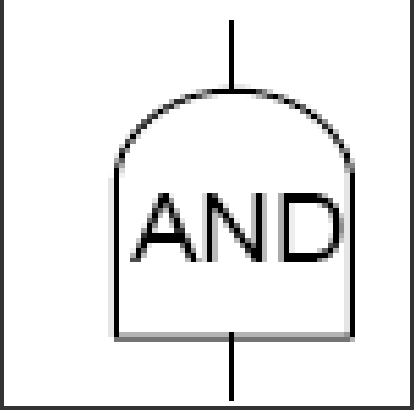
- The fault tree itself is a graphic model of the various parallel and sequential combinations of faults that will result in the occurrence of the predefined undesired event.
- A fault tree thus depicts the logical interrelationships of basic events that lead to the undesired event-which is the top event of the fault tree

Reliability Analysis of Fault Tree

- The construction of the Fault Tree always starts from the TOP event. Those fault events that are the immediate, necessary, and sufficient causes should be carefully identified and connected to the TOP event through a logic gate.
- A fault tree is tailored to a particular failure of interest. The failure of interest is called the Top Event.

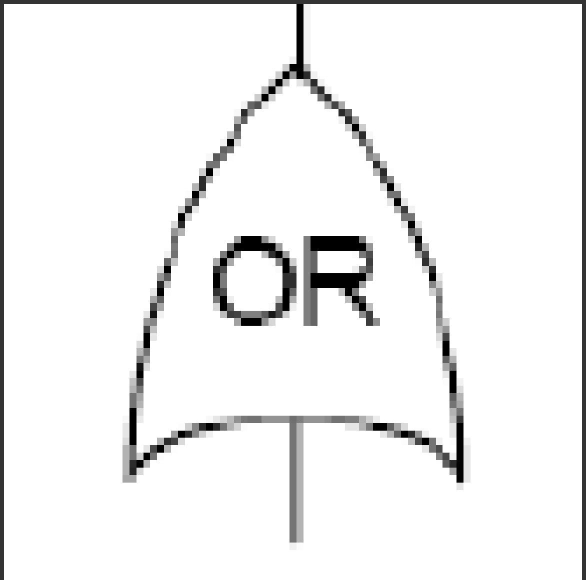
Reliability Analysis of Fault Tree

- Gates: the two most commonly used gates in a fault tree are the AND and OR gates.
- AND-gate: The AND-gate indicates that the output event occurs only if all the input faults occur at the same time.



Reliability Analysis of Fault Tree

- OR-gate : The OR-gate indicates that the output event occurs only if one or more of the input events occur.



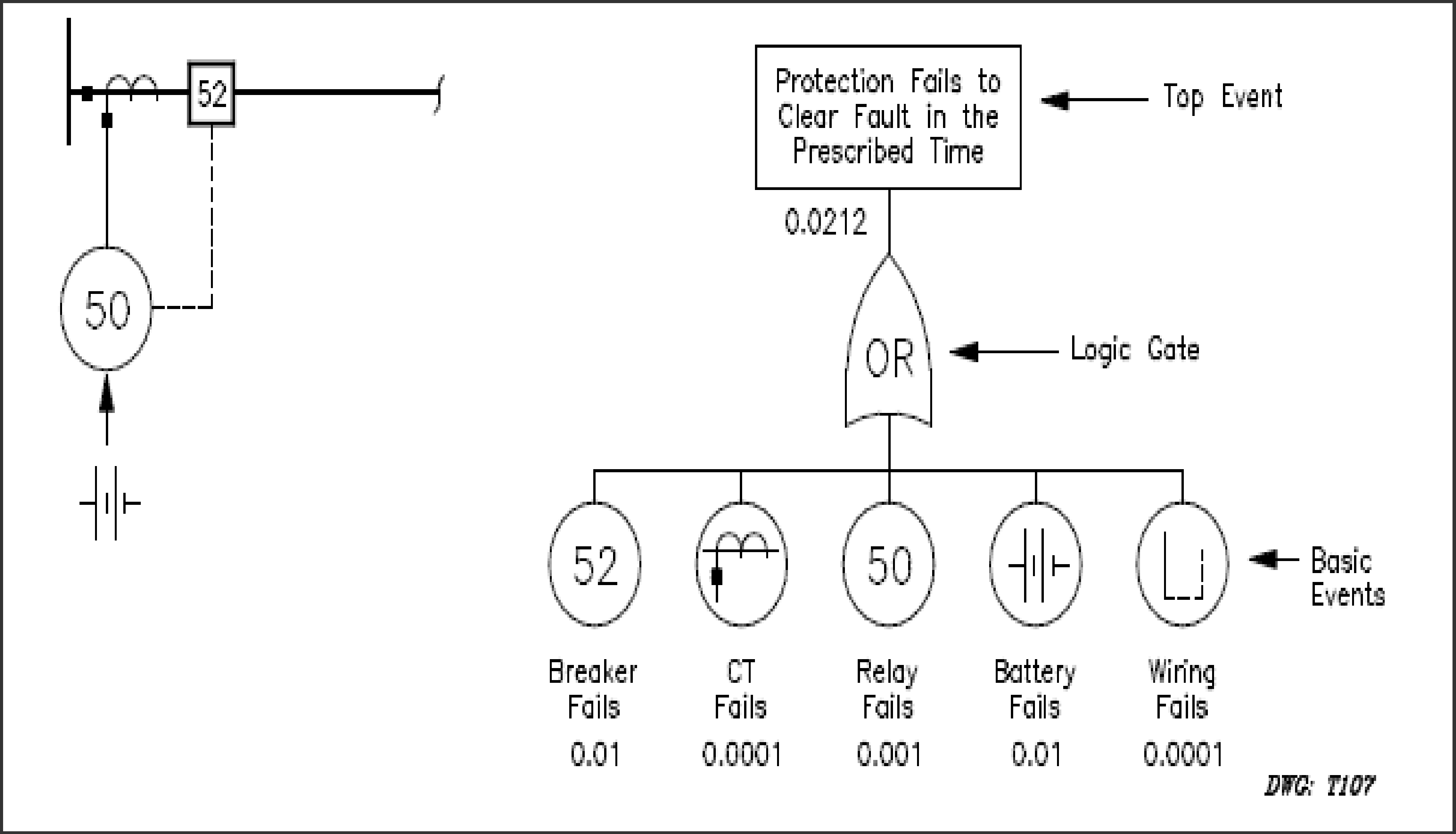
Reliability Analysis of Fault Tree

FAULT TREE CONSTRUCTION

- Figure 1 shows a protective system consisting of a circuit breaker, a ct, a relay, a battery, and associated control wiring.

