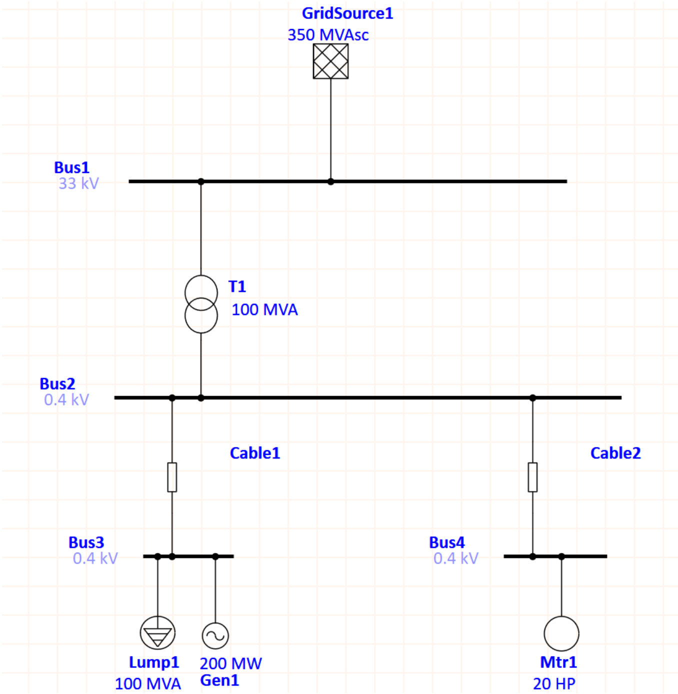
1 One line view drawing

- Cable properties selection

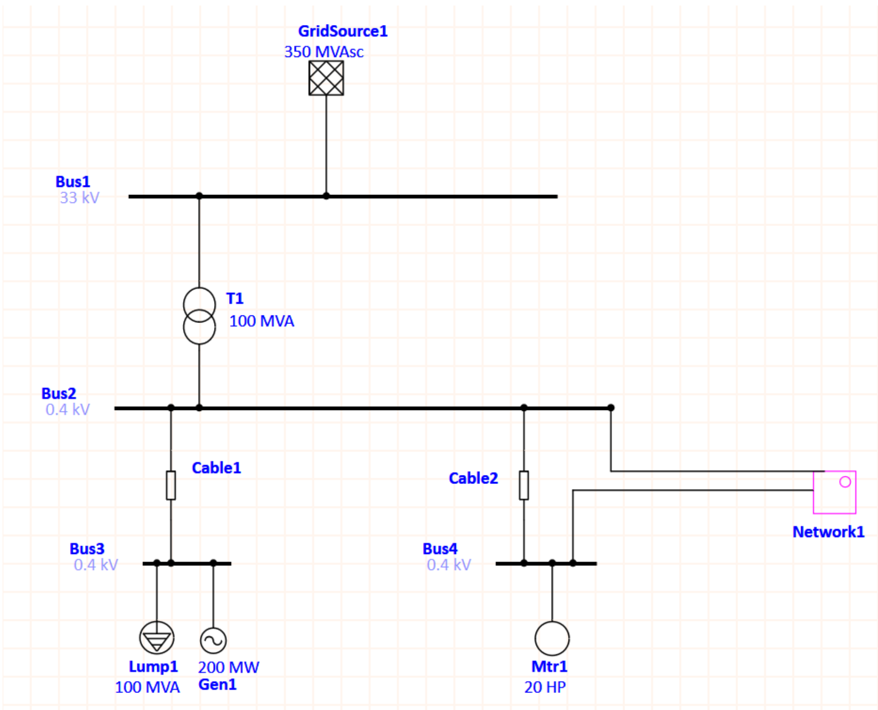


First one-line drawing of ETAP (above), it presents:

The one-line drawing represents a medium-voltage grid connection feeding a low-voltage distribution system, with both loads and local generator connected. ETAP can use this structure for load flow, short-circuit, protection coordination and stability studies.

- Grid source: utility supply with 350 MVAsc short circuit capacity, the upstream source feeding the entire system
- Bus1: a medium voltage bus that is the connection between the grid and the transformer
- Transformer: a step-down transformer that converts 33kV to 0.4 kV making the systems supplies low-voltage distribution network
- Bus2: main low-votage bus, feeds multiple downstream circuits, it acts as a contral LV distribution point
- Cable1: a low voltage feeder cable
- Lump1: it represents large load
- Gen1: a local distributed generator, it can operate in grid-connected mode, island mode, and emergency backup
- Mtr1: a small motor load, 20HP (15kW), it represents a rotating load for motor-starting studies

The function of 'Composite Network' block:



Q: What does the 'composite network' mean here?

- More like a subsystem

2 Transformer Configuration and Sizing

Horsepower to kilowatts: 1 hp = 0.7457 kW

$$kVA = \frac{kW}{PF}$$

The load factor represents how much pf the rated capacity is actually used:

$$kVA_{actual} = kVA_{rated} \cdot Load\ Factor$$

$$Load\ Factor = \frac{P_{avg}}{P_{pk}}$$

Methods of sizing:

- **Total connected load**
  - All connected load are considered regardless of their operating condition and system function. The sizing is performed from the downstream transformer toward the main.
  - This method is a more conservative approach when sizing the transformer and will provide better system voltage profile on the secondary side, but it generates and injects more fault current. This is mainly due to higher kVA transformer rating and consequently higher short-circuit injection to the system.

$$S_{transformer} = 1.2 * \sum S_{each\ load}$$

  - Example: in a grid connection, there has three motor loads (VFD: Variable Frequency Drive):

Loads	Voltage	Rated HP	Power Factor	Eff	VFD pf	VFD eff	Load Factor	kVA Rating
No.1	4160	600	0.85	0.9			1	585.09
No.2	4160	250	0.85	0.95			1	230.96
No.3	4160	600	0.85	0.9	0.95	0.97	1	539.7

    - kVA Rating of No.1: $kVA = (600hp * 0.7457) \div 0.9 \div 0.85 = 585.09\ kVA$

- kVA Rating of No.2: $kVA = (250hp * 0.7457) \div 0.95 \div 0.85 = 230.96\,kVA$
- kVA Rating of No.3: $kVA = (600hp * 0.7457) \div 0.97 \div 0.95 \div 0.9 = 539.7\,kVA$
  - When VFD is considered, the VFD power factor will be considered instead of the motor power factor.
- And the total kVA rating from these three loads is 1355.75 kVA

With the equation $S_{transformer} = 1.2 * \sum S_{each\,load}$, $S_{transformer} = 1626.9kVA$

- So, the kVA rating of the transformer is selected as 2000 kVA.

- **Total operating load (Load Factor is considered)**

$$S_{transformer} = 1.2 * \sum (LF * S)_{each\,load}$$

  - Typical power transformer are equipped with fixed taps that are designed to adjust the transformer voltage at the primary or secondary side. Therefore, it's recommended to sue this capability to increase (or decrease) system voltage if needed.
  - Example, a connected grid has three loads with load factors shown in the below table:

Loads	Voltage	Rated HP	Power Factor	Eff	VFD pf	VFD eff	Load Factor	kVA Rating
No.1	4160	600	0.85	0.9			0.8	468
No.2	4160	250	0.85	0.95			0.75	173.22
No.3	4160	600	0.85	0.9	0.95	0.97	0.8	431.76

- kVA Rating of No.1: $kVA = \left((600hp * 0.7457) \div 0.9 \div 0.85\right) * 0.8 = 468\,kVA$
- kVA Rating of No.2: $kVA = \left((250hp * 0.7457) \div 0.95 \div 0.85\right) * 0.75 = 173.22\,kVA$
- kVA Rating of No.3: $kVA = \left((600hp * 0.7457) \div 0.97 \div 0.95 \div 0.9\right) * 0.8 = 431.76\,kV$
- And the total kVA rating from these three loads is 1072.98 kVA

With the equation $S_{transformer} = 1.2 * \sum S_{each\,load}$, $S_{transformer} = 1287.576kVA$

- So, the kVA rating of the transformer is selected as 1500 kVA.

There are several considerations that will determine which method to use, such as required design margin, project specification, cost, space availability and impact on voltage drop and available fault current.

ANSI C57.12.00 Standard

The typical standard size kVA for three-phase transformer based on ANSI C57.12.00 typically range between 15 and 100,000kVA which are based on the output of the transformer. The input kVA is expected to be higher by 1% to 5% (i.e. refers to transformer efficiency) due to transformer losses in its core and windings, dissipated as heat.

3 Construction of underground cables

The construction of cable:

- Conductor: made from electrolytic grade pure copper or aluminium
  - Aluminium requires larger sizes to carry the same current as copper, but the weight is lighter. Less expensive than copper.
- Conductor screen: semi-conducting tape or an extruded layer of a semi=conductive compound. It's generally used in MV and HV cables to maintain uniform electric field and minimize electrostatic stresses.

- Insulation
- Insulation screen
- Metallic Sheath: provides protection to the cable from moisture and other chemicals present in the environment.
- Bedding: a low-grade insulator that protects the metallic sheath from corrosion and from mechanical injury dur to armouring
- Armouring: it provides mechanical protection from various stresses the cable may get exposed to during its installation and operational life. It's usually a steel tape wound
- Serving: low grade insulator, protect the steel from atmospheric contaminants and agents.

Types of underground cables:

- Low tension cables: maximum voltage handling capacity of 1000V
- High tension cables: maximum voltage handling capacity of 11kV
- Super tension cables: maximum voltage handling capacity of 33kV
- Extra high tension cables: maximum voltage handling capacity of 66kV
- Extra super voltage cables: voltage requirement above 132kV

4 specifications of cables

LV cable sizing steps:

- Application
  - The choice of insulation (XLPE or PVC): determined through economic and availability on the market
  - The choice of conductor (Aluminium or Copper): installation cost
- Load to be supplied
  - The current supplied by the source:
    - In single phase: $I_b = \frac{S}{V} = \frac{P}{V*PF}$, where V is the line voltage, S is the power rating
    - In three phase: $I_b = \frac{S}{\sqrt{3}*V} = \frac{P}{\sqrt{3}*V*PF}$
- Environmental conditions of installation
  - According to the standard IEC 60287, when the installation conditions differ from standard, the derating factors in the appropriate sections must be used: $I_z = \frac{I_b}{DF}$, where I_b is the base current, and I_z is the adjusted value based on distribution factor (or derating factor) DF
  - $DF = K_1K_2K_3K_4K_5$, it depends on the K_1 soil thermal resistivity (determined through industry standard); K_2 ambient temperature derating factor (only chosen when the cable is in the air); K_3 ground temperature derating factor (only chosen when the cable is under the ground); K_4 burial depth derating factor; K_5 grouping factor
- Voltage drop calculation
  - The voltage drop across the cable shouldn't exceed 5% for residential applications and 2% for power applications
- Prospective fault current

- Electric cables are designed to operate below a certain maximum temperature. Cable selection should not exceed these temperature limits

$$I_{sc} = \frac{A * K}{\sqrt{t}}$$

- Where I_{sc} is the short circuit current, A is the cross-sectional area (larger area, more metal, more thermal capacity, and higher withstand current), K is the material constant, and t is the fault duration:
  - K = 115 for PVC/Copper, 143 for XLPE/Copper, 76 for PVC/Aluminium, 92 for XLPE/Aluminium

5 Example of cable sizing

The residential distribution panel of 10kVA at 400V line-to-line voltage, 3 phases. Select the best circuit breaker and cable (Cu/XLPE) to apply this panel buried in the wet soil of 50 Celsius degrees at 0.8m below the ground. And the entire length of the cable is 70 meters

- Compute the three-phase rated current (load current): $I_b = \frac{S}{\sqrt{3}*V} = \frac{P}{\sqrt{3}*V*PF} = \frac{10kVA}{\sqrt{3}*400} = 14.434A$
- Compute the nominal rating current of the protective device (The current the breaker must be rated for):

$$I_n = 1.25 * I_b = 18.04A$$

  - 1.25 comes from the IEC standard: a protective device must be rated at 125% of the continuous load. It ensures no overheating, no nuisance tripping, long-term reliability
  - Above, a 20A standard rated circuit breaker is selected
- Determine the distribution factor based on derating factors:

Nature of Soil	**K1**
Very wet soil (saturated)	1.21
Wet soil	1.13
Damp soil	1.05
Dry soil	1
Very dry soil (sunbaked)	0.86

  - K1 = 1.13
  - K2 is not used as the cable is not operated in the air:

Air temperature Celsius	20	25	30	35	40	45	50	55
PVC cable rated 70 degrees	1.29	1.22	1.15	1.08	1	0.95	0.82	0.71
XLPE cable rated 90 degrees	1.18	1.14	1.10	1.05	1	0.90	0.89	0.84

  - ground temperature derating factor (K3 = 0.85)

Ground temperature Celsius	15	20	25	30	35	40	45	50	55
PVC cable rated 70 degrees	1.25	1.19	1.13	1.07	1	0.93	0.85	0.76	0.65
XLPE cable rated 90 degrees	1.16	1.13	1.09	1.04	1	0.95	0.9	0.85	0.8

  - burial depth derating factor (K4 = 0.97)

Depth of laying (m)	Cable cross section		
	Up to 70 mm2	95 Up to 240 mm2	300 mm2 and above

0.5	1	1	1
0.6	0.99	0.98	0.97
0.8	0.97	0.96	0.94
1	0.95	0.93	0.92
1.25	0.94	0.92	0.89
1.5	0.93	0.90	0.87
1.75	0.92	0.89	0.86
2	0.91	0.88	0.85

- grouping factor K5 = 1, as there only has one cable to supply

Direct in the ground					Inside duct		
No.of Cables	Touching	150mm	300mm	450mm	touching	300mm	450mm
2	0.81	0.87	0.91	0.93	0.90	0.93	0.95
3	0.70	0.78	0.84	0.87	0.82	0.87	0.90
4	0.63	0.74	0.81	0.86	0.78	0.85	0.89
5	0.59	0.70	0.78	0.83	0.75	0.82	0.87
6	0.55	0.67	0.76	0.82	0.72	0.81	0.86
No. of cables	1	2	3	6	9		
Cable touching	1	0.90	0.84	0.80	0.75		
untouched	1	0.95	0.90	0.88	0.85		

- Compute the adjusted current for cable $I_z = \frac{I_b}{DF} = \frac{20A}{1.13*0.85*0.97*1} = 21.5A$
- Select the cable size based on the industry chart and current I_z, it has 1.5 mm2 surface area, 15.43 Ω/km impedance and 26.726 voltage drop factor (the parameters can be used for computing voltage drop of the cable)
- Compute the voltage drop from the cable

$$V_{drop} = \frac{\sqrt{3} * I\ (load\ current) * Z(cable\ impedence) * distance(cable)}{V\ (line\ voltage)}$$

$$= \frac{\sqrt{3} * 14.434A * 15.43\Omega/km * 0.07km}{400V} = 6.7\%$$

Or

$$V_{drop} = 10^{-3} \frac{voltage\ drop\ factor * I\ (load\ current) * cable\ distance}{V(line\ voltage)}$$

$$= 10^{-3} \frac{26.726 * 14.434A * 70m}{400V} = 6.7\%$$

  - Based on the standard, the cable size should be selected to an even larger one (2.5 mm2) as the voltage drop is bigger than 5%
- Short circuit calculation for 2.5 mm2 Cu/X:PE 4 cores cable
  - For the selected circuit breaker, it will trip within 0.5 seconds when the short-circuit current 350A flows. So, the circuit breaker will clear the fault in at most 0.5 seconds.

$$I_{sc} = \frac{A * K}{\sqrt{t}} = \frac{2.5mm^2 * 143}{\sqrt{0.5sec}} = 505.58A$$

■ The above formula tells that the selected cable can safely withstand up to 505A current without being thermally damaged for a fault lasting 0.5 seconds.

