Munch, Lunch and Learn:

High Voltage Design

Steve Mackay

- Dean of Engineering
- Worked for 30 years in Industrial Automation
- 30 years experience in mining, oil and gas, electrical and manufacturing industries

Munch, Lunch and Learn: High Voltage Design

- During the session, a brief review of the key concepts of High Voltage Design referring to the applicable standards
- Update your knowledge on HV design and installations issues
- Review the essentials of AS 2067-2008 standard

AS2067 – 2008

Substations & HV

Installations exceeding 1kV$_{ac}$

AS 2067- Scope

High voltage installation

- **Electricity network substation**, under control of electricity network operator or entity authorized by license/other legal instrument to convey electricity
- High voltage parts of electrical installation of **power station** including all auxiliary systems, interconnecting lines, cables between power stations, if on same site
- High voltage parts of **electrical installation not covered in (a) and (b) above.** May include but not limited to **consumer and customer electrical** installations serving premises such as factories, commercial facilities, industrial plants, institutional facilities and mine sites”

Scope & definitions

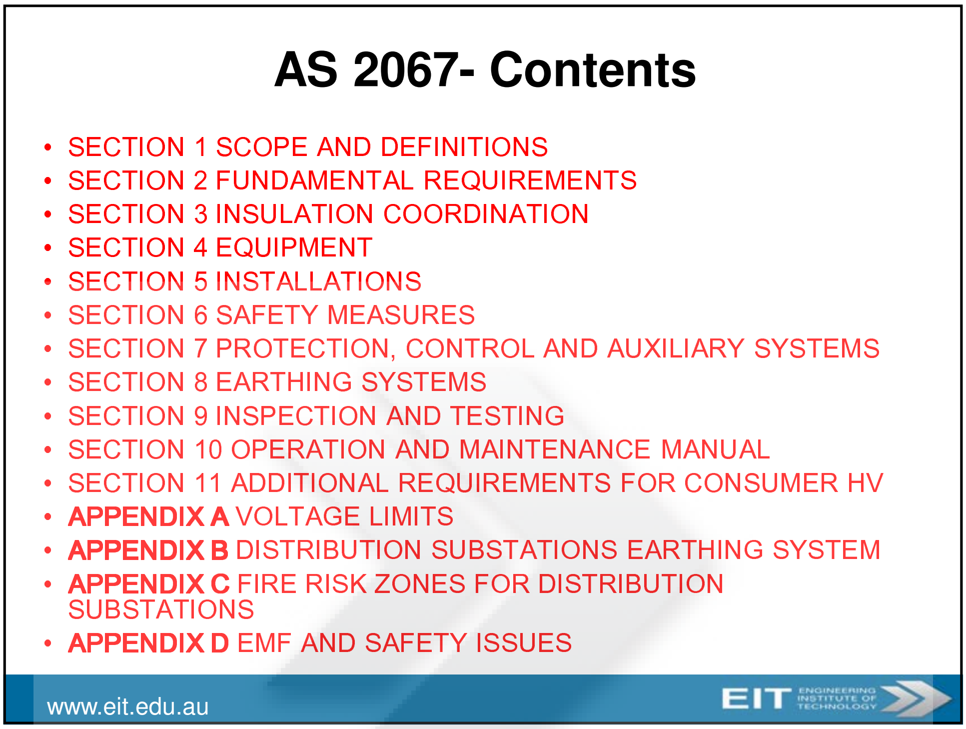
- AS 2067 refers to mine site electrical installations by exception; Standard applies to mine site electrical installations, parts of such installations for which mining specific legislation does not set other or additional requirements
- AS 2067 contains mandatory requirements for Western Australian mine sites as per “*Mines Safety and Inspection Regulations” 1995* r. 5.3

AS 2067- Exclusions

- AS 2067 does not apply to design, erection of any of following:
  - Overhead lines, underground cables between separate installations *(Dealt with in AS/NZS 7000)*
  - Ship and offshore installations
  - Mine site electrical installations, parts of such installations *(Fixed infrastructure compliant with AS/NZS 3000 covered by AS 2067)*
  - Switchgear and/or transformers and/or electrical equipment located within closed electrical operating area supplied at LV and where contact cannot be made with HV conductors.
    (*e.g. X-ray equipment)*
  - Test sites

AS 2067- Status

- AS 2067:2008 *"Substations and high voltage installations exceeding 1kV A.C." (replacing AS 2067:1984 "Switchgear assemblies and ancillary equipment for alternating voltages above 1kV")*
- Amendment 1 of AS 2067:2008 published in 2010
- Project approved by Standards Australia to review AS2067 – commenced in 2012
  - Sub-committees have been established to consider:
    - Earthing of installations
    - Arc flash hazards of electrical installations



AS 2067- Contents

- SECTION 1 SCOPE AND DEFINITIONS
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- SECTION 3 INSULATION COORDINATION
- SECTION 4 EQUIPMENT
- SECTION 5 INSTALLATIONS
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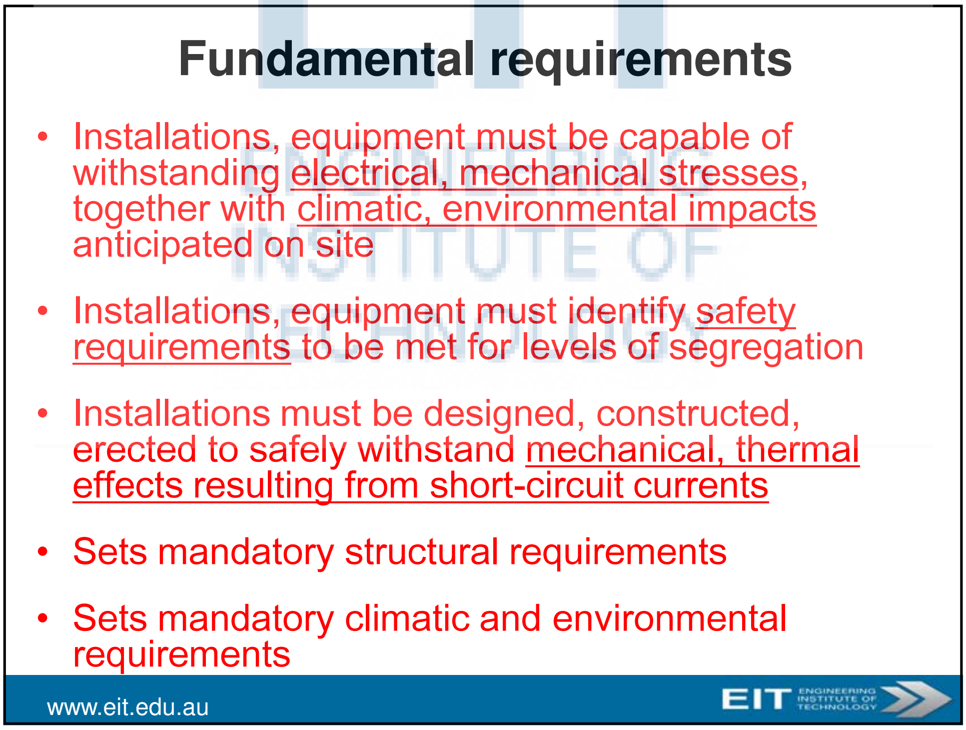
- SECTION 7 PROTECTION, CONTROL AND AUXILIARY SYSTEMS
- SECTION 8 EARTHING SYSTEMS
- SECTION 9 INSPECTION AND TESTING
- SECTION 10 OPERATION AND MAINTENANCE MANUAL
- SECTION 11 ADDITIONAL REQUIREMENTS FOR CONSUMER HV
- **APPENDIX A** VOLTAGE LIMITS
- **APPENDIX B** DISTRIBUTION SUBSTATIONS EARTHING SYSTEM
- **APPENDIX C** FIRE RISK ZONES FOR DISTRIBUTION SUBSTATIONS
- **APPENDIX D** EMF AND SAFETY ISSUES