Reliability Analysis of Fault Tree

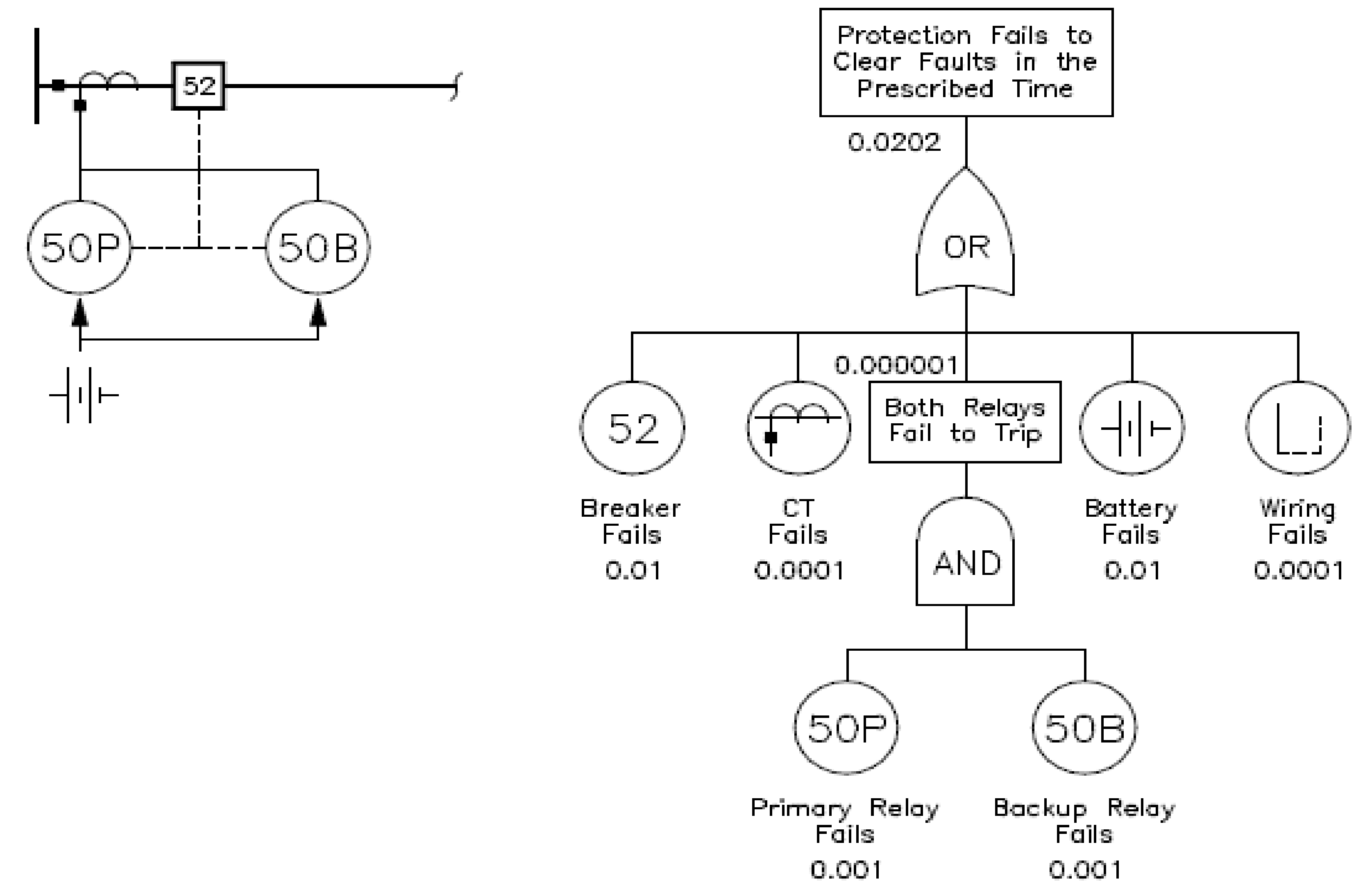
- Construction of Fault Tree



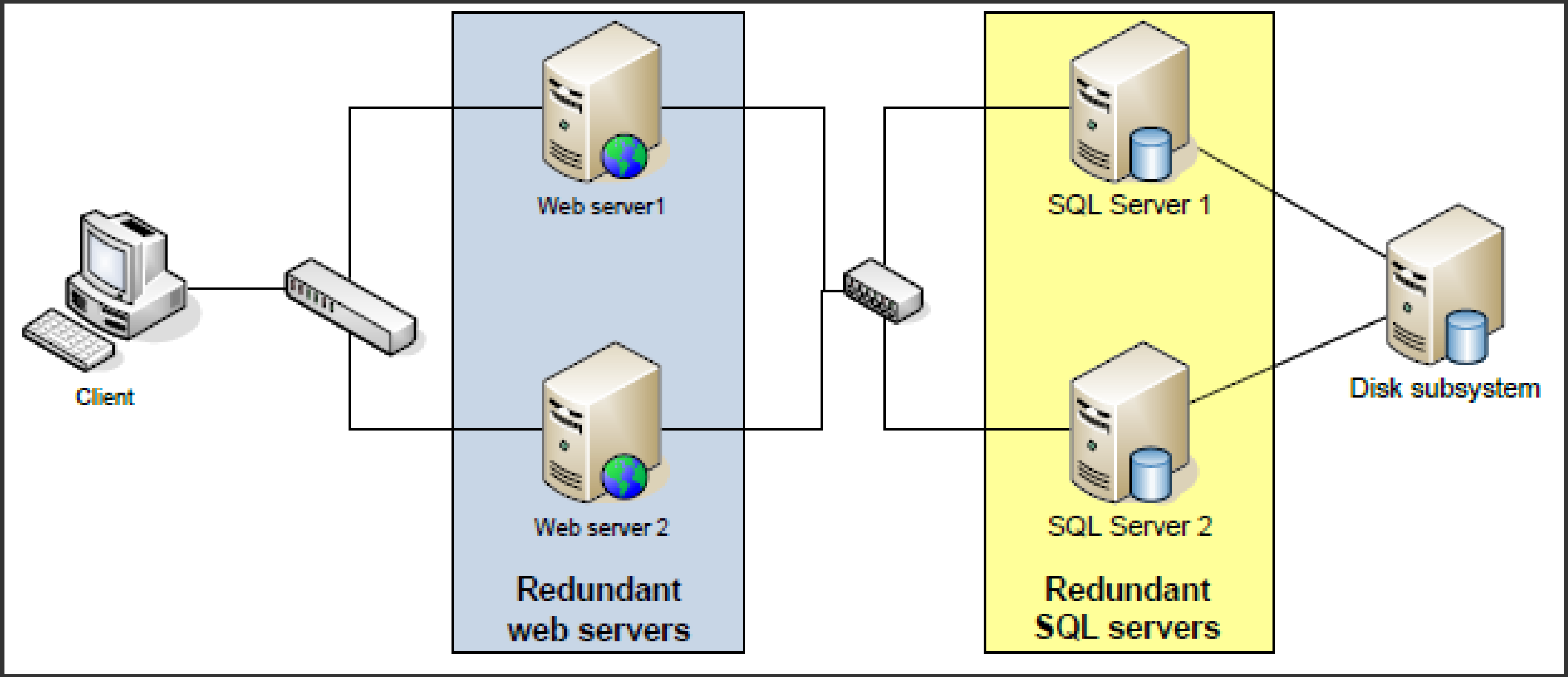
FAULT TREE CONSTRUCTION

- Let us improve the system by adding a redundant relay. The fault tree of Figure 2 contains an AND gate.
- This AND gate expresses the idea that both protective relays must fail for the event “Relays Fail to Trip” to occur.

Reliability Analysis of Fault Tree

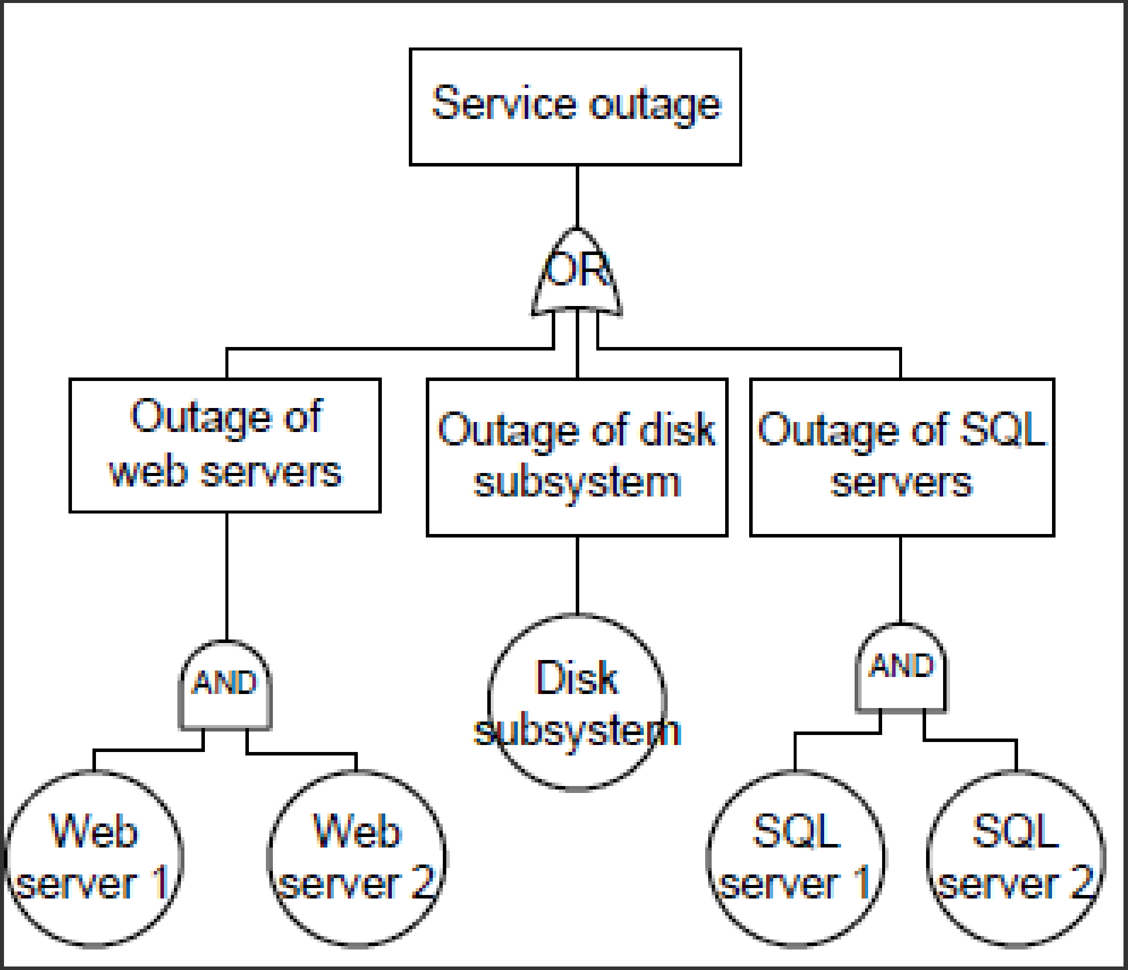


Web infrastructure



Reliability Analysis of Fault Tree

Web infrastructure



Distribution Reliability Indices

- Utilities typically keep track of customer reliability by using reliability indices. These are average customer reliability values for a specific area.
- This area can be the utility's entire service area, a particular geographic region, a substation service area, a feeder service area, and so on.
- The most commonly used reliability indices give each customer equal weight.