6 Power Flow Analysis

Load flow technique

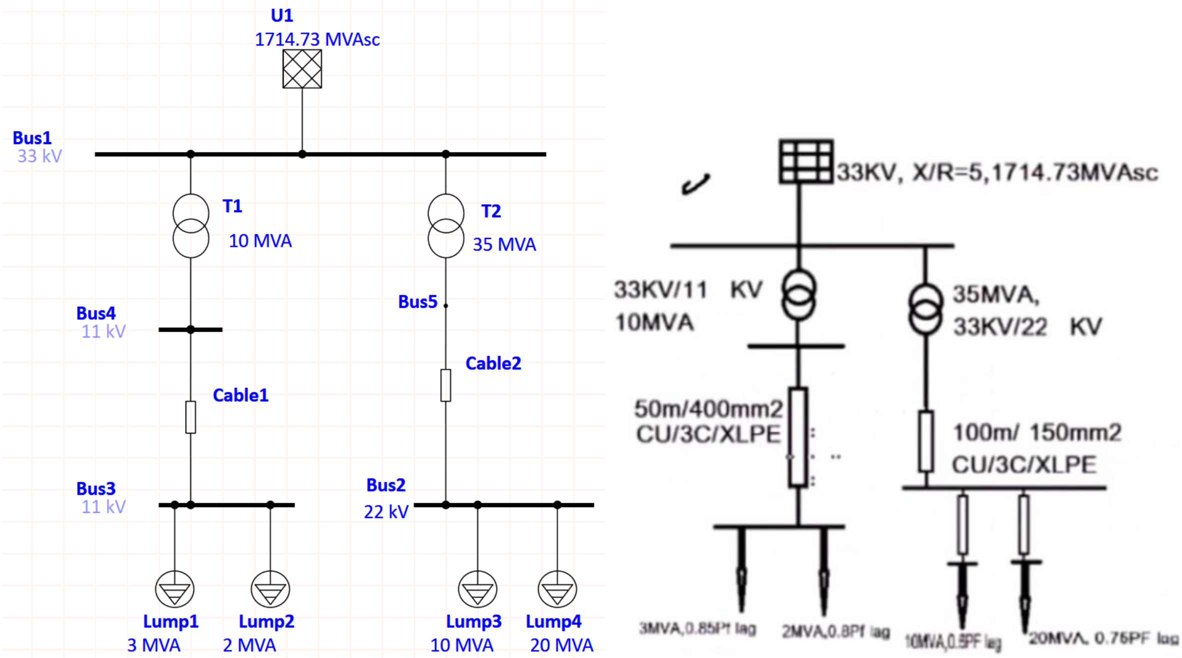
- Guess Seidel
- Newton Raphson
- Fast decoupled

Types of Buses

- Load bus or PQ bus: The active power P and reactive power Q are known, but the voltage magnitude and phase angle are missing
- Generator bus or PV bus: the active power P and voltage magnitude V are known, but the reactive power Q and phase angle are missing
- Slack bus, Swing bus, reference bus or infinite bus: voltage magnitude and the phase angle are known, but the active power P and reactive power Q are missing (this type of bus is connected to the largest generator)

Power flow (load flow) analysis for a power grid network in ETAP

- Construct one-line power grid in ETAP based on scheme and specifications



■ The single-line diagram shows the electricity power flows from a high-capacity source through transformers and cables to several loads at different voltage levels.

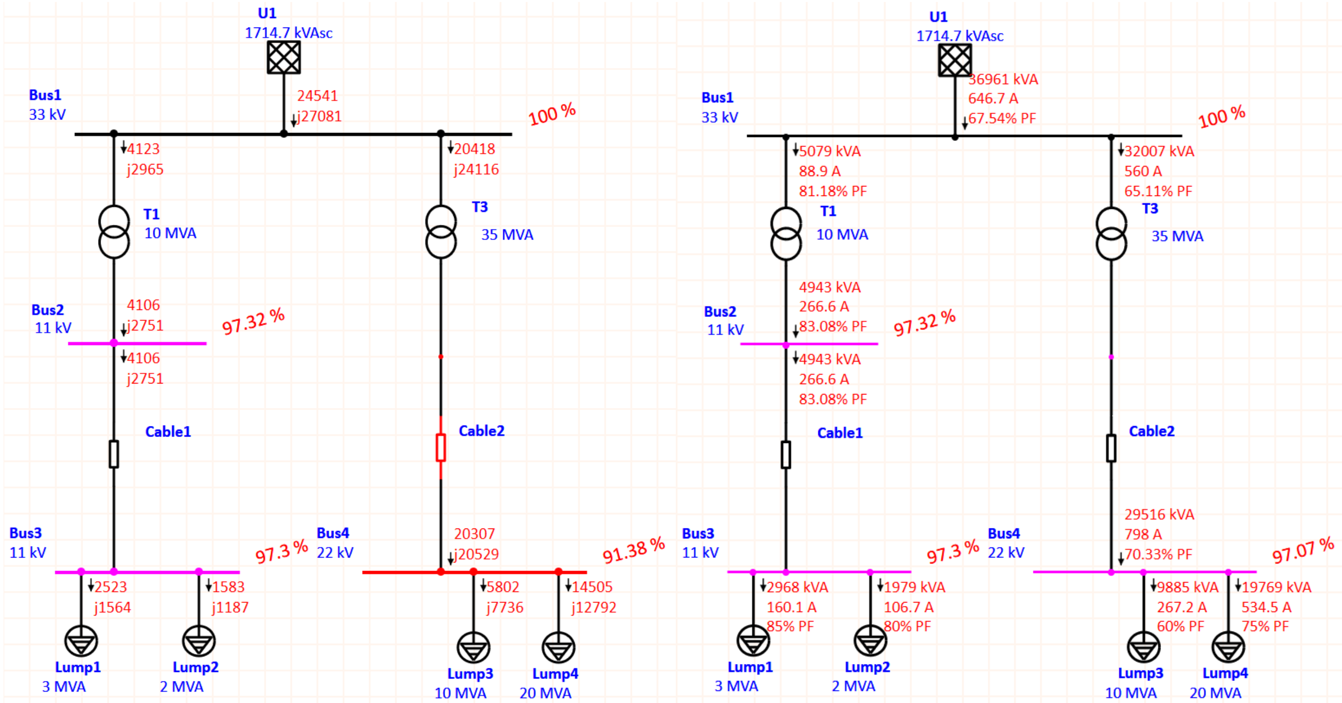
◆ Source: upstream grid or utility

◆ Bus1: first distribution bus at high voltage

◆ Transformer T1: step down voltage from 33kV to 11kV

■ A power distribution system with two voltage levels and multiple load centres.

- Load flow analysis for the above power grid



- From the above power flow analysis, the critical alerts have:
  -
  - Cable 2 is overloaded (it's designed for 301.976Amp, but it's operating under 829.244 Amp), it's overloading by 274.6%

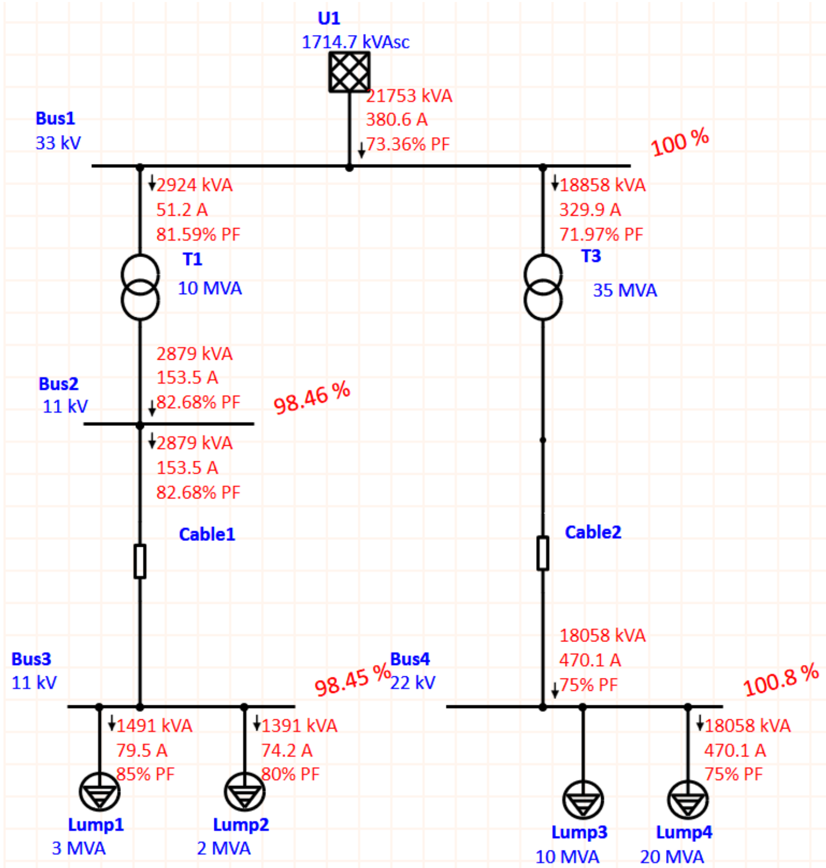
301.976 Amp	829.244	274.6

    - Solution: increase the number of cables or increase the size of the cable
    - Here the three cables are used to handle the overloading issue
  - Bus4 and Bus5 are under voltage

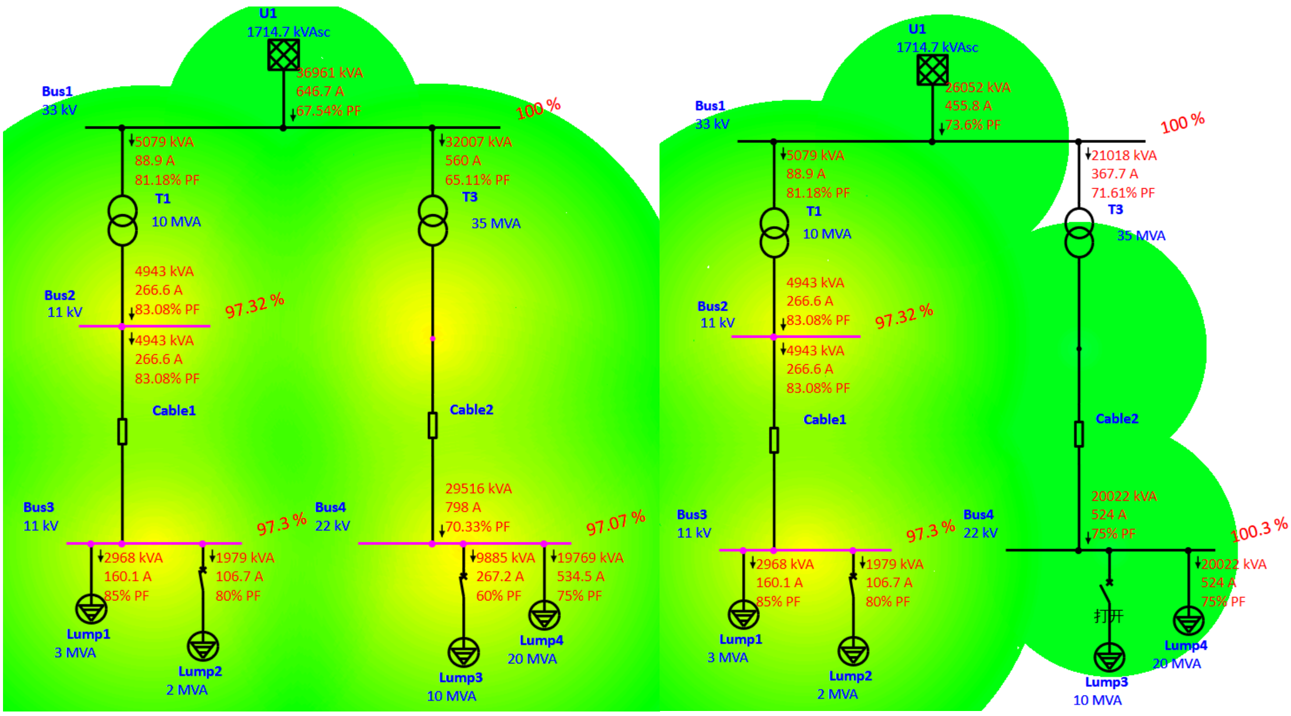
22 kV	20.123	91.5
22 kV	20.132	91.5

    - Solution for Bus5: increase the percentage of the tap at the primary side to -5%
      - A negative tap percentage on primary side means the primary voltage rating is reduced 33kV*95% = 31.35kV, it compensates the line voltage drop
      - According to IEC standards, the 5% voltage drop is acceptable

- Winter operation
  - Adjust the percentage of the operation power of the loads under the winter operation
  - Simulate the power flow analysis under winter load condition



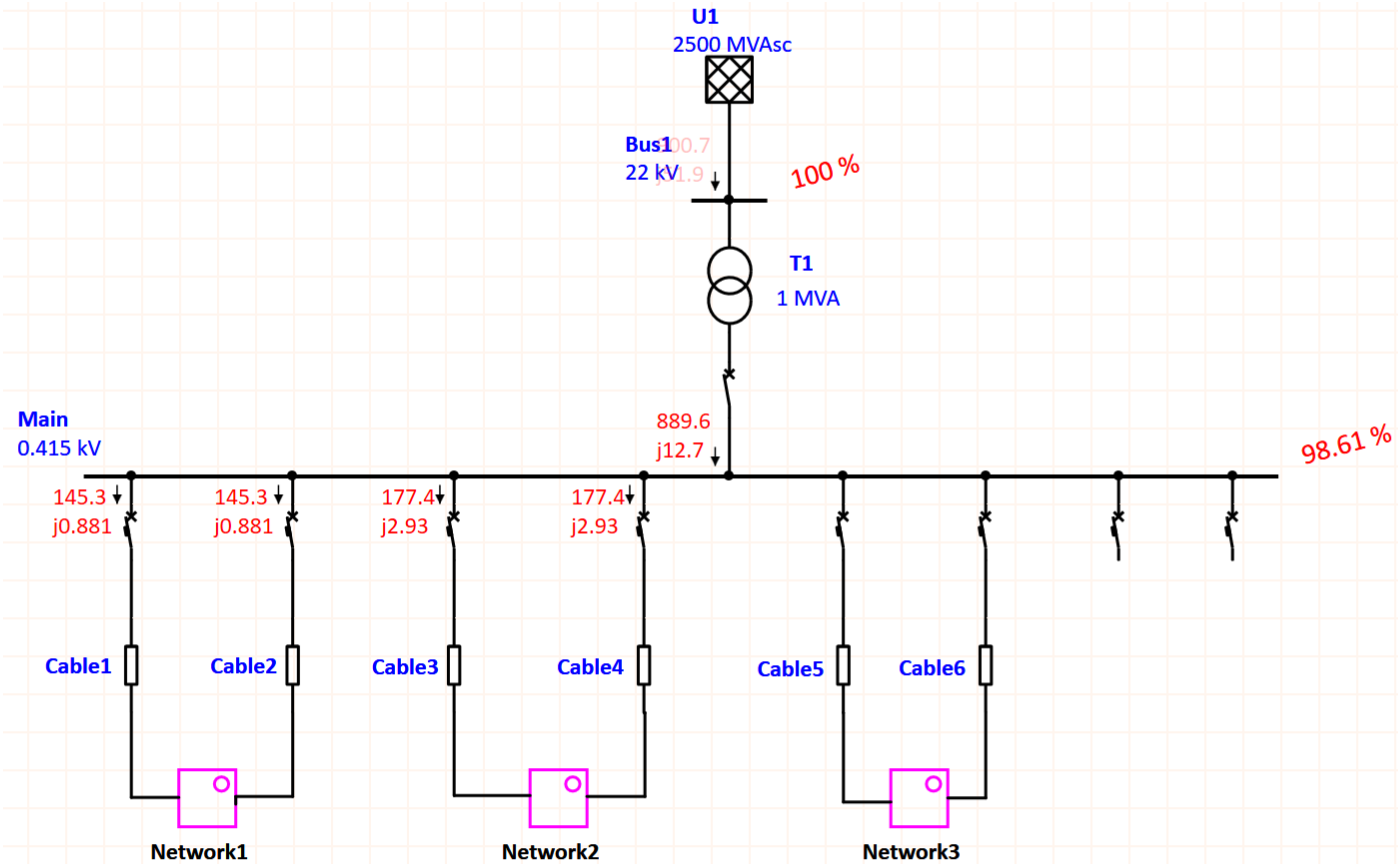
- Automatic load flow analysis (real-time load flow analysis)
  - It helps when there has circuit breaker
- Contouring for overloading of bus bars