Fundamental requirements

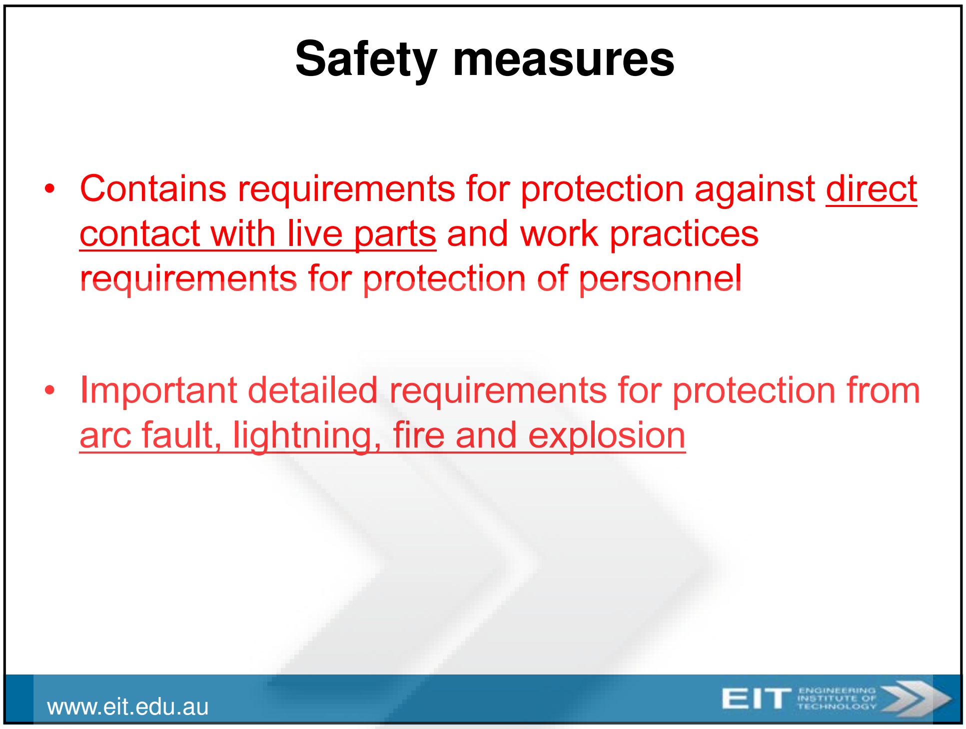
- Installations, equipment must be capable of withstanding electrical, mechanical stresses, together with climatic, environmental impacts anticipated on site
- Installations, equipment must identify safety requirements to be met for levels of segregation
- Installations must be designed, constructed, erected to safely withstand mechanical, thermal effects resulting from short-circuit currents
- Sets mandatory structural requirements
- Sets mandatory climatic and environmental requirements

Equipment

- Covers specific primary equipment selection requirements
- Includes circuit breakers, disconnectors, power transformers, reactors, gas insulated switchgear (GIS), CTs, VTs, surge arresters, and capacitor banks
- AS 2374 power transformers, AS 62271 HV switchgear and control gear contain additional detailed requirements
- Additional specific requirements for cables
- Overhead lines shall comply with C(b)1

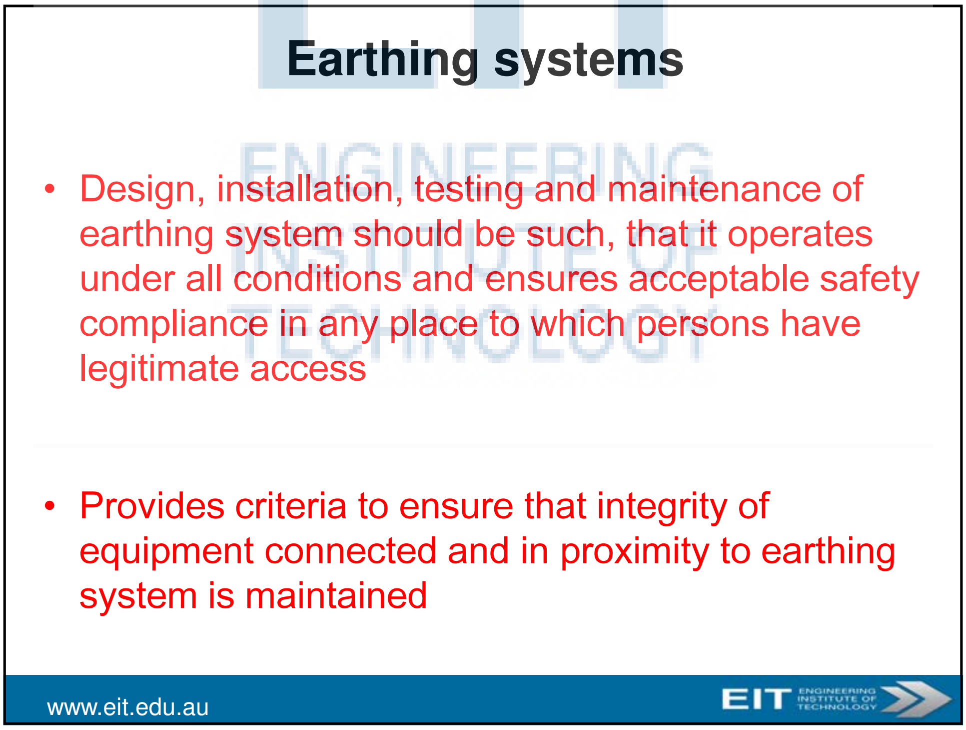
Installation

- General requirements for circuit arrangement, circuit documentation, lighting, operational safety and labelling
- Specific requirements for open type indoor, outdoor installations
- Specific requirements for indoor switchboard installations
- Specific requirements for buildings including prefabricated substations, installations on mast, pole or tower
- Contains drawings of operational application of safety clearances