Distribution Reliability Indices

Reliability indices typically consider such aspects as :

- The number of customers;
- The connected load;
- The duration of the interruption measured in seconds, minutes, hours, or days;
- The amount of power (kVA) interrupted; and
- The frequency of interruptions.

Distribution Reliability Indices

- In order to quantify the effects of long interruption, interruption indices are defined as Interruption Frequency and Interruption Duration.
- Interruption frequency represents the number of interruptions on average per year per customer.
- Interruption duration is the average duration of customer interruptions.

Distribution Reliability Indices

- System Average Interruption Duration Index (SAIDI): It is commonly referred to as customer minutes of interruption or customer hours, and is designed to provide information as to the average time the customers are interrupted.
- $\text{SAIDI} = \frac{\text{Sum of customer interruption durations}}{\text{Total number of customers served}} = \frac{\sum_{\mathrm{i}} r_{\mathrm{i}} \mathrm{N}_{\mathrm{i}}}{N_T}$
- Where: r_i is the outage time for each interruption event.

Distribution Reliability Indices

System Average Interruption Frequency Index (SAIFI): It is the average frequency of sustained interruptions per customer over a predefined area. It is the total number of customer interruptions divided by the total number of customers served

$$\mathrm{SAIFI} = \frac{\text{Total number of customer interruptions}}{\text{Total number of customers served}}$$

$$= \frac{\sum_{\mathrm{i}} \lambda_{\mathrm{i}} \mathrm{N}_{\mathrm{i}}}{N_T}$$

Where: λ_i is the failure rate at load point i and N_i is the number of interrupted customers for each interruption event during the reporting period at load point i. N_T is the total no of customers served for the area.

Distribution Reliability Indices

- Customer Average Interruption Duration Index (CAIDI): It is the average time needed to restore service to the average customer per sustained interruption. It is the sum of customer interruption durations divided by the total number of customer interruptions.
- $$\mathrm{CAIDI} = \frac{\text{Sum of customer interruption durations}}{\text{Total number of customers interruptions}} = \frac{\sum_i r_i N_i}{\sum_i \lambda_i N_i} = \frac{\mathrm{SAIDI}}{\mathrm{SAIFI}}$$

Distribution Reliability Indices

- Average Service Availability Index (ASAI): This index represents the fraction of time (often in percentage) that a customer has power provided during one year or the defined reporting period.
- $\mathrm{ASAI} = \frac{\text{Customer hours of available service}}{\text{Customer hours demanded}} = \frac{\sum_i N_i x8760 - \sum_i r_i N_i}{\sum_i N_i x8760}$

Distribution Reliability Indices

Average Service Unavailability Index (ASUI): This index is the complementary value to the average service availability index (ASAI).

- $\mathrm{ASUI} = \dfrac{\text{Customer hours of unavailable service}}{\text{Customer hours demanded}} = \dfrac{\sum_i r_i N_i}{\sum_i N_i x8760}$

Distribution Reliability Indices

Energy Not Supplied Index (ENS): This index represents the total energy not supplied by the system.

$$\mathrm{ENS} = \sum_{i} L_{a(i)} r_i$$

Where: $L_{a(i)}$ is the average load given by:

$$L_{a(i)} = L_{p(i)} L_{F(i)} = \frac{E_{d(i)}}{t}$$

L_p is the peak load demand, L_F is the load factor, E_d is the total energy demanded in the period of interest t.

Average Energy Not Supplied Index (AENS):

This index represents the average energy not supplied by the system.

$$\mathrm{AENS} = \frac{\text{Total energy not supplied}}{\text{Total number of customers served}}$$

$$= \frac{\sum_{\mathrm{i}} \mathrm{L}_{\mathrm{a(i)}} \mathrm{r}_{\mathrm{i}}}{N_T}$$

Distribution Reliability Indices

Average Customer Curtailment Index (ACCI):
This index represents the total energy not supplied per affected customer by the system.

- $$\mathrm{ACCI} = \frac{\text{Total energy not supplied}}{\text{Total number of customers affected}} = \frac{\sum_i L_{a(i)} r_i}{\sum_i N_o}$$

- Where: $L_{a(i)}$ is the average load, N_o is the number of customers affected.

Distribution Reliability Indices

Average Load Interruption Frequency Index (ALIFI): This factor is analogous to the System Average Interruption Frequency Index (SAIFI) and describes the interruptions on the basis of connected load (kVA) served during the year by the distribution system.

$$\mathrm{ALIFI} = \frac{\text{Total load interruption}}{\text{Total connected load}} = \sum_{i=1}^{m} \frac{L_i}{L}$$

Where: m is number of interruptions in a subdivision of the network (feeder, substation, operating district, etc.) for a given time period, L is total connected load (kVA) in subdivision, L_i is total connected load (kVA) interrupted by i^{th} interruption.