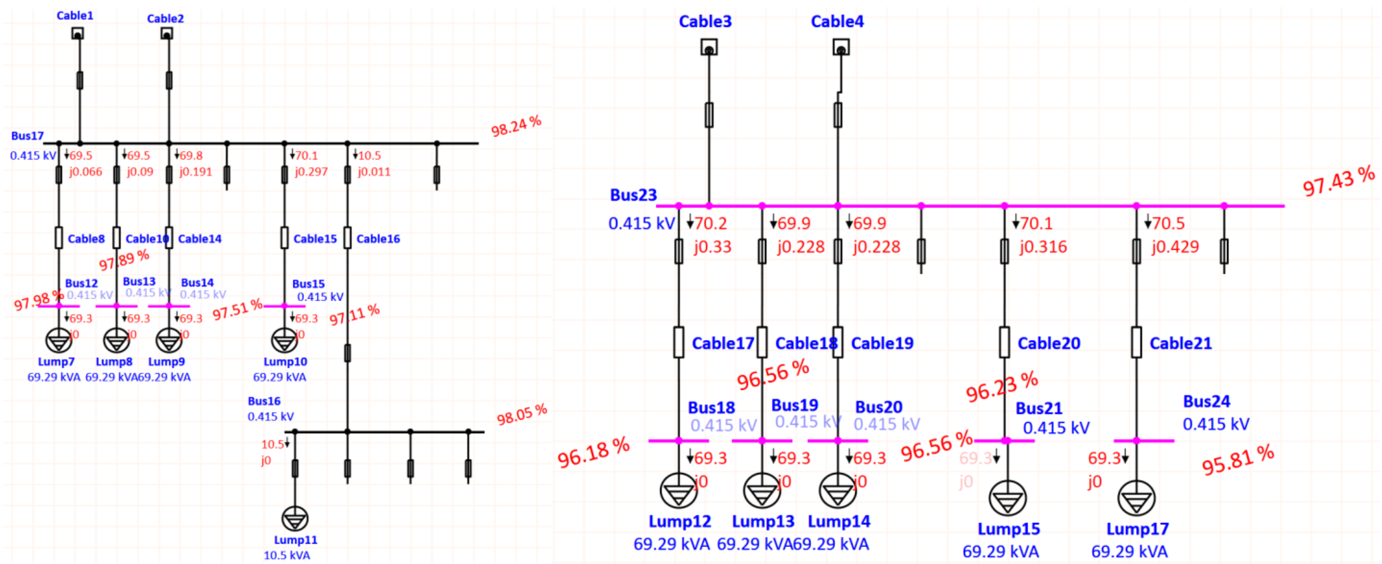


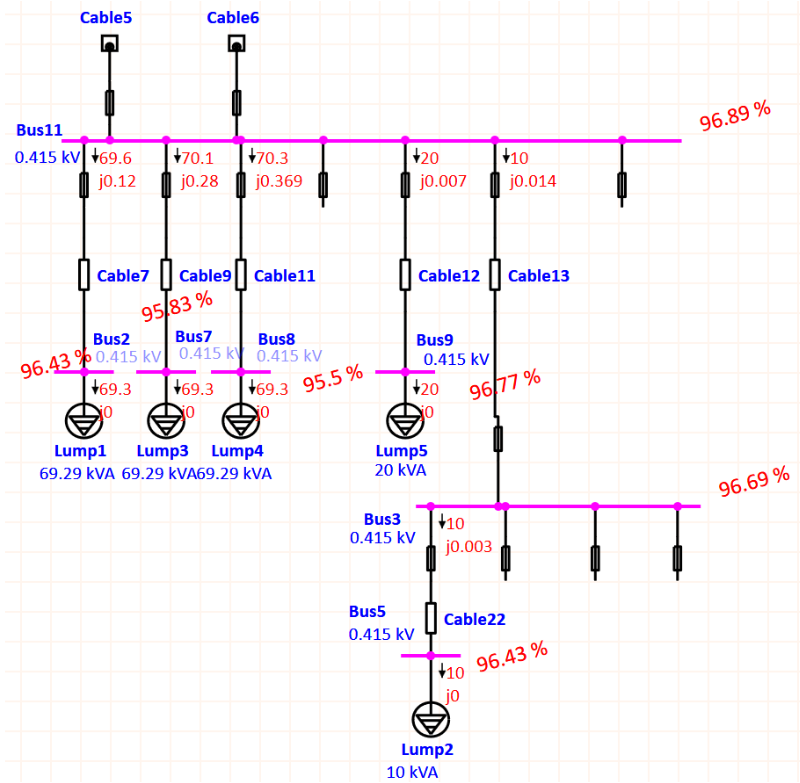
  - The above graph shows the highlight of the bus bar operation is near their limits (marginal alert)
  - When the circuit breaker for the Lump3 load opens, the bus4 back to normal operation

7 Voltage drop analysis

- Build a ETAP single-line diagram based on the scheme from CAD Elec
  - The one line diagram presents an utility source feeds three downstream networks through medium voltage bus, transformer, and a low voltage bus.
  - Network 1 is a low voltage (LV) feeder to small industrial loads with several buses and loads that connected through known cables and fuses.
    - Based on the load flow analysis, this network has a moderate voltage drop between 3 – 4%
  - Network 2 is another LV feeder to industrial loads, but the voltage drop is slightly higher than network1 as the cable length is longer.
  - Network3 has the highest voltage drop based on load flow analysis

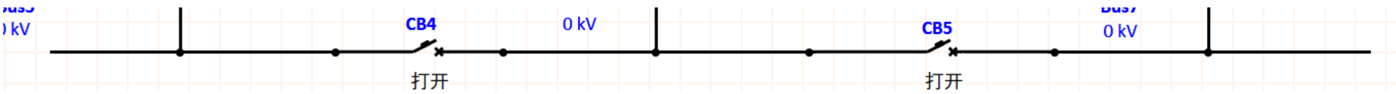




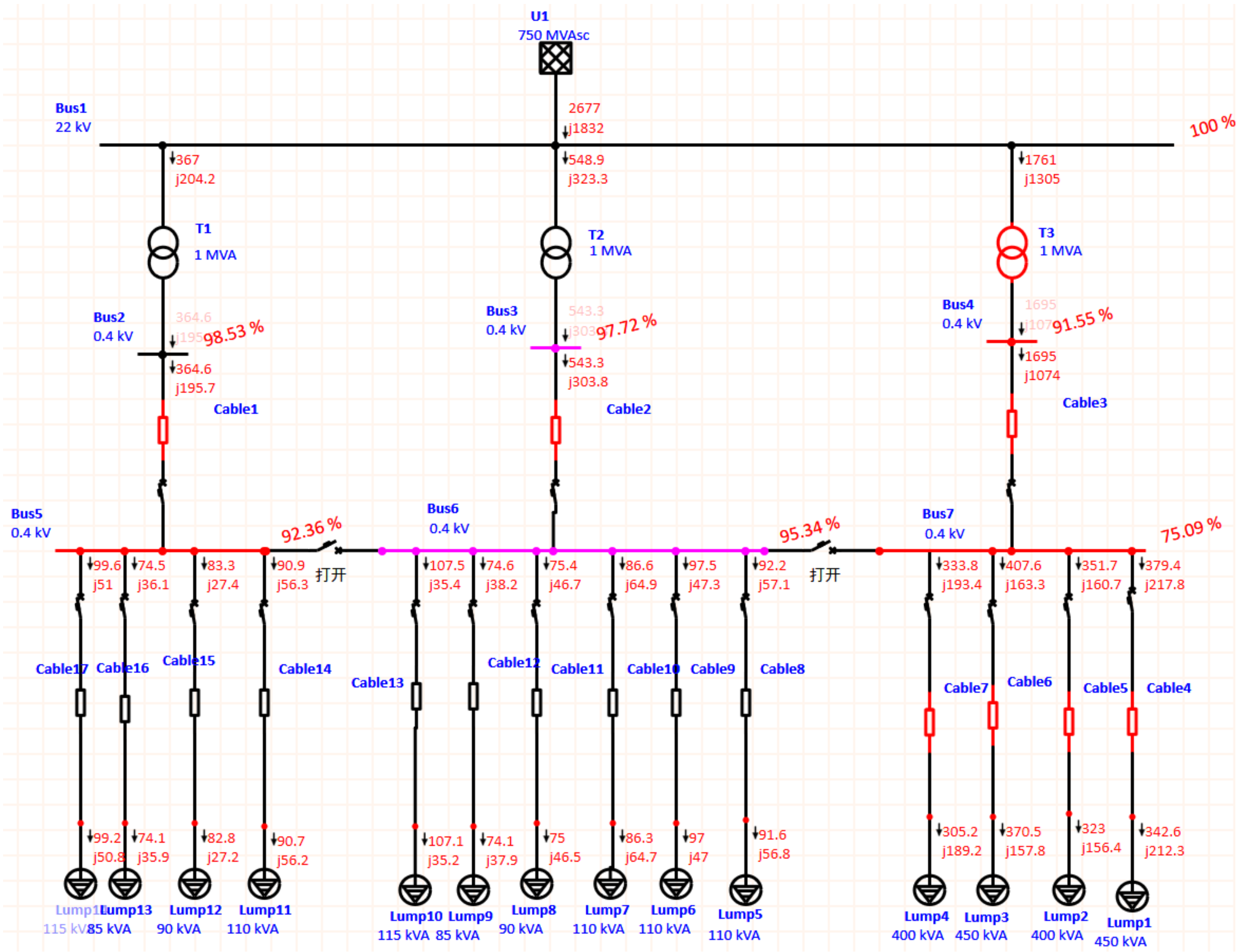


- Check the load flow values between the ETAP load flow analysis results and the manually calculated load flow results of the CAD Elec

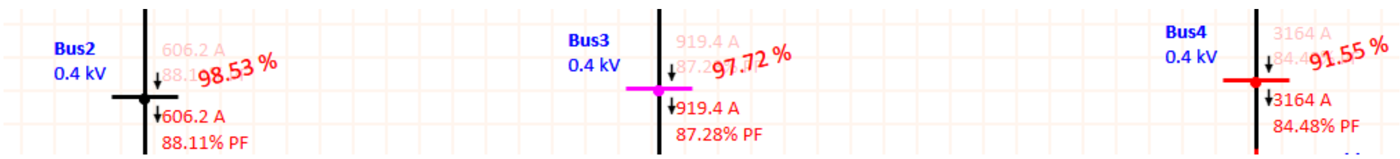
- Three transformers with three different loads
  - Mission: check if the voltage drop across each load is within the limits of the standard, otherwise the cable parameters need to be adjusted (resize)
  - Q: what's the function of low voltage circuit breaker?
  - Q: what's MDB?
    - Main distribution board: central low-voltage distribution panel that receives power from the main source and distributes it to downstream
  - Q: What's the function of low voltage circuit breaker between bus bars?



    - In LV and MV, the circuit breaker between bus bars is called bus-tie breaker (BTB).
    - The breaker allows two bus bars to operate independently (opened) or as a single combined bus (closed)
    - If a fault happens, the BTB prevents fault from propagating to the other bus, it limits the fault current and protects upstream equipment
    - It also temporary feeding of a bus during maintenance or outage
    - With a BTB, we can de-energize one bus for maintenance, keep the other bus energized, or temporarily back feed the offline bus

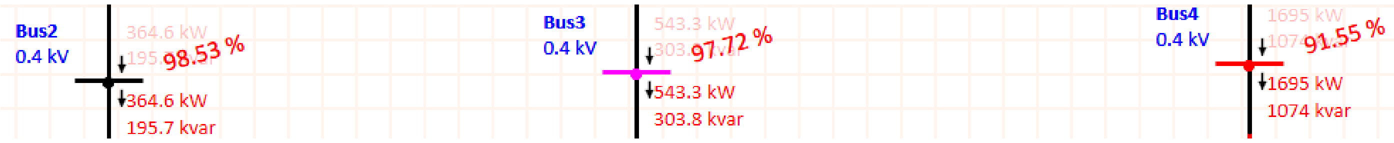


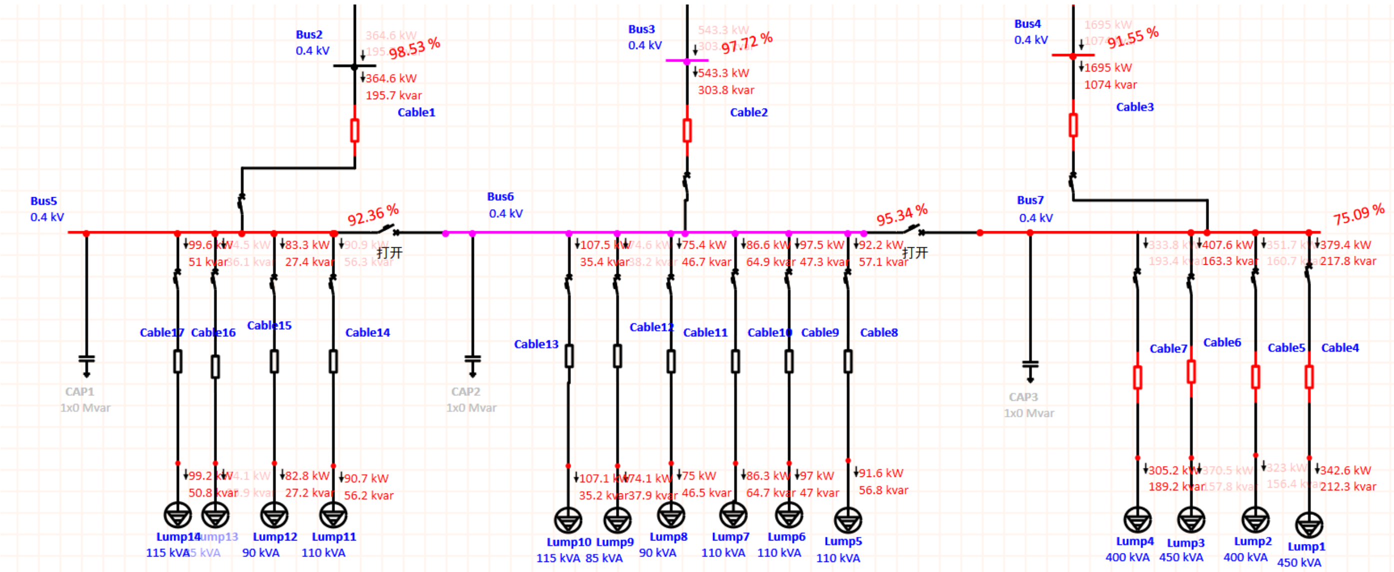
- The above is the one-line diagram for an electricity source with a MDB to several loads. And the results of the load flow analysis are shown on the graph as well.
  - From the above load flow analysis, the cable 1 to cable 7 are overloaded, which means the cable size needs to be readjusted
  - And the bus4 bus bar has a high voltage drop (beyond 5% dropping limits)
- By checking the power factor of the bus bars, the PF on bus2 to bus4 are low, which means the supplied power are not used effectively.



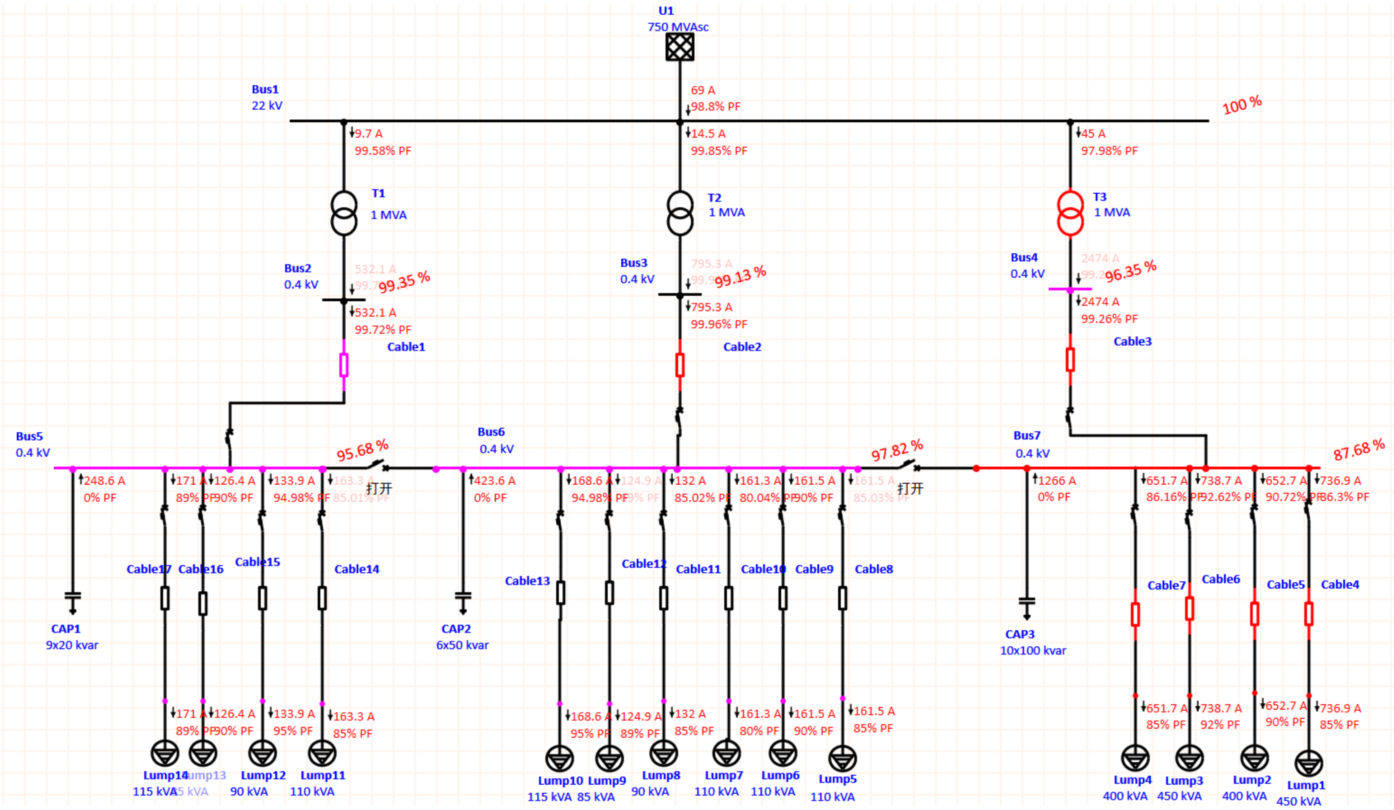
- Q: how to decide if the power factor is high or low?
  - 0.95 – 1: high; 0.9-0.95:acceptable; below 0.9: low PF.
- To address the issue, the capacitors are added on bus5, bus6, and bus7 separately
- Q: How can a capacitor address low power factor issue?
  - Because capacitor inject reactive power (kVAr) into the system, which reduces the amount if reactive power the utility must supply
  - e.g. the transformer one (T1) is supplying 195.7kVAr to bus2, to reduce the supplied reactive power from upstream, a capacitor (compensator) can be added to bus5

- Q: how to decide the maximum voltage of the compensator?
    - Slightly above the bus voltage.