Safety measures

- Contains requirements for protection against direct contact with live parts and work practices requirements for protection of personnel
- Important detailed requirements for protection from arc fault, lightning, fire and explosion



Earthing systems

- Design, installation, testing and maintenance of earthing system should be such, that it operates under all conditions and ensures acceptable safety compliance in any place to which persons have legitimate access
- Provides criteria to ensure that integrity of equipment connected and in proximity to earthing system is maintained

Earthing - Safety criteria

- Shock hazard to human beings - Current that is sufficient to cause ventricular fibrillation flowing through region of the heart
- Current limit, for power-frequency purposes, shall be derived from AS/NZS 60479.1
- For HV installation design, this current limit should be translated into voltage limits for comparison with calculated step and touch voltages, taking into account impedance present in body current path

Earthing - Safety voltage limits

- Shall take into account following factors:
  - Proportion of current flowing through region of heart (based on Heart Current Factor, Table 5 in AS/NZS 60479.1:2002);
  - Permissible ventricular fibrillation (based on Figure 14 in AS/NZS 60479.1:2002)
  - Body impedance along current path (based on values of Table 5.1 of AS/NZS 60479.1:2002)
  - Resistance between body contact points (e.g. metal structure to hand including glove, feet to ground including shoes/gravel)
  - Fault duration
  - Probability of fault occurrence, presence of human beings in location where they will be exposed to voltage

Insulation coordination

- Insulation coordination *shall be* in accordance with AS 1824 “Insulation Coordination”
- However, Basic Impulse Level (BIL) coordination is difficult to inspect
- Insulation strength must be coordinated to withstand **lightning and switching impulse level**
- Must have a coordinated BIL - Power transformers, earthing compensators, circuit breakers, CTs, VTs, cables, cable joints, cable sealing ends

Insulation coordination

- Process of determining proper insulation levels of various components in power system and their arrangements
- Selection of insulation structure that will withstand voltage stresses to which system/equipment will be imposed to, together with proper surge arrester
- Process is determined from known characteristics of voltage surges and characteristics of surge arresters

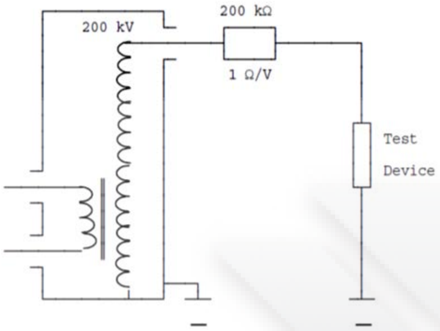
Basic insulation level (BIL)

- Insulation strength of equipment (transformers, circuit breakers, etc.) should be higher than that of lightning arresters, other surge protective devices
- To protect equipment from overvoltages, necessary to fix insulation level for system so that no insulation should break down or flash over below this level
- Reference insulation level expressed as impulse crest (or peak) voltage with standard wave not longer than 1.2 x 50 μsec wave
- Impulse takes 1.2 μsec to reach peak and then decays to 50% of peak in 50 μsec

Power frequency test

- Sustained low frequency tests conducted at 50 Hz
- Performed on:
  - Insulation materials to determine dielectric strength, dielectric loss
  - Routine testing of supply mains
  - Work tests on HV transformers, porcelain insulators and such apparatus
- Tests carried out at highest possible voltage (e.g. 2000 kV for insulators, HV cables)
- A.C. HV tests as routine tests on LV equipment:
  - 1kV + (2 x Working voltage)
  - 1.5 ~ 2 kV for a 230 V equipment

Power frequency test



- HV test voltage generated using transformer - need not be of high power rating
- Transformers designed with poor regulation – Reduced voltage during insulation breakdown
- Series resistance to limit breakdown current

High Voltage Design and Installations Master Class

2. Power system planning

Learning objectives

- Planning criteria
- Load forecasting
- Voltage selection
- Site conditions
- Security of supply
- System studies
  - Load flow analysis
  - Fault calculations

Importance of planning

- Client often unsure of electrical features/ implications, may need assistance. May not have experienced electrical team.
- Design engineer not always aware of client's specific needs
- Different parties involved in design must follow same rules
- Outcome - Often confusion, reworking, arguments, delays and budget blowouts
- Client may get a system that doesn't always meet expectations

Meeting with customer

- Need to agree on basic system requirements, power supply conditions
- Client needs to liaise with Supply Authority or packaged power station vendor
- Details that do not affect cost/ program can be discussed later
- Sooner all features are agreed, lesser the confusion, time wastage

Planning criteria

- Systems:
  - Safety
  - Reliability
  - Flexibility
- Load forecasting (average, peak, base load, etc.)
- Voltage selection
- Power quality (harmonics, voltage flicker, BIL, etc.)

Cont….

Planning criteria

- Site conditions (IP rating, soil resistivity, etc.)
- Security of supply (duration of outages, frequency, Busbar configurations)
- System studies
  - Load flow analysis
  - Fault calculations

System safety

- Enough clearance distances between live parts, between live parts and ground
- Efficient grounding system - Transformer neutral grounding, soil resistivity, numbers of earthing rods, size of earthing cables
- Appropriate recloser shots, timings. Not enabling reclosers in close vicinity of residential areas
- Fast clearance of faults
- Adequate insulation discs on O/H line insulators

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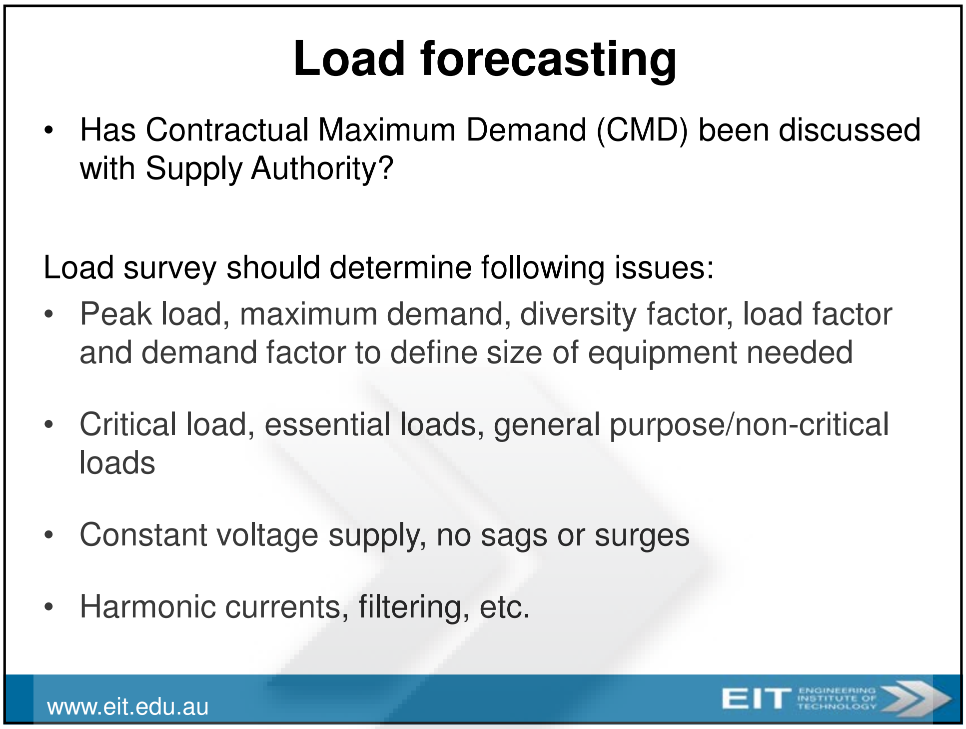
System safety