Reliability Data

Country	SAIFI Int. /customer/Year	SAIDI Hrs. /customer/Year
German	0.5	0.383
Italy	2.2	0.967
Netherlands	0.3	0.55
Spain	2.2	1.73
Ethiopia	20	25
Addis Center	120	43.8
Adama City	176	141
Jimma City	321	184

Impact of Station Arrangement on Reliability

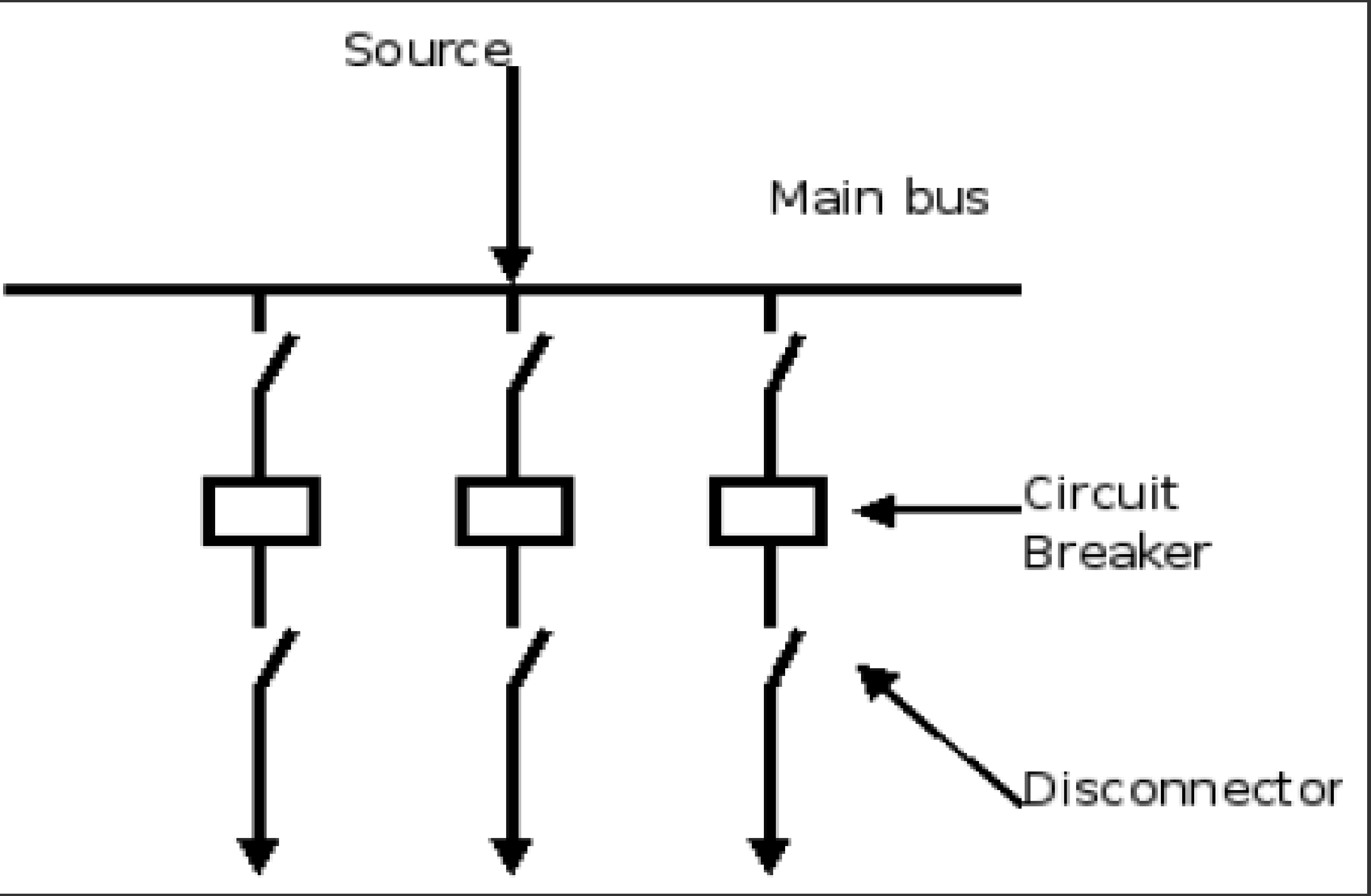
- The feeder and CB arrangement has an impact on the reliability of the system.

Station Arrangement

Radial feeder arrangement

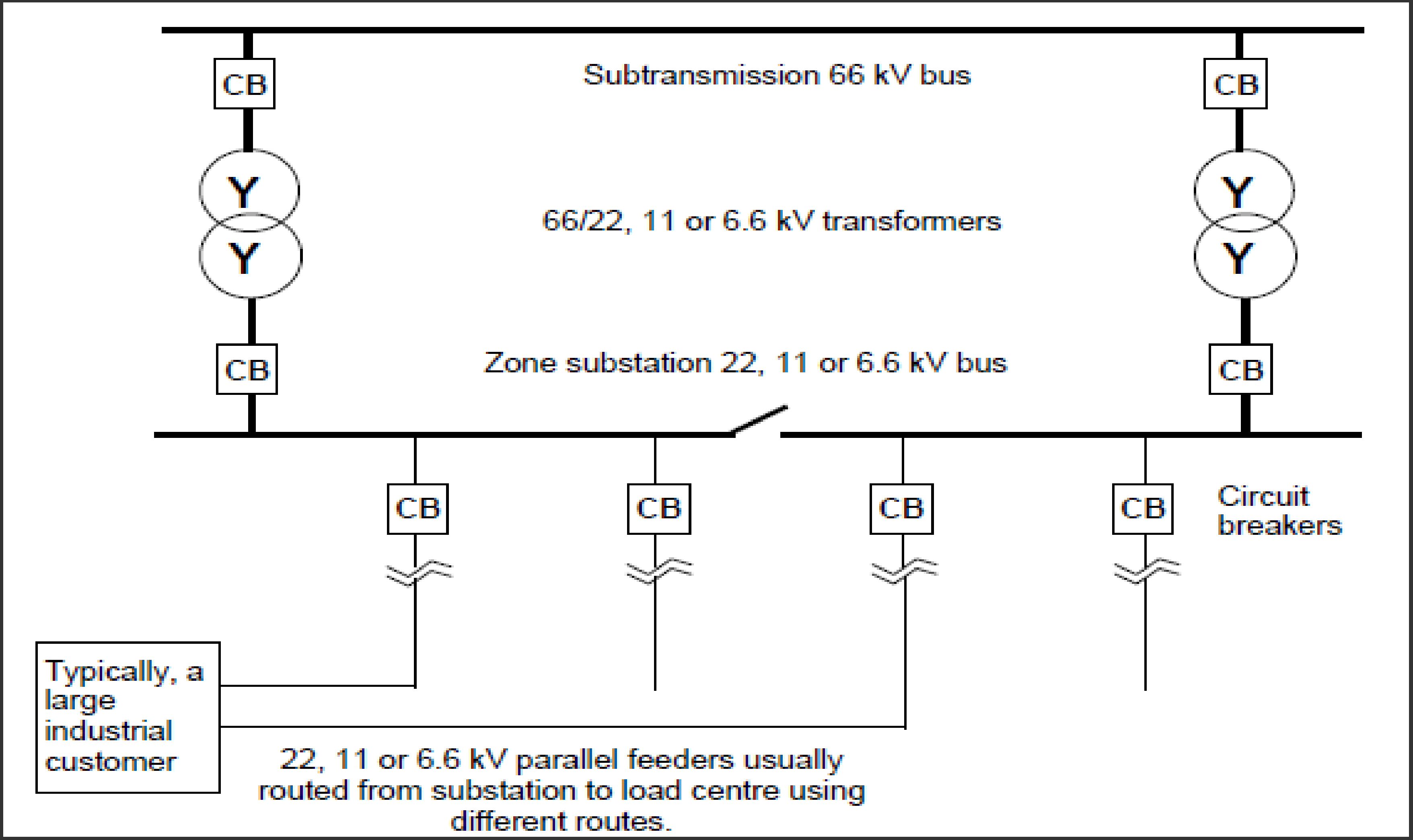
- Fig. shows the single-line diagram of a simplified single bus arrangement. It is the simplest arrangement with the worst reliability indexes. In the arrangement shown, the maintenance of breakers has to be undertaken with the outgoing line disconnected, and thus the load experiences a long service interruption.