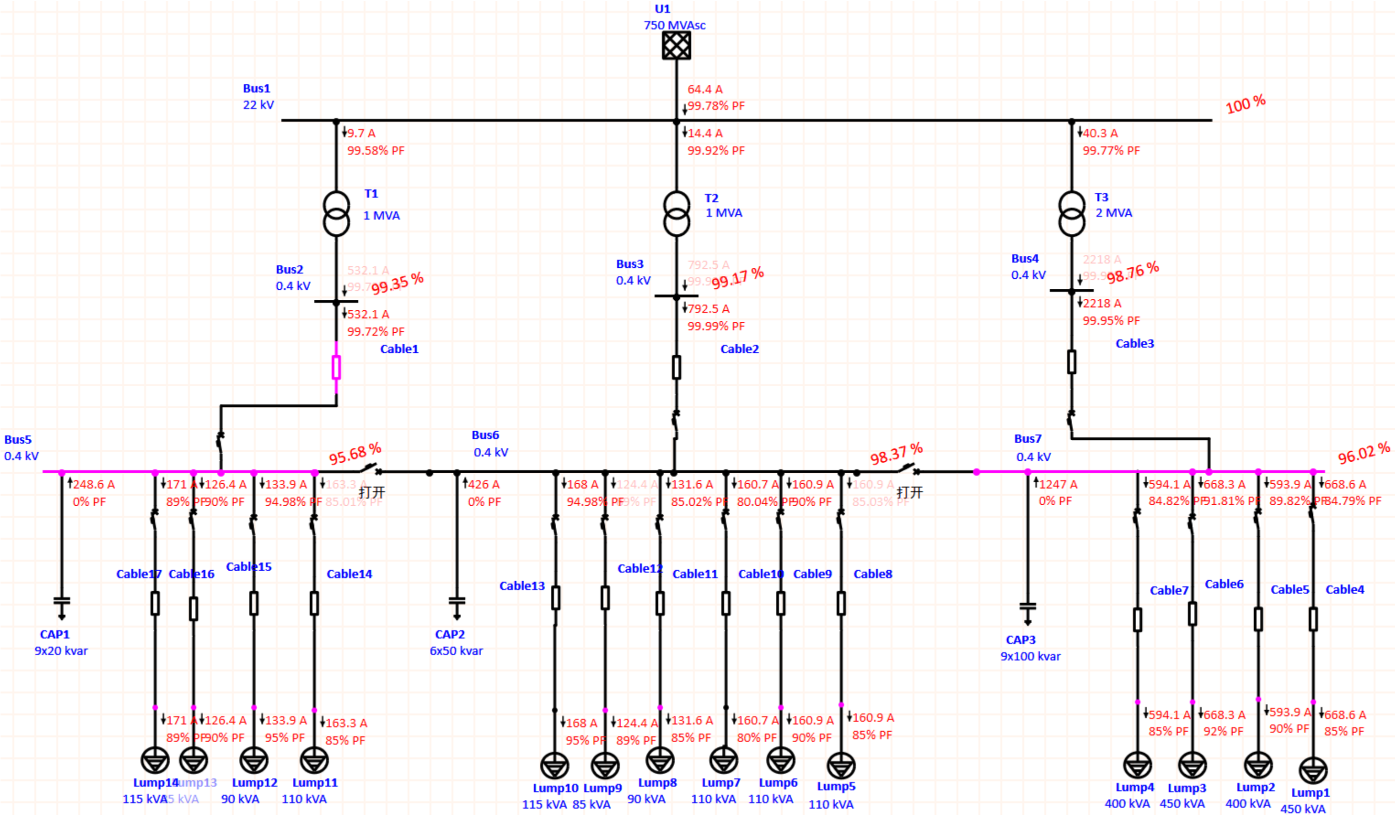


- For the capacitor 1, it needs supply 195.7kVAr to increase the PF of bus 2. Same as capacitor 2 and capacitor 3
- See from the results below, the PF of bus2, bus3, and bus4 are successfully increased after the supplying of capacitors. But the overloading issue of cables are still existed

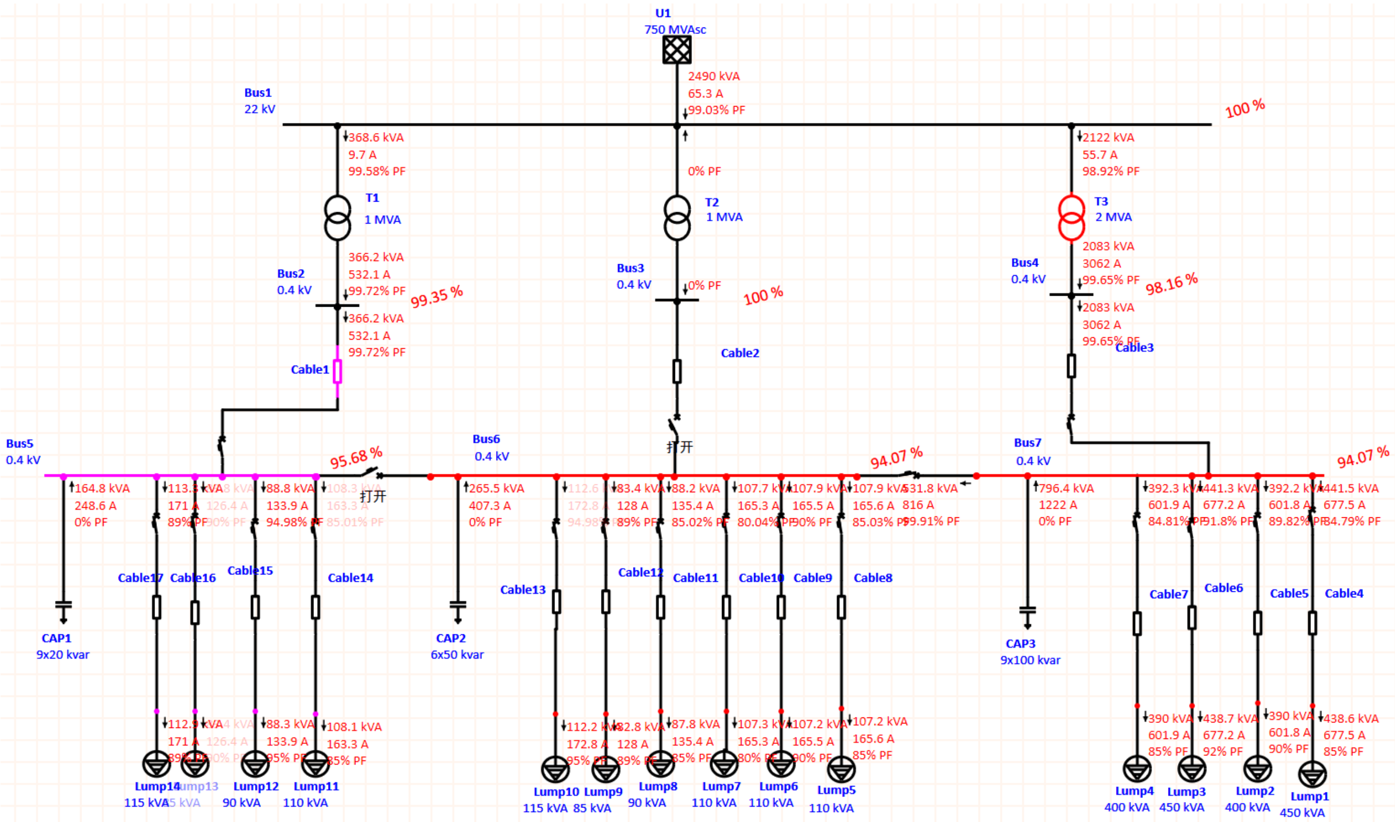


- The cable overloading issue is addressed by increasing the size of cable and add one more cable for each phase to supply the downstream. The final power flow analysis result of this grid one-line drawing is shown below
- The overloading issue of the transformer 3 is addressed by increasing the size (rated

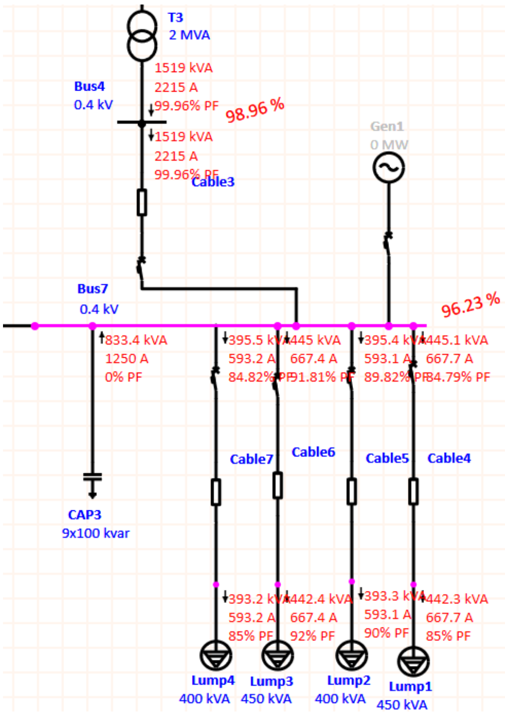
power) of the transformer to 2MVA from 1MVA

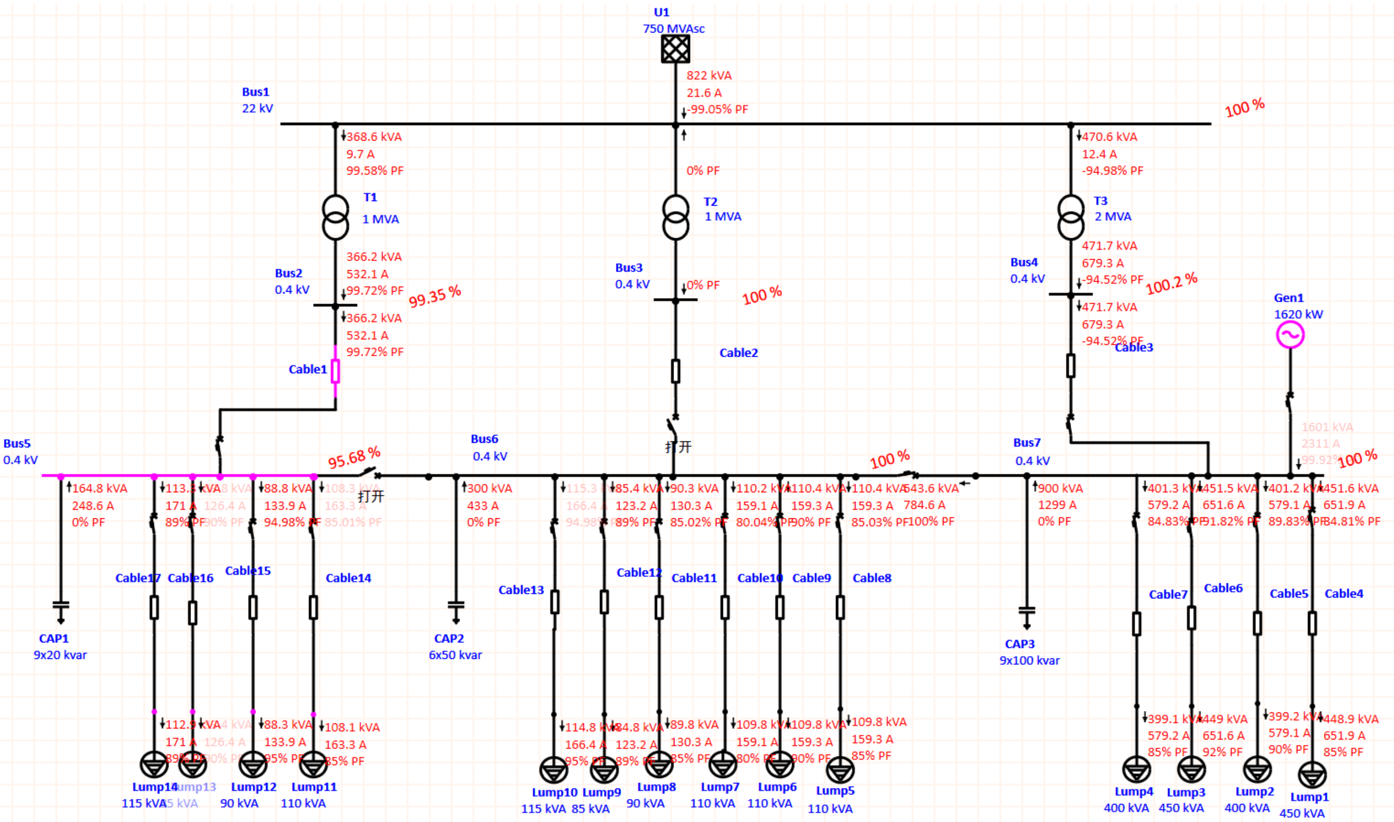


- In addition, if we close the circuit breaker between bus5 and bus6, and open the circuit breaker of the bus2-bus5 downstream, it leads bus3 starts supply the power to bus6. In this case, cable 2 needs bigger size and more cables (# of cables) to supply both bus5 and bus6
- E.g. supply bus6 and bus7 through transformer3 (T3) only by closing the circuit breaker between bus6 and bus7, and opening the circuit breaker od cable2. Basically, it simulates the scenario when transformer 2 is out of service.



- From the above power flow analysis, the transformer 3 is overloading, and the voltage drop of bus6 and bus 7 are beyond limitation 5%
- To address the above issue, generators are added. How much power the generator needs to supply should be determined.
    - Isolate bus7 to check how much apparent power the generator needs to supply.
    - From the power flow analysis result, the generator needs to supply at least 1519 kVA to ensure the normal operation of bus7





- From the above power flow analysis result, the grid simulation is under normal operation. The reliability of the grid is increased by adding an extra generator.

8 Short circuit study

Q: why do we need short circuit study?