- Appropriate size cables, lines - Ampacity, short circuit capacity
- Enabling switch-onto-fault (SOTF) feature on numerical relays
- Application of surge arresters at power transformer bushings
- Adopting simple systems instead of complicated systems (e.g. single bus instead of main and transfer bus)

System flexibility

- Can add/change loads without difficulty - Proper busbar configurations, connections
- Spare feeders even if breakers are not furnished
- Spare space in substations - Future transformer bays, incoming feeders for any significant load rise in future
- Enough ampacity, short circuit capability for line conductors, cables with regard to prospective future load increases
- Enough capacity for transformers to prevent overloading during future expansion projects



Load forecasting

- Has Contractual Maximum Demand (CMD) been discussed with Supply Authority?

Load survey should determine following issues:

- Peak load, maximum demand, diversity factor, load factor and demand factor to define size of equipment needed
- Critical load, essential loads, general purpose/non-critical loads
- Constant voltage supply, no sags or surges
- Harmonic currents, filtering, etc.

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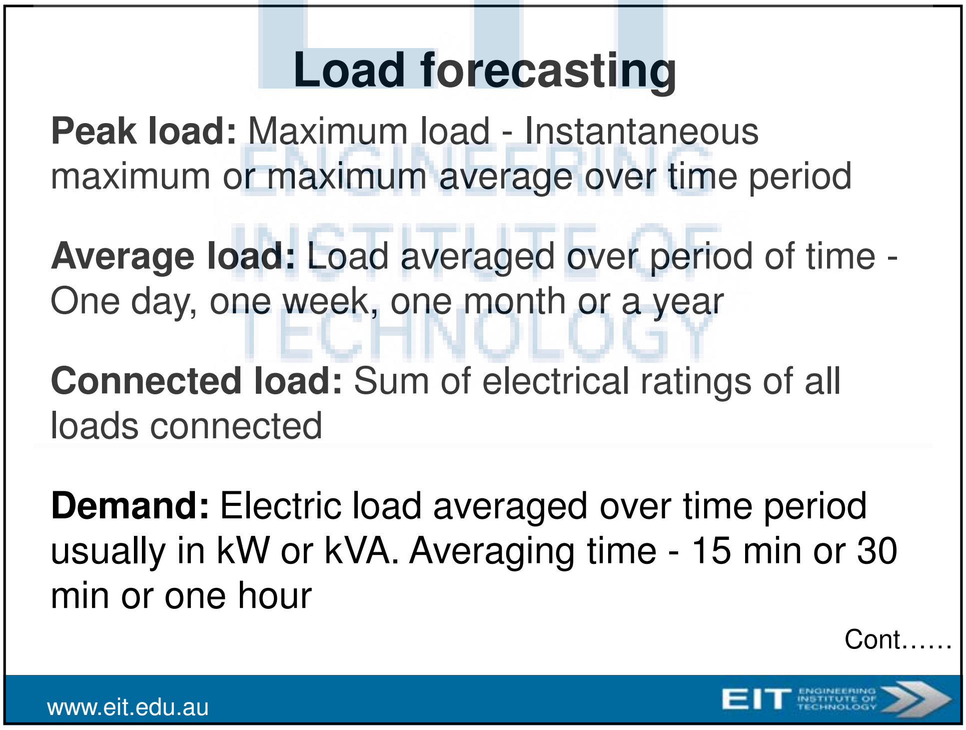

Load forecasting

Peak load: Maximum load - Instantaneous maximum or maximum average over time period

Average load: Load averaged over period of time - One day, one week, one month or a year

Connected load: Sum of electrical ratings of all loads connected

Demand: Electric load averaged over time period usually in kW or kVA. Averaging time - 15 min or 30 min or one hour

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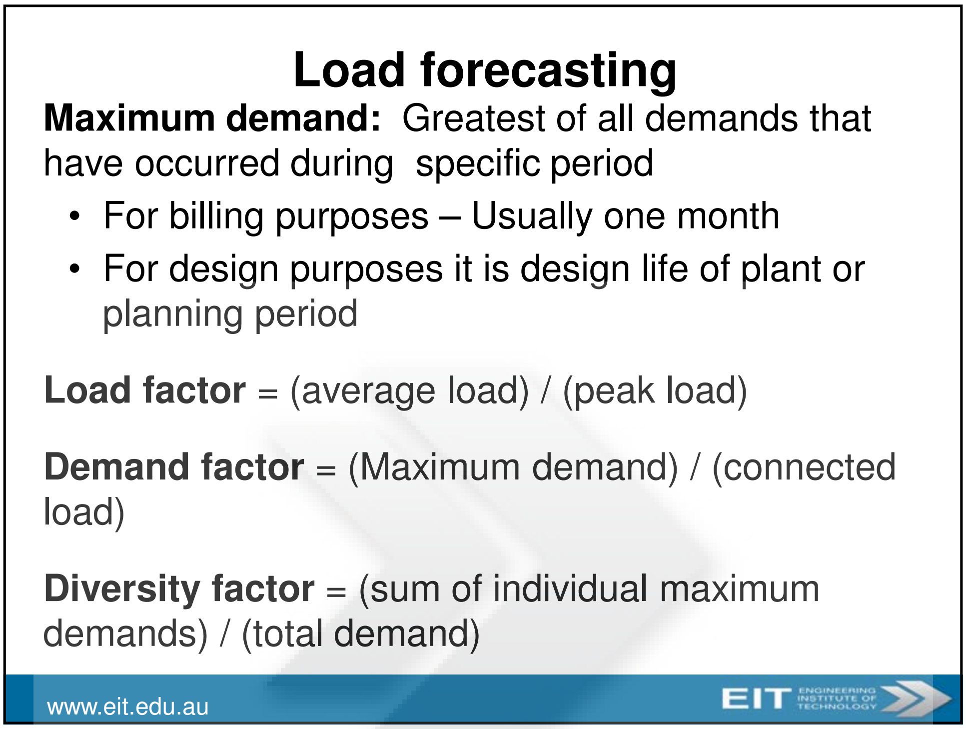