Station Arrangement



Planning and Design Considerations

Parallel feeders



Feeder Switching Arrangement

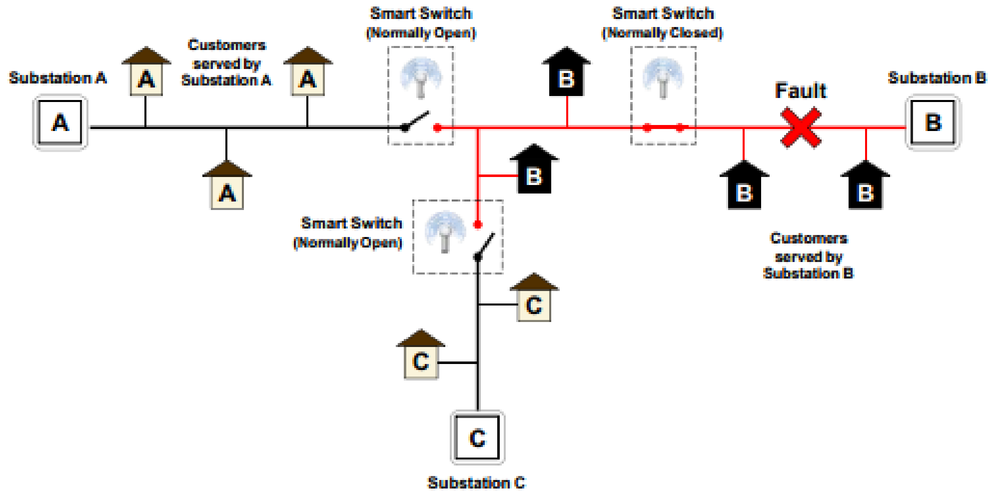
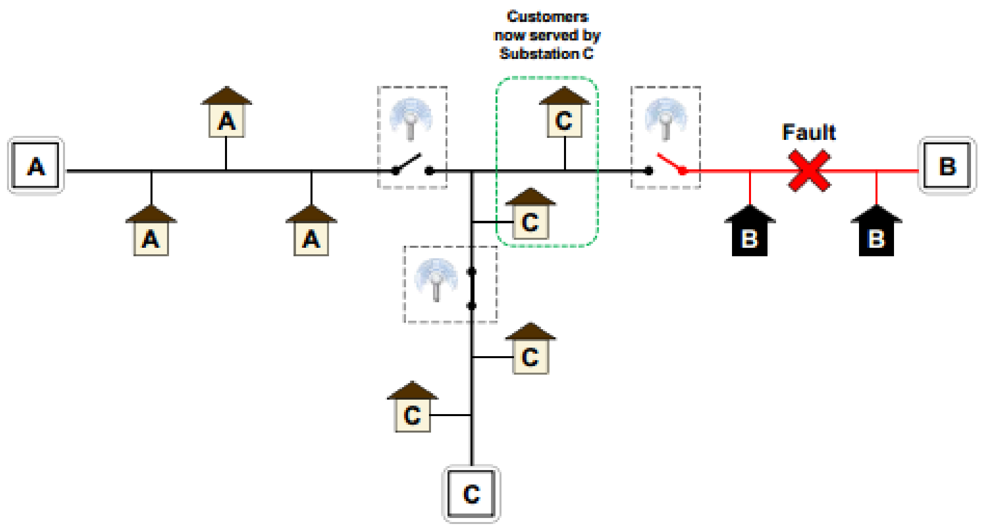
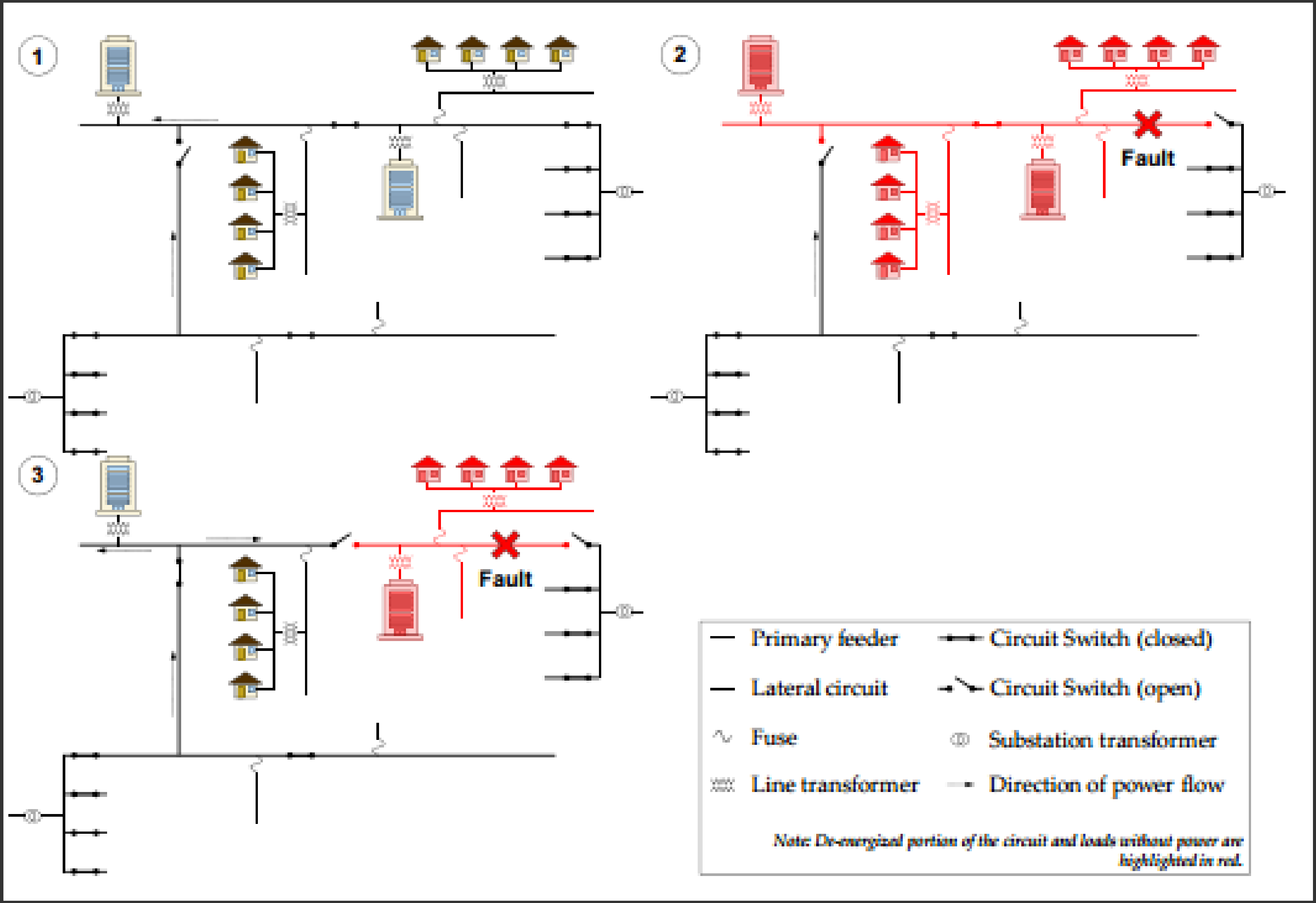