- To be able to select switch gear equipment as circuit breaker, fuse, isolators and etc.
- To adjust relay settings which can distinguish between full load current and fault current
- Used in stability studies of power system

Types of the faults in Power system

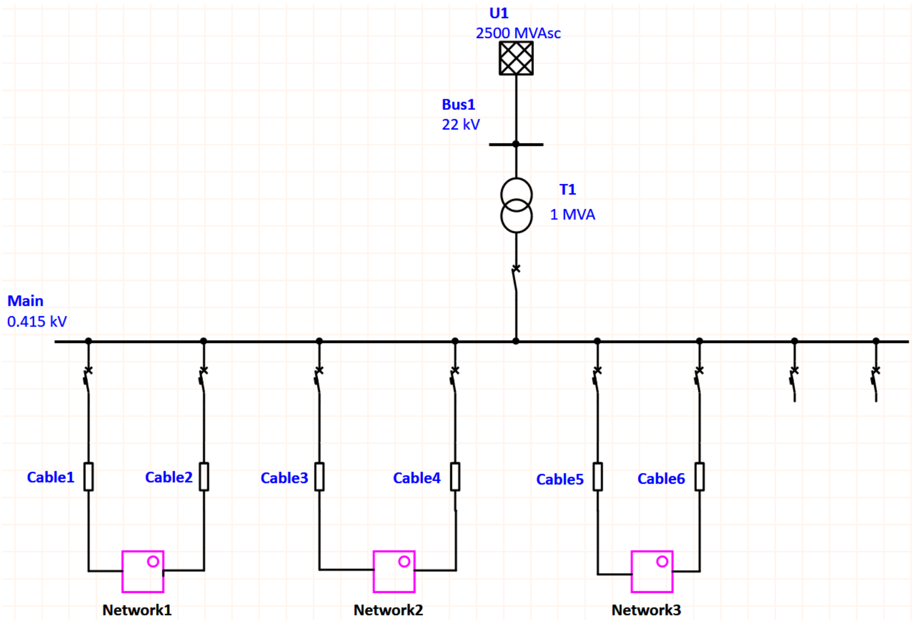
- Symmetrical faults ‘3 phases fault’
  - L-L-L (line to line to line)
  - L-L-L-G (line to line to line to ground)
- Unsymmetrical faults
  - L-L (line to line. According to IEC 60909)
  - L-L-G (line to line to ground)
  - L-G (line to ground)

Causes of faults in power system

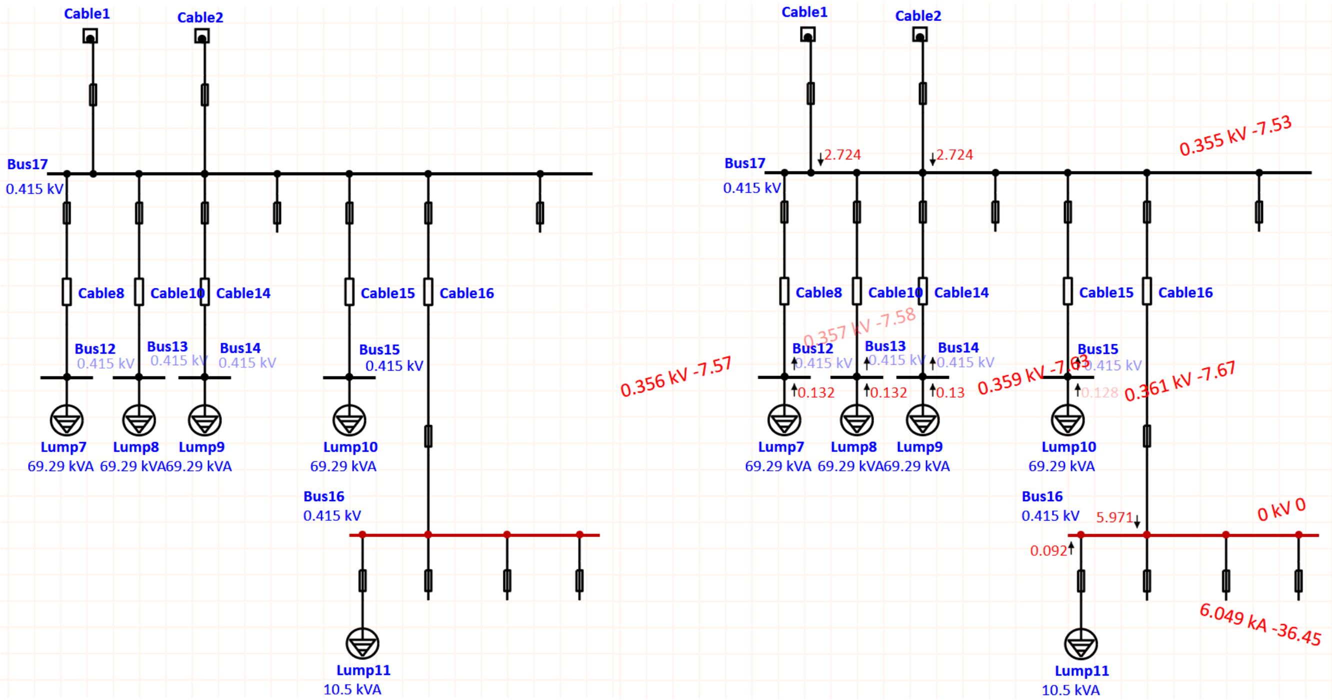
- Insulation failure of cables or equipment due to the aging
- Temporary faults as phase to phase touching due to wind or tree
- Cutting of transmission or distribution lines
- Flashover by lighting strikes to transmission lines

Examples of short circuit study

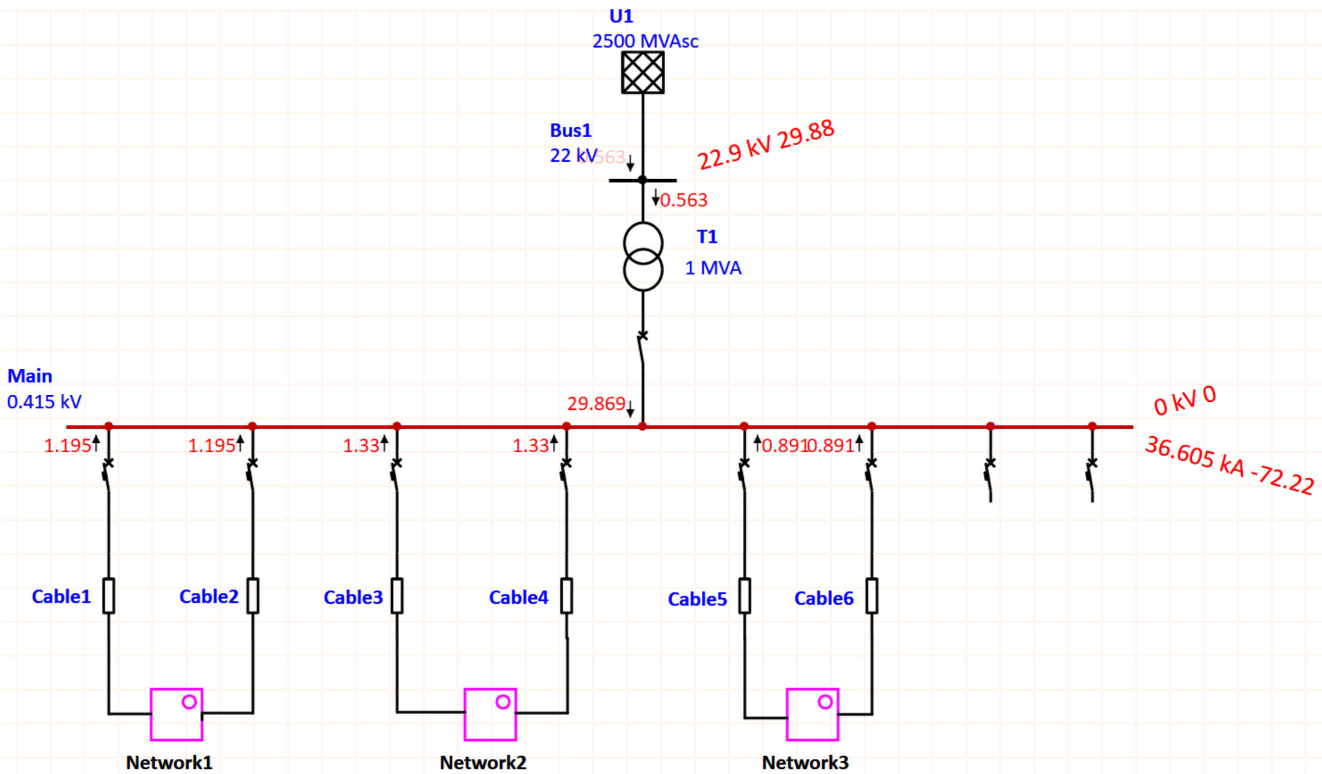
- The short circuit study example is from below one-line grid drawing based on a CADElec scheme. It’s established in the project ‘projectvoltagedrop.OTI’.



- Then IEC60909 short circuit analysis is operated.
- The first short circuit study is for the bus16 under network 1.



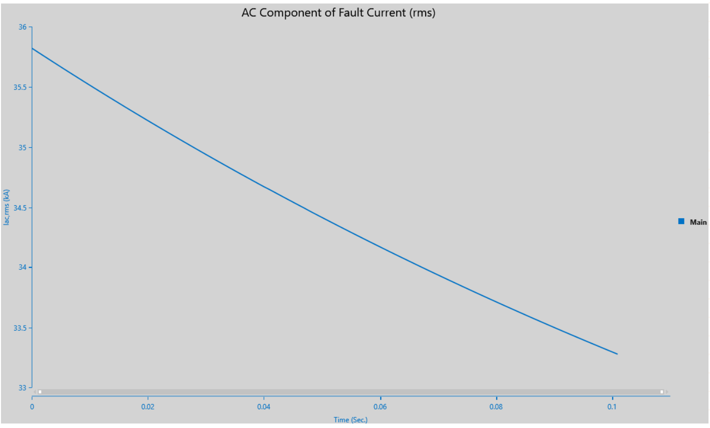
- From the above short circuit study result, the bus16 must handle 6.05kA short circuit current.
  - It means if a short circuit fault occurs at bus16, any equipment connected to bus16 must be able to safely withstand a fault current at least 6.05kA for 3 phases
  - Normally, the 3 phase short circuit current is the highest compared to other types of short circuit current such as L-G etc.
  - If any equipment is rated below 6.05kA, it may explode during a fault, it's not comply with electrical code (IEC etc.)
  - The short circuit current value shall be obtained for each bus bar under the short circuit study.
  - For the main bus bar, the 3 phases short circuit current is 36.605kA (Under the short circuit study of IEC60909

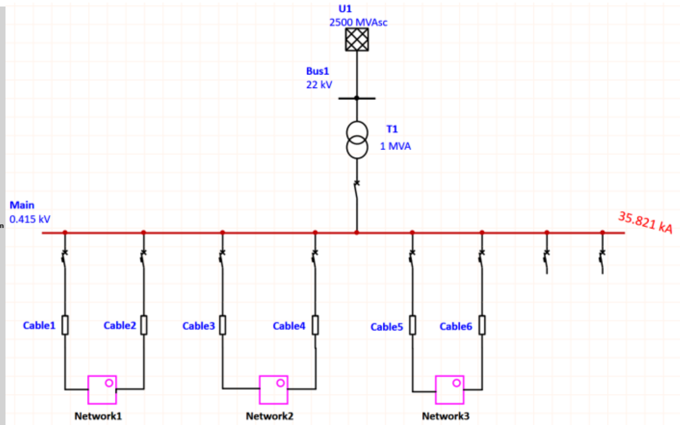


- The red numbers with arrow in the above graph indicate the fault ampes they contribute and flow into the main bus fault. The fault current in kA they contribute are:

$$1.195 * 2 + 1.33 * 2 + 0.891 * 2 + 29.869 = 36.701kA$$

- The above matches the short circuit study result of the main bus.
- The property of the main bus should be set to withstand its short circuit current
  - It has continuous current and bracing current, bracing current is the peak short circuit current it should withstand for 1 second, and continuous current is the one during normal operation (non-fault)
- Also, the IEC 61363 short circuit study is analyzed





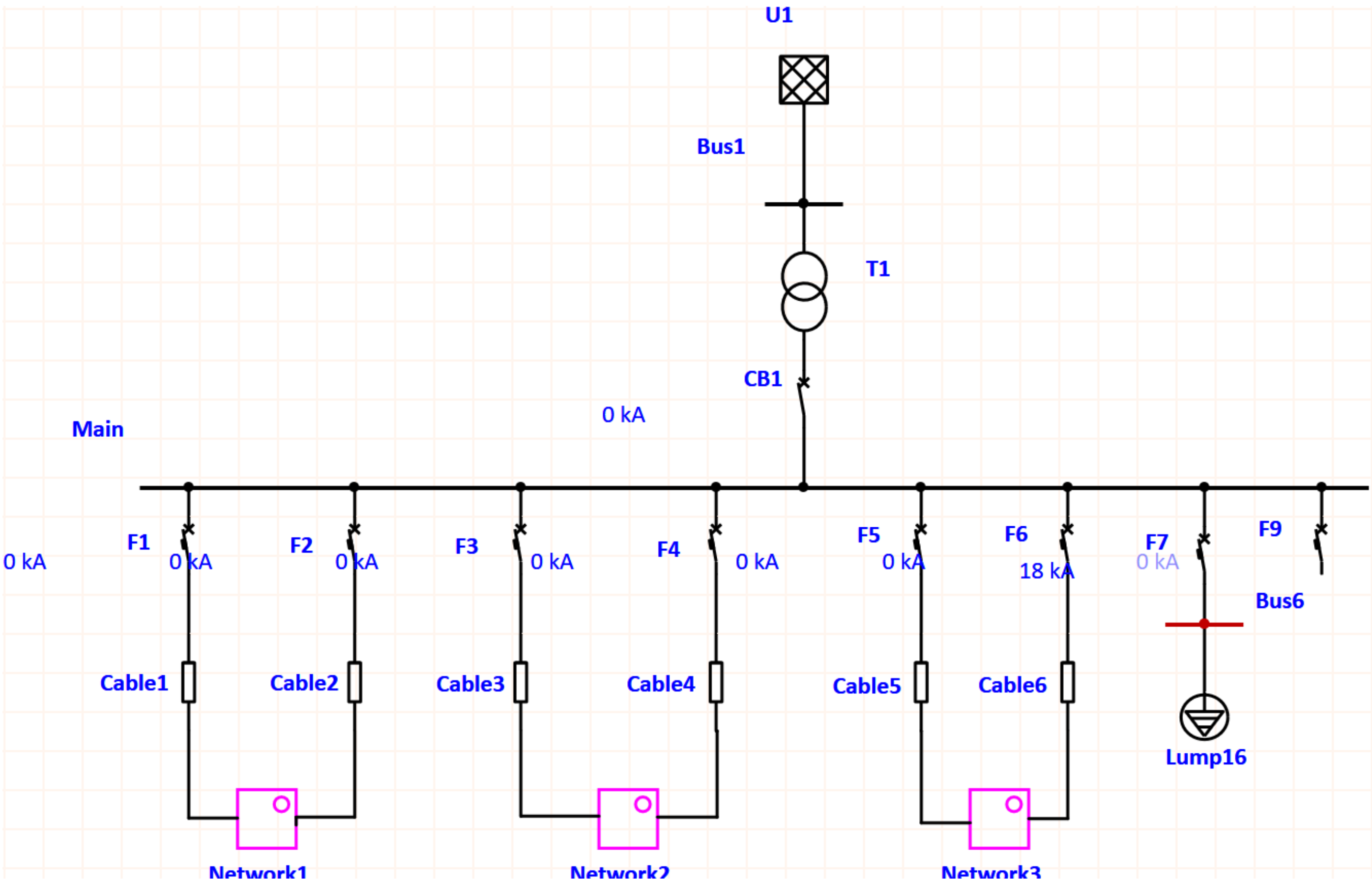
- Q: if the short circuit current for the main bus bar is 10kA, and the short circuit current for the downstream bus bar under the main bus is 5kA. What's the current of each equipment under the downstream bus bar should withstand? 10kA or 5kA?
  - Equipment on the downstream busbar must be rated for at least 5kA, and the equipment on the main busbar must be rated for at leaset 10kA

9 Arc Flash Study

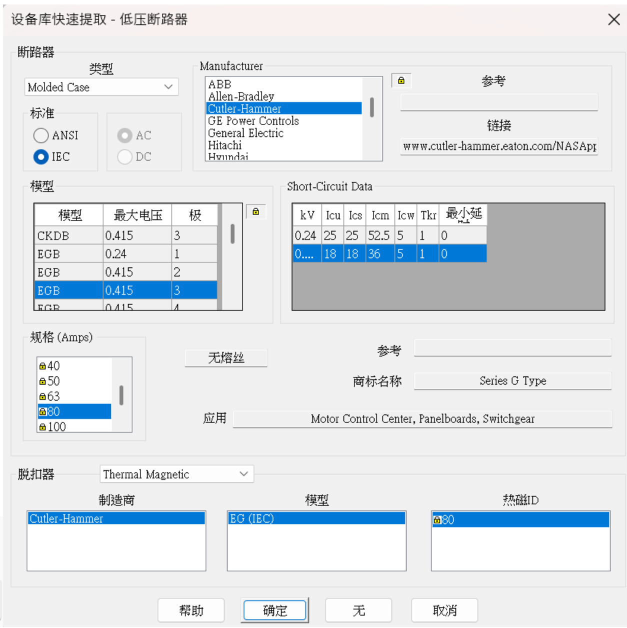
- It occurs when current flows through an air gap between two conductors
- Arc flash occurs when several electrical conductors are placed close to each other with significant high current (fault)
- The effect of arc flash
  - Large shock wave which can blow the person off their feet
  - Loss of memory or brain damage
  - Hearing loss
  - Shock hazard due to touching the energized conductor
  - Degree of injury depends on how powerful the arc flash is, the distance of the person from the arc flash and weather the person is wearing personal protective equipment (PPE)
- ETAP provides the values of:
  - incident energy 'arc flash power'
  - safety distance from the equipment (between hands and the point of arc flash)
  - required PPE (Personal protective equipment) according to NFPA (national fire protection association), PPE has 0-4 five categaries
- Arc flash boundaries
  - It's calculated according to 'incident energy' with unit Cal/cm2
    - Incident energy: the amount of thermal energy (heat) that reaches a worker's body at a specific distance from an arc flash.
    - Basically it means: how much heat per square centimeter will hit the body if an arc flash occurs
  - The arc flash boundaries are: the line which nobody should pass without training and PPE
  - It includes:
    - Prohibited approach boundary
    - Restricted approach boundary
    - Limited approach boundary
    - Arc flash protection boundary