Load forecasting

Maximum demand: Greatest of all demands that have occurred during specific period

- For billing purposes – Usually one month
- For design purposes it is design life of plant or planning period

Load factor = (average load) / (peak load)

Demand factor = (Maximum demand) / (connected load)

Diversity factor = (sum of individual maximum demands) / (total demand)

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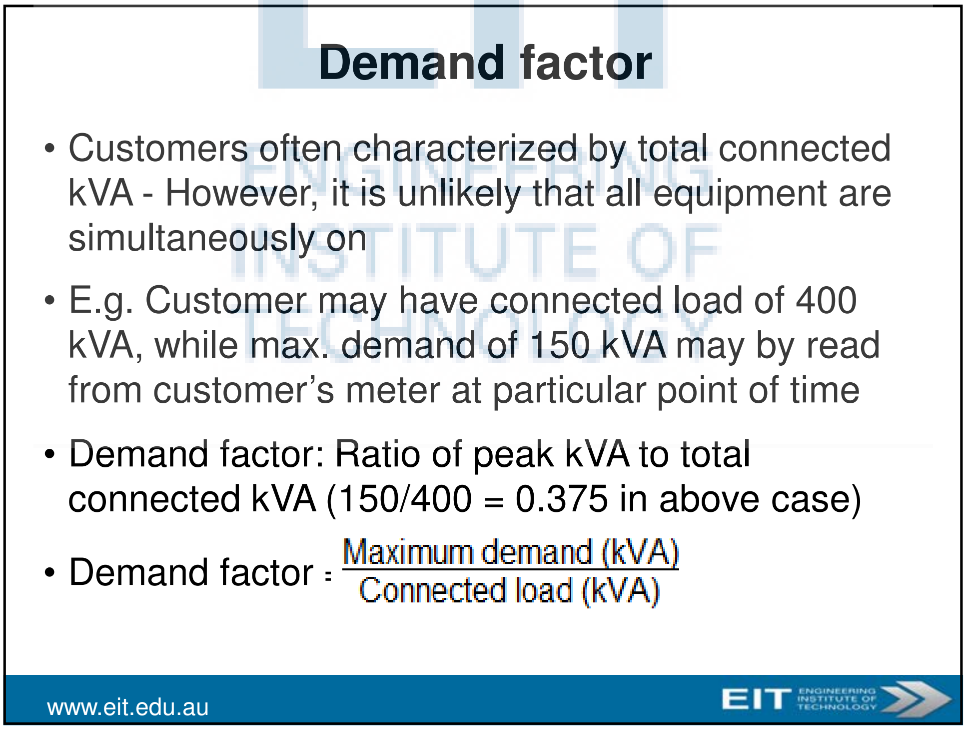

Demand factor

- Customers often characterized by total connected kVA - However, it is unlikely that all equipment are simultaneously on
- E.g. Customer may have connected load of 400 kVA, while max. demand of 150 kVA may by read from customer’s meter at particular point of time
- Demand factor: Ratio of peak kVA to total connected kVA (150/400 = 0.375 in above case)
- Demand factor = $\frac{\text{Maximum demand (kVA)}}{\text{Connected load (kVA)}}$

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Diversity factor

- Most loads are turned on/off randomly
  - Probability of all customers experiencing same peak demand simultaneously is small
  - Probability decreases as number of customers increases
- Distribution systems can be designed to supply less power than sum of individual customer peak demands
- Diversity factor: Ratio of sum of individual customer peak demands to peak system demand
- Diversity factor = $\frac{\sum \text{Individual Peak Demands}}{\text{Peak System Demand}}$

Demand factor and Diversity factor - Calculations

There are four individual feeders having connected loads of 250 kVA, 300 kVA, 350 kVA and 100 kVA. The demand factors for these are 80%, 70%, 75% and 90% respectively. The diversity factor is 1.6.

Calculate the:

1) Total demand of the loads and
2) Size of the transformer required to supply these loads.

Demand factor and Diversity factor - Calculations

Solution:

Calculating demand for feeder loads

250 kVA x 80% = 200 kVA
300 kVA x 70% = 210 kVA
350 kVA x 75% = 262.5 kVA
100 kVA x 90% = 90 kVA

Total demand of the loads = 762.50 kVA

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Demand factor and Diversity factor - Calculations

Total demand of the loads = 762.50 kVA
Diversity factor provided is 1.6
The actual demand of all the loads = 762.5 / 1.6
= 476.6 kVA

Therefore size of transformer required = 500 kVA

Power quality

- Supply authority must provide fault levels at Point of Supply
- Supply authorities nominate power factor limits at Point of Supply (sometimes a specific contract agreement)
- Power authorities concerned about harmonic distortion at Point of Supply
- Supply earthing affects plant earthing, Basic Insulation Levels (BIL)
- Need protection details at Point of Supply for grading with downstream protection devices

Voltage limits

- Defining site voltage levels, limits a common problem
- One criterion could be to restrict voltage levels to max. voltage drop of x%. Can be confusing, as it often does not consider upstream voltage values
- Better to nominate absolute values of voltage at a node, avoiding concerns about which elements of supply system are involved

Voltage level selection

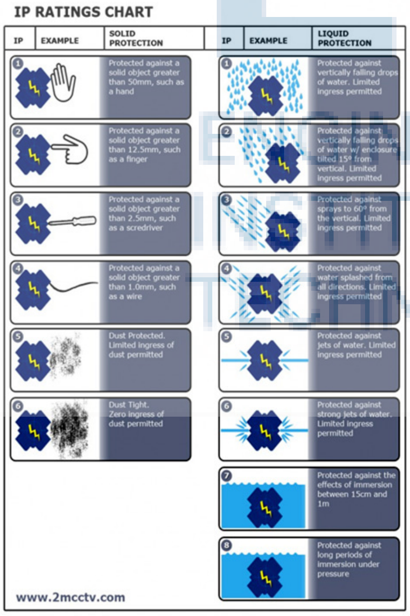
- Important for economic, operational aspects of system
- Higher the voltage, lower the current needed for any load
- Conductor size and voltage drop in feeders directly result of current to be carried
- Too small conductors will not have physical strength to handle all conditions
- Higher voltages can be more expensive because of increased insulation