Figure E-1. Configuration of Feeder Before Switching

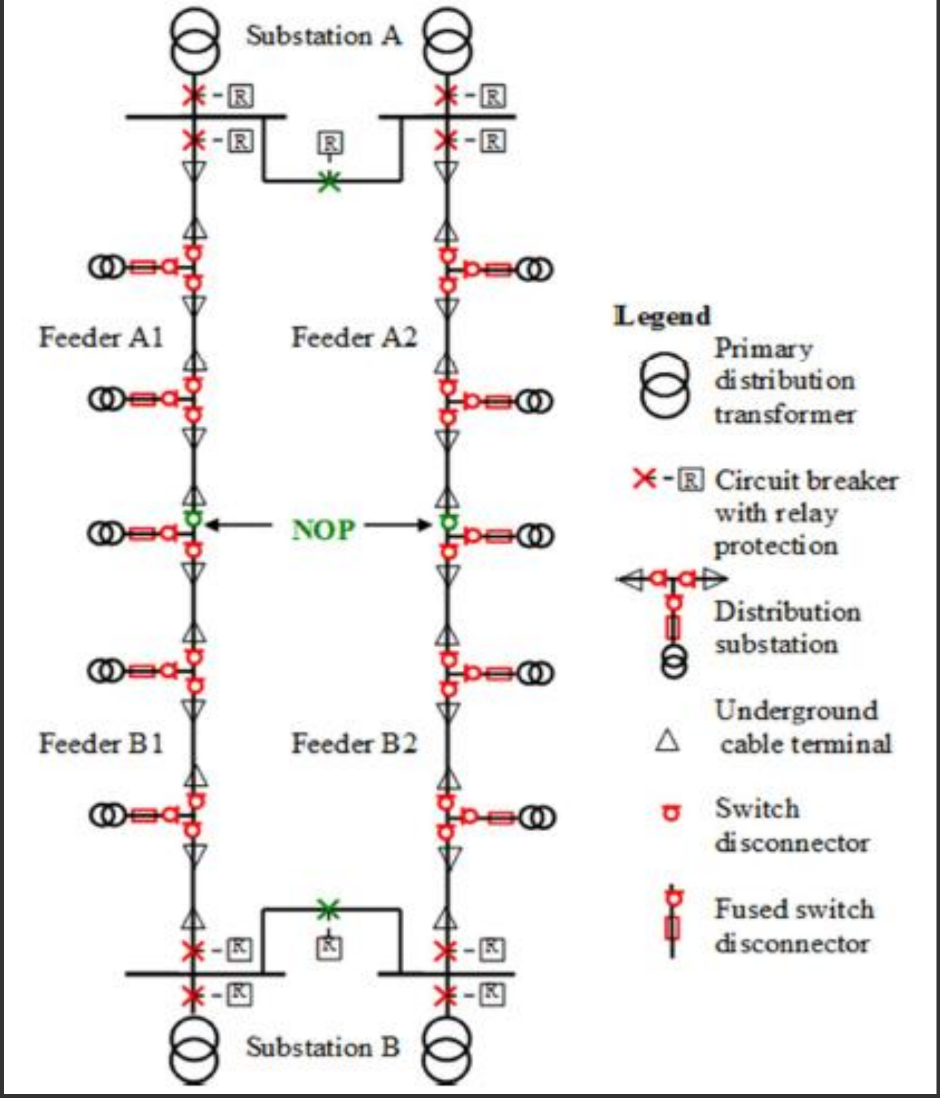


Looped Feeder Switching Arrangement

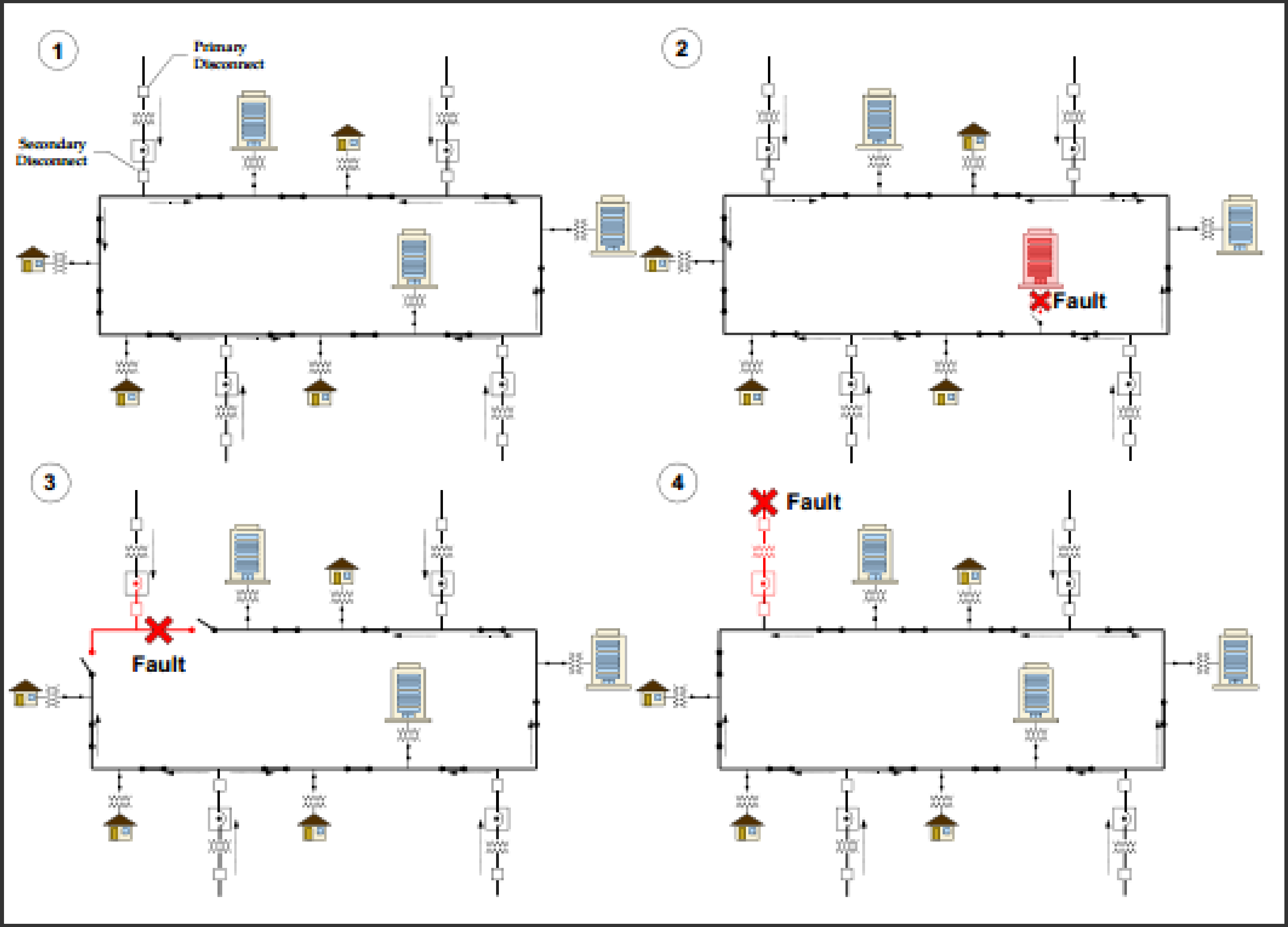


Planning and Design Considerations

Network System



Network Feeder Switching Arrangement



Economics of Reliability

Outage costs are generally divided between

- utility outage costs and
- customer outage costs.

Economics of Reliability

Utility outage costs include the

- loss of revenue for energy not supplied, and
- the increased maintenance and repair costs to restore power to the customers affected.

The maintenance and repair costs can be quantified as

$$C_{m\&r} = \sum_{i}^{n} C_i + C_{comp}$$

Where: C_i is the labor cost for each repair and maintenance action, and C_{comp} is the component replacement or repair cost.

Economics of Reliability

The total utility cost for an outage is:

$$C_{out} = (ENS) x (cost/kWh) + C_{m\&r}$$

Where: ENS is the Energy Not Supplied.

Economics of Reliability

- While the outage costs to the utility can be significant, often the costs to the customer are far greater. These costs vary greatly by customer type.
- In general, customer outage costs are more difficult to quantify
- The customer outage cost by sector is:

$$COST_i = \sum_{i=1}^{n} IC_i X L_i$$

Where: L_i is the energy demand for load point i.

IC is the interruption cost for the load point.

References

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