Arc flash example

Arc flash analysis is processed for the below grid one-line diagram

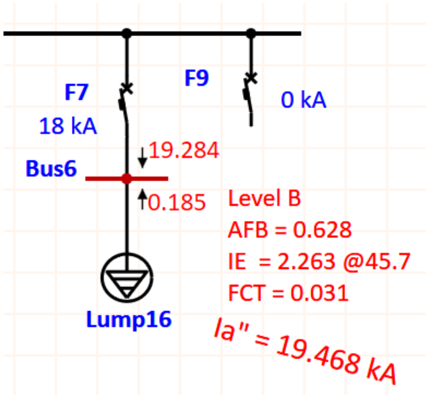


- Arc flash for the fault bus bar 16 will be analyzed
- Before the arc flash analysis, the LV short circuit breaker should be selected based on the current of the lump load:



kVA	kW	kvar	% PF	电流
50	42.5	26.34	85	69.56

- The short circuit breaker with 80Amps rated current is selected as the current flows through the load is 69.56Amps.
- The arc flash analysis result for bus bar 16 is shown below:



- Level B means low hazard level based on the categories of NFPA 70E 2012

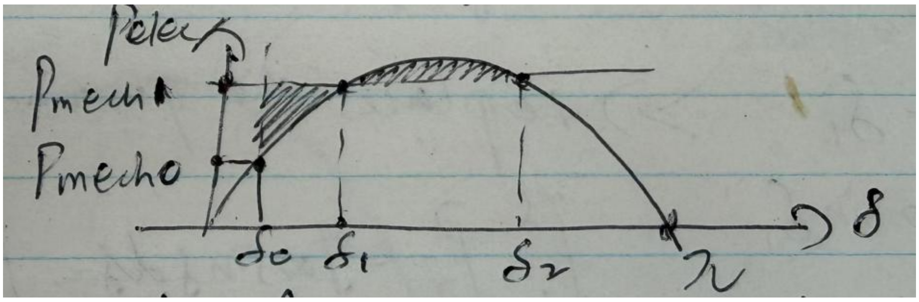
ID	cal/cm²
Level A	2
Level B	4
Level C	8
Level D	25
Level E	40
Level F	100
Level G	120
Level H	0
Level I	0
Level J	0

- AFB = 0.628 indicates the Arc Flash Boundary, this is the distance from the equipment where the incident energy drops to 1.2cal/cm2, the threshold for a second-degree burn. Basically it means the worker must wear arc-flash PPE if they are closer than 0.63m to the equipment during energized work.
- IE = 2.263@45.7 indicates the incident energy at the working distance
  - 2.263 cal/cm2 is the thermal energy a worker would be exposed to if an arc flash occurred
  - 45.7cm is the assumed working distance
  - This indicates a category 1 PPE can be enough for this working condition
- FCT = 0.031 is the Fault Clearing Time of the protective device
- Ia" = 19.468kA means the Arcing Current (or predicted arcing fault current), the current that actually flows during an arc flash

10 Power system transient stability study

- Key points:
  - When a generator is running normally, it means it's sync with the grid. And $P_{mech} = P_{elec}$ (steady state) with initial angle δ_0
  - When the rotor of the generator pushes harder (more mechanical power), the angle δ increases
  - The transient stability relates to the maximum angle δ_{max} the generator can reach before it becomes unstable
  - After the generator operates under the maximum angle δ_{max}, if the generator is transient stable, it will swing down to a new angle δ_1
    - Q: why the genrator need a new steady angle after the disturbance? why can't it back to original angle?
      - After the disturbance (mechanical power increases), as $P_{elec} = P_{max}sin\delta$, and in a steady state: $P_{mech} = P_{elec}$, that's why a new angle δ is needed
    - Q: why the unstable angle point $\delta_{max} = \pi - \delta_1$?
- Definition: if a generator can spin at the same rhythm as the grid after a disturbance happened. If the generator can recover its rhythm
  - The rhythm of the grid: 60Hz steady electrical frequency (North America)
  - So the generator has to spin at 60Hz as well
- Transient means short-term (few seconds)
- Disturbance can be caused through a short circuit, lightning strike, etc.
- Transient stability checks (it should be done the first couple seconds after the disturbance fault):
  - Generator speed
  - Generator angle
  - Mechanical power vs electrical power
    - mechanical power is the physical power delivered to the generator shaft by the mover that is used to spins the generator rotor.
    - Electrical power is the power the generator sends into the grid
  - System voltage and frequency
  - Clearing time of protection devices

- Manual calculation example
  - Asynchronous generator can develop 500MW power per phase, and it operates at a power angle of 8 degrees. By how much can the input shaft power of the generator be increased suddenly without loss of transient stability? Assume maximum power P_{max} remains constant.



- First step: calculate the initial electrical power generated from the generator. The initial electrical power equals to the mechanical power when the generator is under transient stability

$$P_{mech0} = P_{elec} = P_{max}sin\delta_0 = 500MWsin8° = 69.6MW$$

- The mechanical power will be increased when there has disturbance, the mechanical power increased from P_{mech0} to P_{mech1}. And the mechanical power equals to the electrical power under transient stability

$$P_{mech1} = P_{elec} = P_{max}sin\delta_1$$

  - δ_0 is the phase angle of generator under normal operation, and δ_1 is the new angle after the disturbance (mechanical power increased).
  - The goal is finding the δ_1 that provides the value of maximum mechanical power under transient stability

- From the above graph. The shadow area from δ_0 to δ_1 represents the acceleration of the rotor. The energy is gained while accelerating as $P_{mech} > P_{elec}$ at these time duration
- The shadow area from δ_1 to δ_2 represents the deacceleration of the rotor. The energy is lost while deaccelerating as $P_{mech} < P_{elec}$ at these time duration
- If P_{mech1} is the maximum mechanical power the generator can stay in transient stability, the energy generated and lost should equal to each other:

$$\int_{\delta_0}^{\delta_1}(P_{mech1} - P_{max}sin\delta)d\delta = \int_{\delta_1}^{\delta_2}(P_{max}sin\delta - P_{mech1})d\delta$$

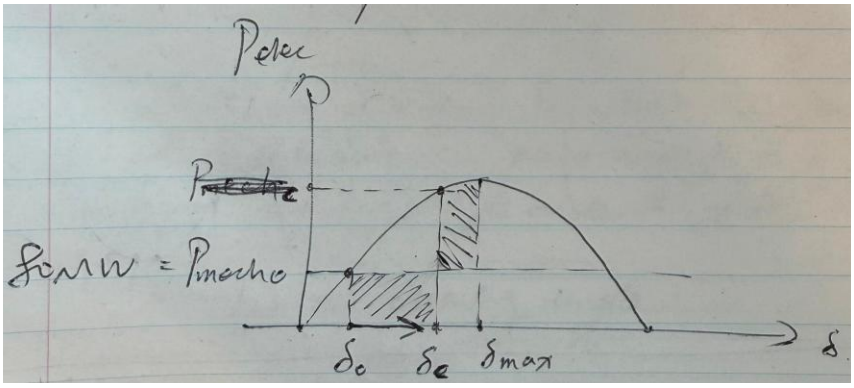
$$\delta_2 = \pi - \delta_1$$

$$\delta_1 = 50°$$

- Above, the maximum sudden increase of the mechanical power the generator can handle to still stay under transient stability is:

$$P = P_{max}sin\delta_1 - P_{max}sin\delta_0 = 383MW - 69.6MW = 313MW\ per\ phase$$

- Manual calculation example 2: A 50Hz synchronous generator capable of supplying 400MW of power is connected to a large power system and is delivering 80MW when a three phase fault occurs at its terminals, determine: 1) the time in which the fault must be cleared if the maximum power angle is to be 85 degrees. Assume H=7MJ/MVA on a 100MVA base. 2) the critical clearing angle



- Info from the question:
  - Inertia constant H presents the amount of kinetic energy stored in the rotor when it's spinning at rated speed, it basically means how heavy the generator rotor feels

electrically.

- ◆ Under normal operating conditions, $P_{mech0} = P_{elec} = 80MW$
- ◆ $P_{elec} = 0MW$ when fault occurs
- ◆ Generator backs to normal operation condition $P_{elec} = P_{max}sin\delta$ after fault is cleared

■ Firstly, calculate the initial power angle of the generator under normal operation:

$$P_{mech0} = P_{elec} = P_{max}sin\delta_0 \rightarrow 80MW = 400MWsin\delta_0 \rightarrow \delta_0 = 0.2\ radians$$

■ Apply the area equal equation based on the energy balance theory:

- ◆ When fault happens (during fault), $P_{mech} > P_{elec}$, generator starts accelerating, which means the rotor angle of the generator starts increasing (the angle between generator internal voltage and the grid voltage). The energy is gained during this accelerating process from δ_0 to δ_c.
- ◆ The rotor needs to release the energy after the fault is cleared, which leads the rotor angle keeps increasing for a while from δ_c to δ_{max}. Under this process $P_{mech} < P_{elec} = P_{max}sin\delta$, the energy is lost.
- ◆ δ_c is the fault clearing angle, where the fault is cleared at this moment; and δ_{max} is the maximum rotor angle the angle before the generator looses its synchronism.
- ◆ Based on the theory, we can have

$$\int_{\delta_0}^{\delta_c} P_{mech0}\, d\delta = \int_{\delta_c}^{\delta_{max}} (P_{max}sin\delta - P_{mech0})d\delta$$

$$80MW(\delta_{max} - \delta_0) = 400MW(cos\delta_{max} - cos\delta_c)$$

$$\delta_c = 70°$$

■ Apply swing equation to obtain the fault clear time:

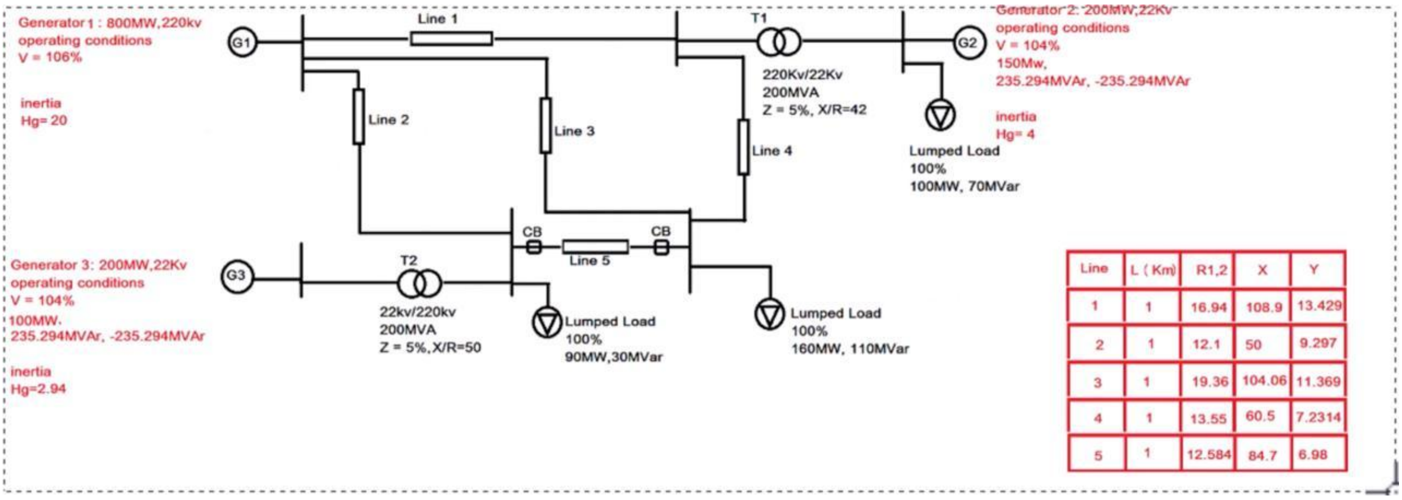
$$t = \sqrt{\frac{2H(\delta_c - \delta_0)}{\pi f P_a}} = 0.377sec$$

- ◆ Where H is the inertia constant, f is the frequency of the generator, and P_a is the fault power difference $P_{mech0} - P_{elec_{fault}} = 80MW - 0MW = 80MW$

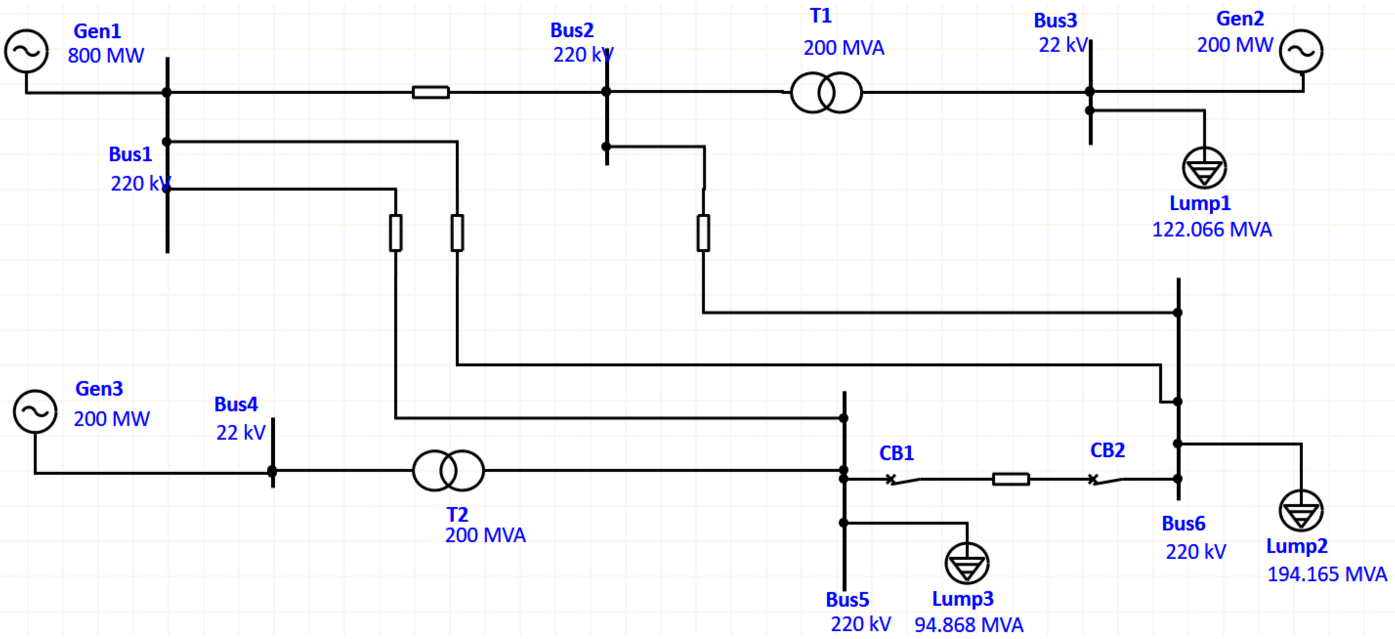
● Transient stability analysis simulation example

■ The stability analysis depends on the losing of the synchronization of synchronous machine

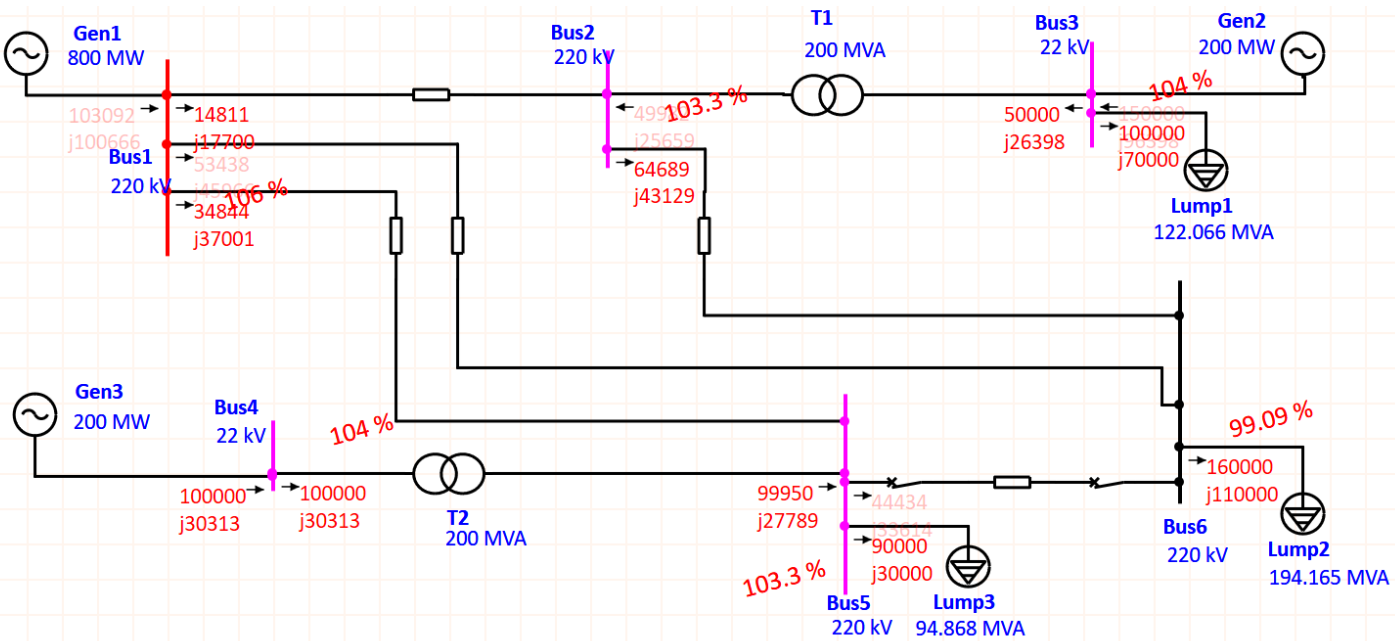
■ The one-line diagram used to operate the transient stability analysis is sketched based on below graph