Voltage level selection

Voltage (V)	Current (A)	Load (KVA)	80% KVA (Load)
480	200	166	133
	400	333	266
	600	500	400
	800	667	532
	1200	1000	800
	1600	1330	1065
	2000	1663	1330
	3000	2500	2000
	4000	3325	2660
2400	400	1663	1330
	800	3333	2660
	1200	5000	4000
	2000	8313	6650
4160	600	4325	3460
	1200	8650	6920
	2000	14410	11530
	3000	21600	17280
12470	600	13720	10975
	1200	25920	20735
	2000	43200	34560
	3000	64700	51835
13200	600	13270	10975
	1200	27435	21950
	2000	45725	36580
	3000	68590	54870
13800	600	14340	11475
	1200	28680	22950
	2000	47800	38345
	3000	71700	57365

Site conditions

- Design ambient temperatures, air conditioning temperature limits plus AC security
- Ground temperatures, soil thermal resistivity
- Wind conditions including those for overhead line summer ratings
- Dust, rain, condensation, corrosion, leading to IP ratings
- Ground conditions including termite prevalence or incompact soil



IP RATINGS CHART

IP	EXAMPLE	SOLID PROTECTION	IP	EXAMPLE	LIQUID PROTECTION
1		Protected against a solid object greater than 50mm, such as a hand	1		Protected against vertically falling drops of water. Limited ingress permitted
2		Protected against a solid object greater than 12.5mm, such as a finger	2		Protected against vertically falling drops of water w/ enclosure tilted 15º from vertical. Limited ingress permitted
3		Protected against a solid object greater than 2.5mm, such as a scredriver	3		Protected against sprays to 60º from the vertical. Limited ingress permitted
4		Protected against a solid object greater than 1.0mm, such as a wire	4		Protected against water splashed from all directions. Limited ingress permitted
5		Dust Protected. Limited ingress of dust permitted	5		Protected against jets of water. Limited ingress permitted
6		Dust Tight. Zero ingress of dust permitted	6		Protected against strong jets of water. Limited ingress permitted
			7		Protected against the effects of immersion between 15cm and 1m
			8		Protected against long periods of immersion under pressure

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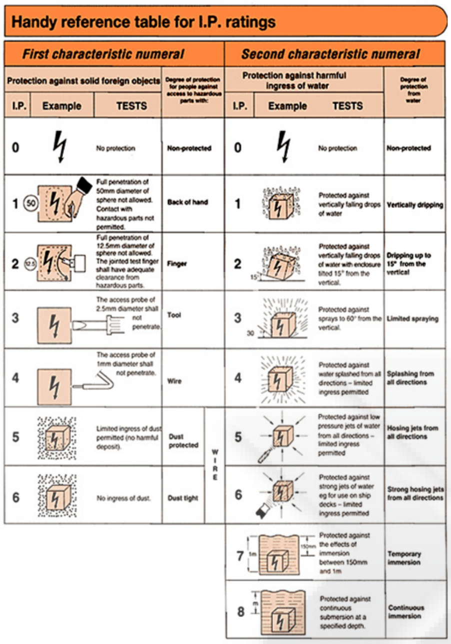
IP Code, Ingress Protection Rating

- Classifies, rates degree of protection provided against intrusion of:
  - Solid objects (including body parts like hands, fingers)
  - Dust
  - Accidental contact
  - Water

in *mechanical casings* and with electrical enclosures



Handy reference table for I.P. ratings

First characteristic numeral					Second characteristic numeral			
Protection against solid foreign objects			Degree of protection for people against access to hazardous parts with:		Protection against harmful ingress of water			Degree of protection from water
I.P.	Example	TESTS			I.P.	Example	TESTS	
0		No protection	Non-protected		0		No protection	Non-protected
1	(50)	Full penetration of 50mm diameter of sphere not allowed. Contact with hazardous parts not permitted.	Back of hand		1		Protected against vertically falling drops of water	Vertically dripping
2	(12.5)	Full penetration of 12.5mm diameter of sphere not allowed. The jointed test finger shall have adequate clearance from hazardous parts.	Finger		2	15°	Protected against vertically falling drops of water with enclosure tilted 15° from the vertical.	Dripping up to 15° from the vertical
3		The access probe of 2.5mm diameter shall not penetrate.	Tool		3	30	Protected against sprays to 60° from the vertical.	Limited spraying
4		The access probe of 1mm diameter shall not penetrate.	Wire		4		Protected against water splashed from all directions – limited ingress permitted	Splashing from all directions
5		Limited ingress of dust permitted (no harmful deposit).	Dust protected	WIRE	5		Protected against low pressure jets of water from all directions – limited ingress permitted	Hosing jets from all directions
6		No ingress of dust.	Dust tight		6		Protected against strong jets of water eg for use on ship decks – limited ingress permitted	Strong hosing jets from all directions
					7	1m 150mm	Protected against the effects of immersion between 150mm and 1m	Temporary immersion
					8	m	Protected against continuous submersion at a specified depth.	Continuous immersion

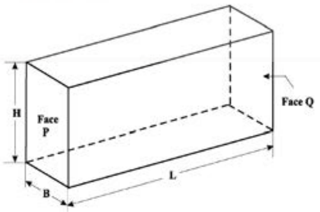
IP22 protection:

- Protection against insertion of fingers
- Will not be damaged, become unsafe during specified test in which it is exposed to vertically or nearly vertically dripping water
- Typical minimum requirement for design of electrical accessories for indoor use

Soil electrical resistivity

- Measure of resistance to current flow in ground
- Earthing effectiveness is a function of low soil resistivity
- Resistivity of soil can vary depending on:
  - Moisture content
  - Conducting salts concentration
  - Compaction level
  - Temperature

Soil resistivity in Ohm meters $p = R * A /$



Area $A = B * H$

Resistance R between faces P and $Q = \rho L / A$

System reliability

- Distribution reliability primarily relates to equipment outages and customer interruptions
- Normal operating conditions - All equipment (except standby equipment) energized and all customers receive power
- Scheduled outages (e.g. maintenance) and unscheduled events disrupt normal operating conditions and can lead to outages, interruptions

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System reliability

- **System Average Interruption Frequency Index**

  SAIFI = (Total number of customer interruptions) / (Total number of customers served)
- **System Average Interruption Duration Index**

  SAIDI = (Total customer interruption durations) / (Total number of customers served)
- **Customer Average Interruption Duration Index**

  CAIDI = (Total customer interruption durations) / (Total number of customer interruptions)

System reliability - Calculations

On 28th of a month five outages were recorded. The table below shows each outage, the duration of the outage, and the number of customers affected by outage. The utility has a total of 50,000 customers. Calculate the following.

a) SAIDI
b) CAIDI
c) SAIFI
d) CAIFI
e) MAIFI

Date	Time	No. of customers	Duration
28th	9:53	10	90
28th	11:02	1000	20
28th	13:15	2	175
28th	20:48	1	120
28th	22:35	1	38

Assume the system had six momentary substation breaker operations on 28th. One breaker operated twice affecting 1015 customers and four other breakers operated once affecting 867, 2005, 1500, and 1330 customers.

System reliability - Calculations

The first outage was at 9:53 in the morning and 10 customers where out of service for 90 minutes (1.5 hours). Therefore, the customer hours are 10 * 1.5 or 15 hours.

Date	Time	No. of customers	Duration	Customer-hours
28th	9:53	10	90	15.00
28th	11:02	1000	20	333.33
28th	13:15	2	175	5.83
28th	20:48	1	120	2.00
28th	22:35	1	38	0.63
Total		1,014	443	356.80

The customer hours are calculated for each outage and then summed for a total of 356.80 customer-hours.
i.e. The result is 356.80 * 60 = 21408 customer-minutes.

System reliability - Calculations

$$\text{SAIDI} = \frac{\text{Sum of all customer interruption durations}}{\text{Total number of customers served}}$$

= 21408/50000
= 0.428 minutes

This says that the average customer was out for 0.428 minutes on the 28th of the month.

$$\text{CAIDI} = \frac{\text{Sum of all customer interruption durations}}{\text{Total number of customer interruptions}} = \frac{\text{SAIDI}}{\text{SAIFI}}$$

= 21408/1014
= 21.1 minutes

On average, any customer who experienced an outage on the 28th was out of service for 21.1 minutes.

System reliability - Calculations

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

= 1014/50000
= 0.020

This says that on the 28th of the month, the customers at this utility had a 0.020 probability of experiencing a power outage.

$$\text{CAIFI} = \frac{\text{Total number of customer interruptions}}{\text{Total number of customers who had at least one interruption}}$$

= 5/1014
= 0.005

This says that the average number of interruptions for a customer who was interrupted is 0.005 times.

System reliability - Calculations

$$\text{MAIFI} = \frac{\text{Total number of customer interruptions less than the defined time}}{\text{Total number of customers served}}$$

MAIFI = ∑ (IDi * Ni) / NT

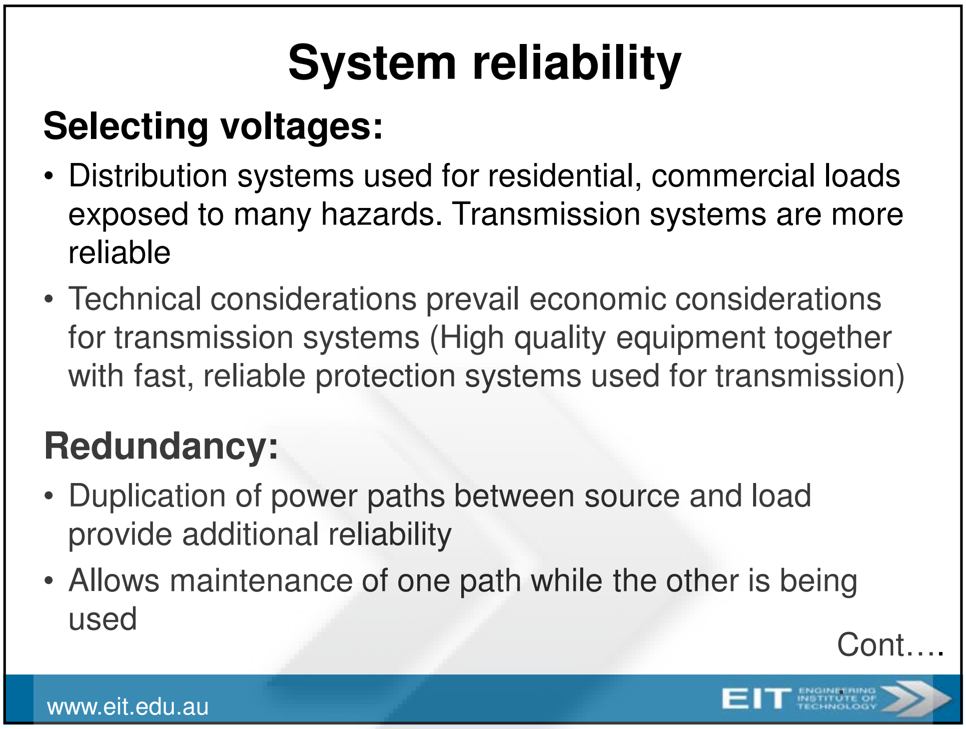
∑(IDi * Ni) = (2 * 1015) + (1 * 867) + (1 * 2005) + (1 * 1500) + (1 * 1330)
= 7732 customer-interruptions

MAIFI = 7732/50000
= 0.154

On average, the customers experienced 0.128 momentary interruptions on the 28th.

Security of supply (S.O.S)

- Categorize site loads into emergency, essential, non-essential loads; Agree on outage criteria and backup arrangement for each
- Permissible out-of-service time - Important parameter in determining backup arrangement for category of supply
- Identify items of plant that can be shed for isolated system
- Failure cause-and-effect analysis will influence switching facilities



System reliability

Selecting voltages:

- Distribution systems used for residential, commercial loads exposed to many hazards. Transmission systems are more reliable
- Technical considerations prevail economic considerations for transmission systems (High quality equipment together with fast, reliable protection systems used for transmission)

Redundancy:

- Duplication of power paths between source and load provide additional reliability
- Allows maintenance of one path while the other is being used

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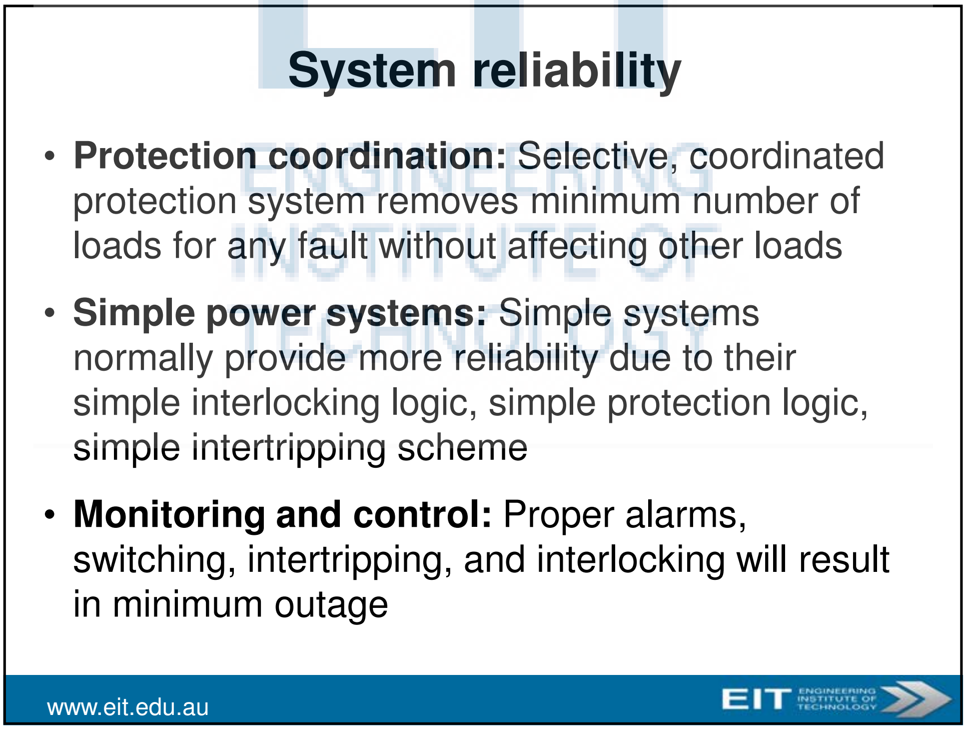

System reliability

- **Protection coordination:** Selective, coordinated protection system removes minimum number of loads for any fault without affecting other loads
- **Simple power systems:** Simple systems normally provide more reliability due to their simple interlocking logic, simple protection logic, simple intertripping scheme
- **Monitoring and control:** Proper alarms, switching, intertripping, and interlocking will result in minimum outage

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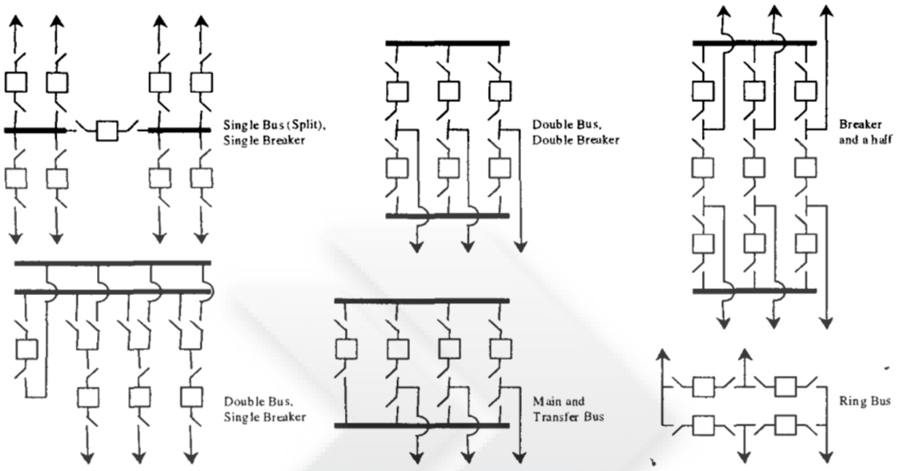
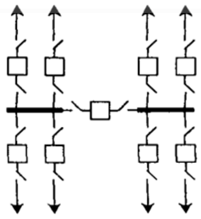
Busbar configurations



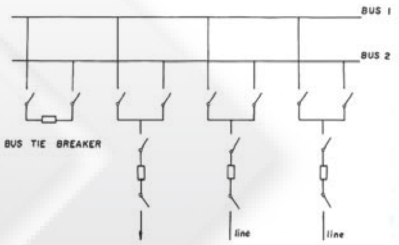
Single busbar with single breaker

- Simple to operate, low cost
- Used generally in small outdoor substations with relatively few outgoing/incoming feeders/lines. Not normally used in major substations
- Economical addition of future feeder bays
- Feeder breaker maintenance involves loss of that circuit
- Minimum reliance on signaling for satisfactory protection
- Each circuit with its own breaker – Plant outage does not necessarily result in loss of supply



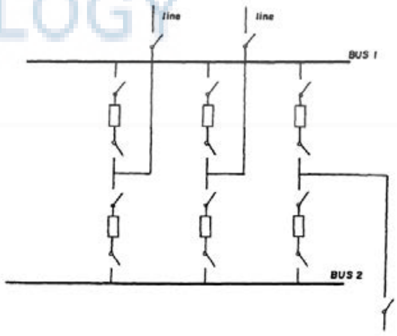
Double busbar with single breaker

- Utilizes single breaker per circuit that can be connected to either bus
- Tie breaker between buses allows circuits to be transferred without being de-energised
- Requires four switches per circuit – Issues like space, maintenance, reliability important
- Double bus with single breaker configuration well suited for GIS applications



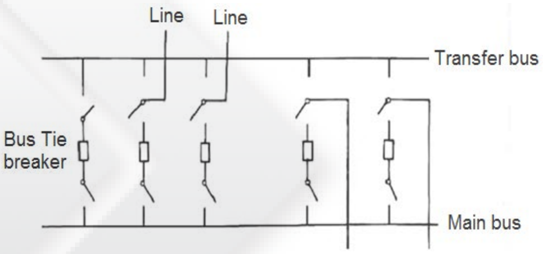
Double busbar with double breakers

- Configuration used for large switching stations
- Requires two breakers for each feeder circuit, makes it expensive
- Each circuit, normally connected to both buses – Makes this configuration reliable and flexible



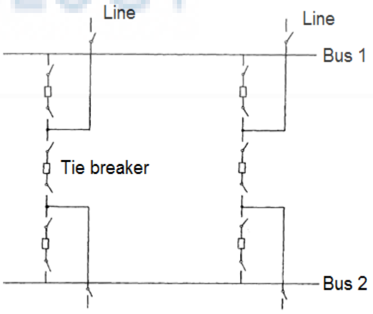
Main and transfer bus

- Configuration used in most distribution systems
- One breaker serves each circuit. Circuits normally connected to main bus – Can be switched to transfer bus using bus tiebreaker
- Transfer bus is standby for emergency purposes
- Circuits on transfer bus not protected by breakers – Fault on one transferred circuit results in outages for all transferred circuits



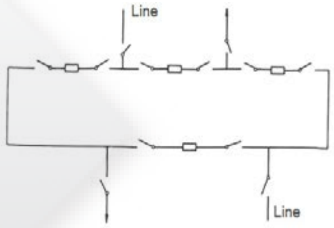
Breaker and a half

- Three series breakers connected between two buses
- All breakers are closed, two main buses energized under normal operating conditions
- Two associated breakers must be opened to trip circuit
- More expensive, but provides high reliability, maintainability and flexibility
- Protective relaying more complex
- Breakers, other system components rated for sum of load of two circuits
- High security against loss of supply



Ring busbar

- Requires only one breaker per circuit - Economical
- Each outgoing circuit has two sources of supply, provides high reliability
- Practical up to five circuits
- Common to initially build a SS as ring bus, convert to breaker and a half when having more requirement
- Natural configuration for GIS applications with any number of circuits
- Protective relaying relatively complex
- Busbar fault causes all circuits to be lost until identified and isolated
- Maintenance of isolator requires outage of both adjacent circuits, unless isolators are duplicated



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