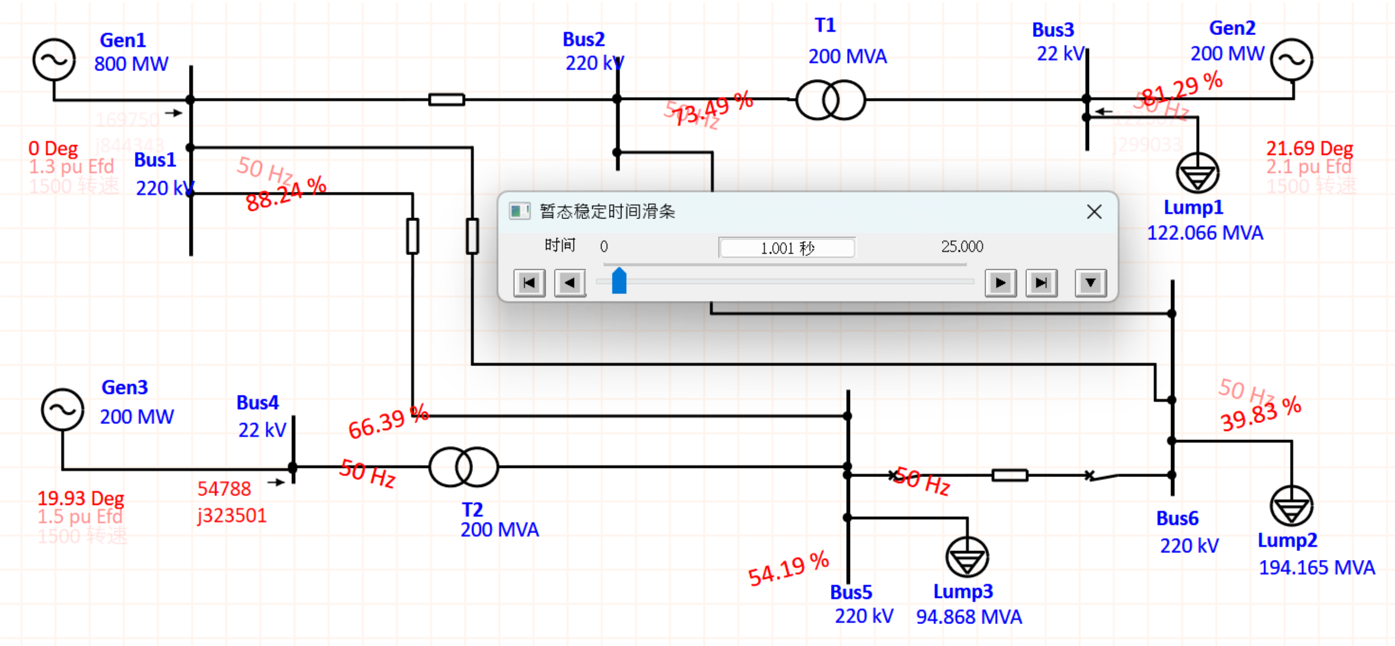
Line	L (Km)	R1,2	X	Y
1	1	16.94	108.9	13.429
2	1	12.1	50	9.297
3	1	19.36	104.06	11.369
4	1	13.55	60.5	7.2314
5	1	12.584	84.7	6.98



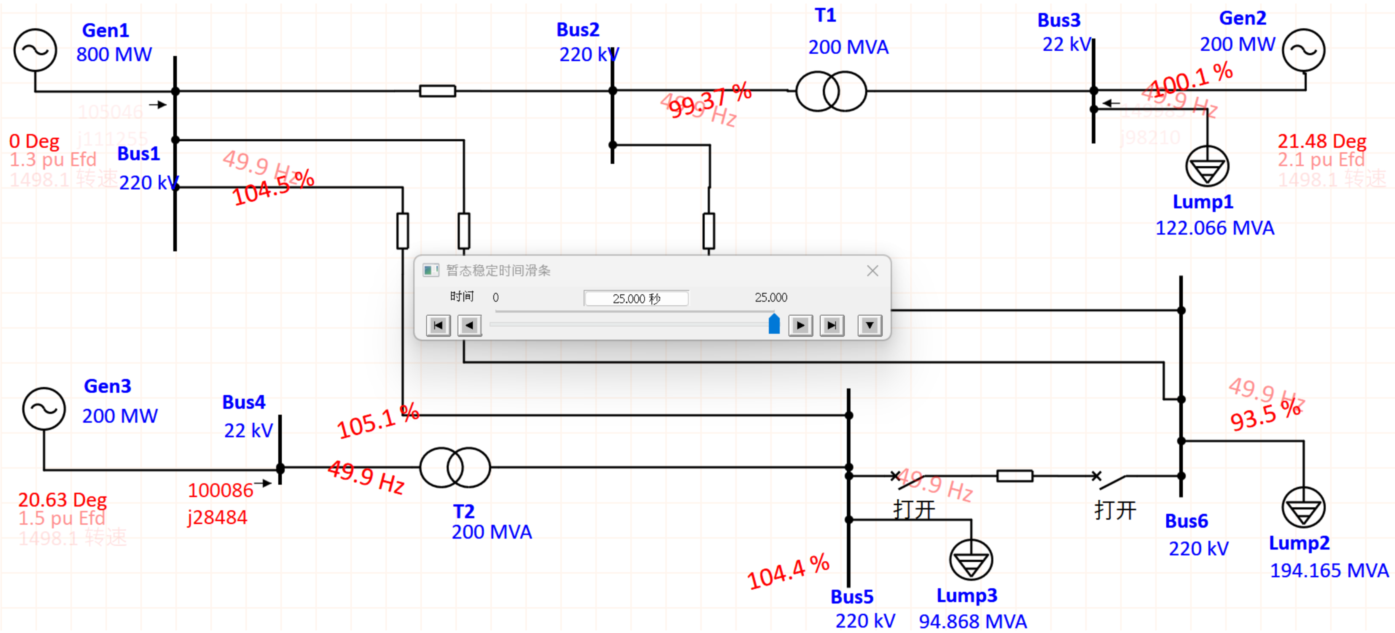
- The one-line drawing in ETAP is created, the information of the generators, transmission lines, transformers, and loads have to be defined.
- Runing load flow analysis to check if the one-line drawing is operational correctly

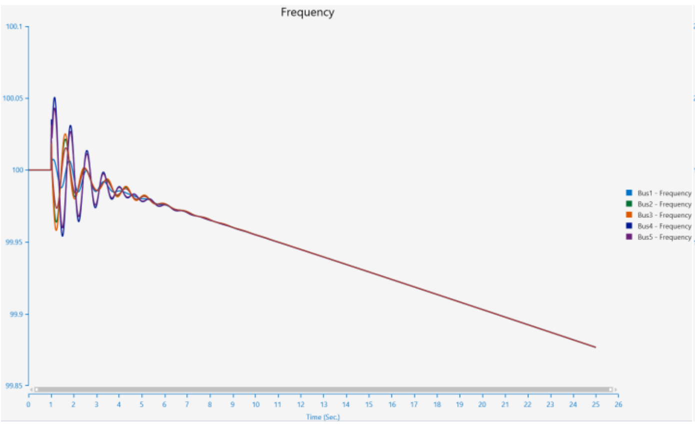


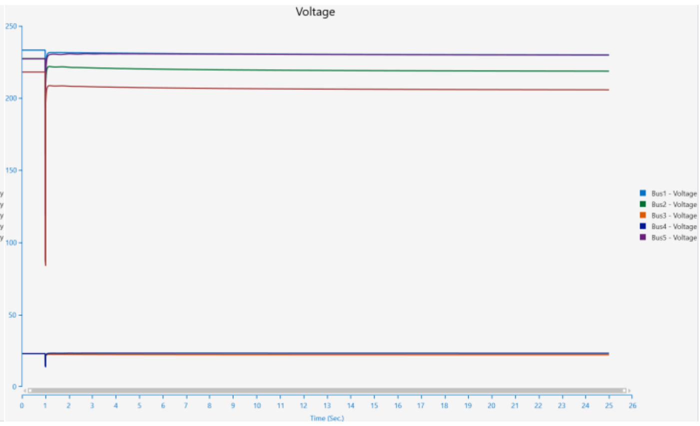
- The damping ratio and inertia need to be set for the generator to analyze the transient stability
- The fault is set to occur at after 1 second operation. The voltages are dropped from the simulation result below:

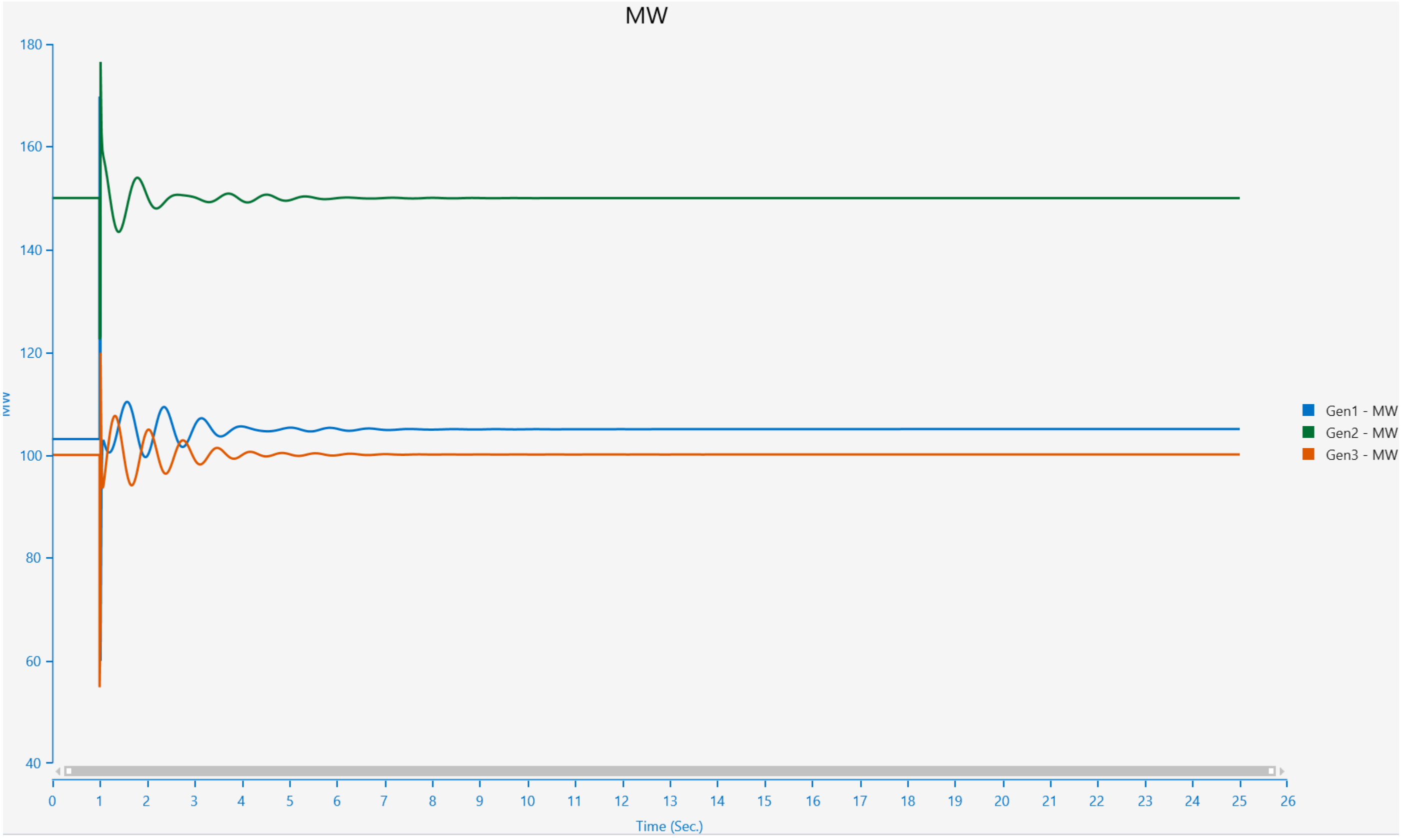


- The fault clear is set within 0.02 seconds. The voltage of the buses are coming back to nominal value, which indicates the transient stability of the grid









- From the frequency result of all buses: all buses follow the same frequency trajectory after the fault oscillation, which indicates the generators remain locked together, there has no loss of synchronism. Overall, the system is frequency stable, no generator is accelerating away from the others.
- From the voltage responses: all bus voltage responses settle quickly after the fault is cleared. And the voltage stability is maintained, which means the system is voltage stable after the fault disturbance
- From the generator real power output responses: all generators show oscillatory swings immediately after the fault disturbance is cleared, and the steady state is reached. The damped out oscillation indicates none of the generators are losing synchronism
- Based on the above results, the proposed system is transient stable for the occurred fault

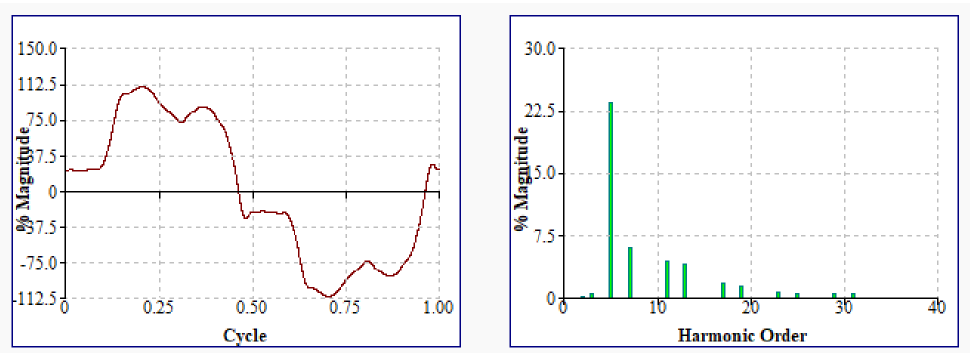
11 Harmonics study

- Definition: a voltage or current with multi-frequencies, there are unwanted higher frequencies which superimposed on the fundamental waveform creating a distorted wave pattern
- Disordered waveform is created by a combination of a fundamental harmonic waveform with a higher order harmonics waveform.
- Harmonic order is integer multiple of fundamental frequency: for example: the frequency of the fundamental waveform is 50hz, then the 2nd order harmonic waveform has 100hz, and the 3rd order harmonic waveform has 150hz
- Harmonics measurement methods:
  - Total harmonics distortion THD: the measure of the amount of harmonics present in the signal:

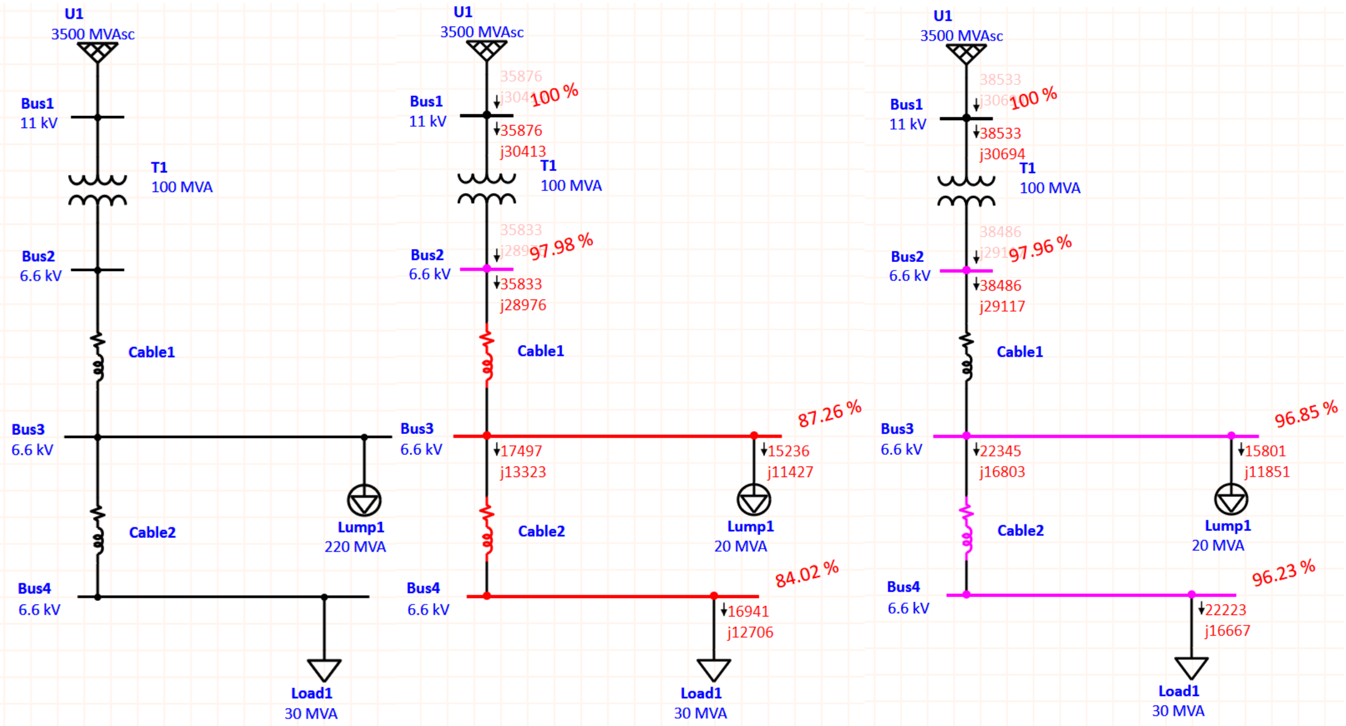
$$THD = \frac{\sqrt{\sum_{n=2}^{\infty}(V_n)^2}}{V_1} = \frac{\sqrt{V_{rms}^2 - V_1^2}}{V_1}$$

    - Total Harmonics Distortion: it measures how distorted a waveform is. V_1 is the fundamental component of the voltage, and V_n is the harmonic components, and V_{rms} is the total RMS voltage
    - THD < 5% means the waveform is clean
    - THD is between 5% and 10% means the waveform has some distortion
    - THD > 10% means significant distortion, which may cause the overheating of transformers, extra power loss
    - Based on the IEEE standard: the THD of the voltage shall not be greater than 5%, the THD of the current shall not be greater than 3%

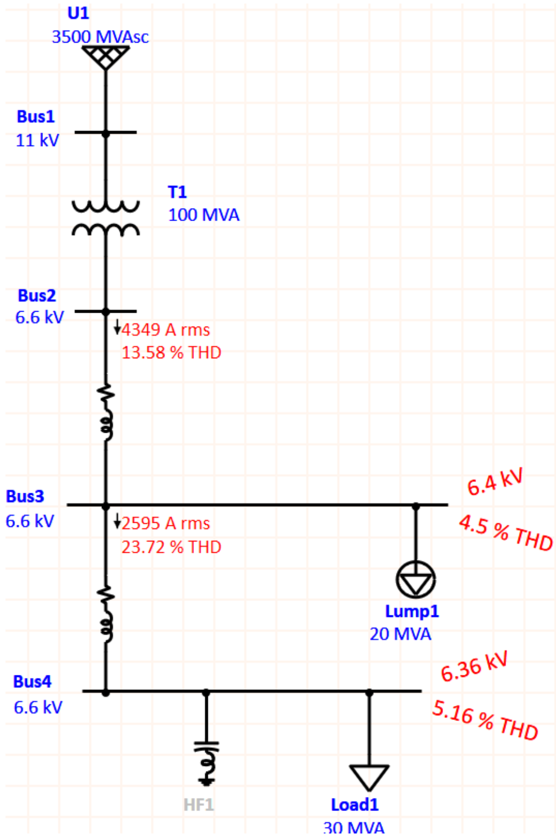
- **Harmonics Example (load)**
  - Discuss system impact due to the harmonics applied on the load
  - The harmonics applied on the load is 6 Pulse VFD from RockWell



  - The below one line drawing shows a medium voltage distribution system, the power flow from a high capacity power grid through a step-down transformer, then through medium voltage cables and finally to loads

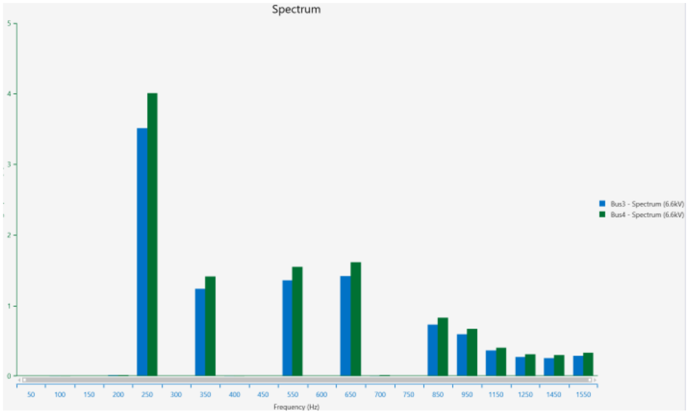


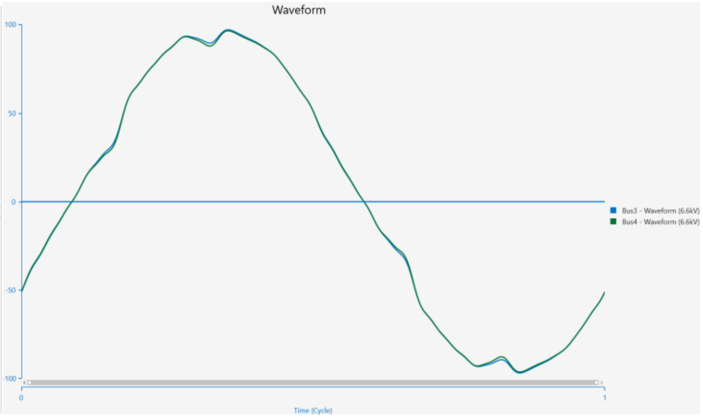
- The above right graph is the initial load flow analysis result, it checks if the components are set correctly. Through the load flow analysis report, the cable 1 and cable 2 are overloaded, and the bus 3 and bus 4 are operated under voltage.
  - Increase the size of the cable 1 and cable 2 to handle the issue occurred during the load flow analysis.
  - After increase the cable size, the voltage drop is controlled within limitation 5%
- The below graph shows the harmonics analysis results for the bus 3 and bus 4.



  - Based on the analysis results: both buses are operating below the 6.6kV nominal voltage

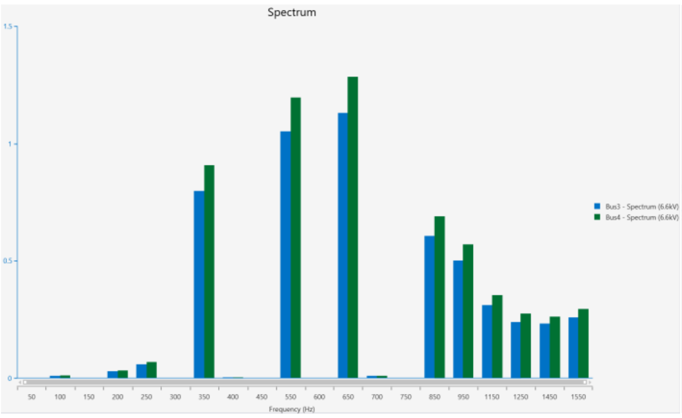
- For bus 3, its THD is 4.5%, it indicates an acceptable value for medium-voltage systems
- For bus 4, its THD is 5.16%, it indicates the THD of bus4 is slightly above the 5% guideline (IEEE standards)
- Since bus 4 is further from the source, the short-circuit strength is reduced, the voltage distortion is increased, and the harmonic voltage drops is amplified
- And load 1 is the harmonic-producing load, it injects harmonic current into bus 4, so higher voltage distortion of the bus 4 is caused by harmonic current

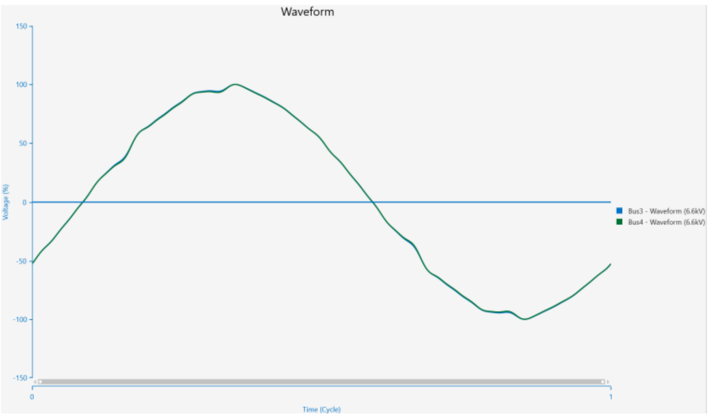


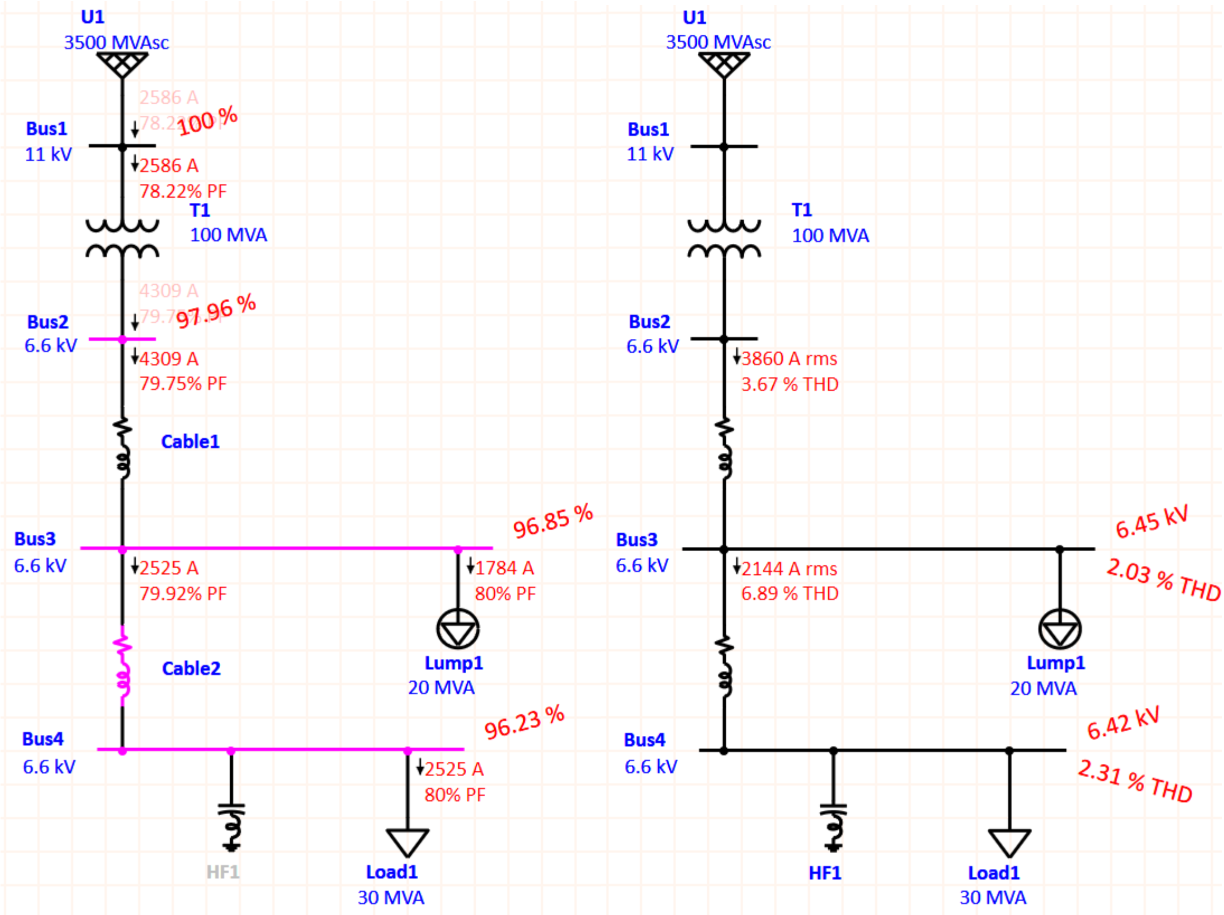


- The above left spectrum plot (frequency domain): x-axis indicates the frequency or the orders of the, and y-axis is the magnitude of each harmonic component. From the spectrum plot, it indicates the distortion is dominated by a 5th order harmonic (associates with the 6-pulse VFD industrial load), and the rest of the spectrum are relatively low.
- The above right spectrum plot (time domain): both waveforms are very close to sinusoidal waveform, the shape of the waveforms match the 5% THD with mild distortion

- Add harmonic filter or capacitor bank in series of the harmonic source to eliminate the harmonic from the power grid
  - Applied harmonic filter with ‘single-tuned’ filter type
  - Based on the power factor of the static load, the harmonic filter will be applied to increase the PF of the static load from 80% to 95%
  - From the previous harmonic analysis, the THD is dominated by the 5th order harmonic. And the harmonic current is 2525A from the load flow analysis.
  - Through the size filter calculation, the parameters of the capacitor, inductor and resistor of the harmonic filter can be obtained.
  - From the below right harmonic analysis result, the THD of the bus 3 and bus 4 have been successfully reduced with the application of the harmonic filter





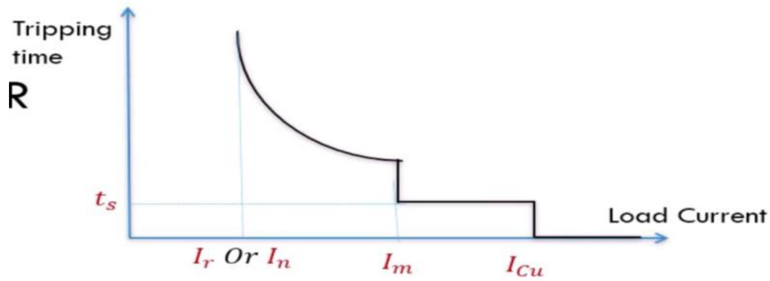


- From above spectrum analysis result, the 5th order harmonic component has been significantly reduced. And the waveform becomes smoother

12 protection and coordination

Overcurrent relay parameters

- Definition of overcurrent relay: a device used to detect fault conditions, and it gives the signal to trip circuit to disconnect the circuit breaker by using terminal plugs.
  - Overcurrent relay is a safety switch: it will disconnect the circuit to protect it when the current is too high
  - Types of fault conditions: overload condition; short circuit condition
- The difference between overcurrent and overload
  - Overcurrent could be overload or short circuit
  - Overload: current is higher than normal but not extremely high, it causes heating and damages the equipment gradually. Time-delay overcurrent relay to handle this situation
  - Short circuit (fault): current is extremely high due to two wires touching, insulation failure etc. it causes equipment damage instantly. Instantaneous overcurrent relay to handle this situation
- Types of tripping
  - Instantaneous time tripping unit: the relay detects the fault instantaneously, when the load current increase above the rated value
  - Time-delay tripping unit: the relay detects overcurrent after specified period of time, when the load current increase above the rated value
  - Inversely time tripping unit
  - The overcurrent relay can use the above three types of tripping at the same time such as IDMT



    - Above the Ir or In rated normal current, the relay will operate under the inverse tripping unit. Above the short circuit current Im, the relay will operate under the time-delay tripping unit or the instantaneous tripping unit. And above the Icu the maximum current capacity, the relay will operate under the instantaneous tripping unit
- Instantaneously overcurrent relay setting for different scenarios
  - Overcurrent relay (OCR) = instantaneous current I_{inst} / Current Transformer Ratio (CTR)

$$OCR = I_{inst}/CTR$$

  - Lines between substations: $I_{inst} = 1.25 * I_{fault}$
  - Distribution lines: $I_{inst} = 0.5 * I_{fault}$ or $I_{inst} = (6\ to\ 10) * I_{rated}$
  - Power transformer unit: $I_{inst} = (1.25\ to\ 1.5) * I_{fault} * \frac{N_2}{N_1}$
- Overload overcurrent setting for different scenarios
  - Overcurrent relay (OCR) = overload current $I_{overload}$ / Current Transformer Ratio (CTR)

$$OCR = I_{overload}/CTR$$

  - The pick-up setting: $I_{overload} = OLF * I_{rated}$, where OLF is the Overload Factor

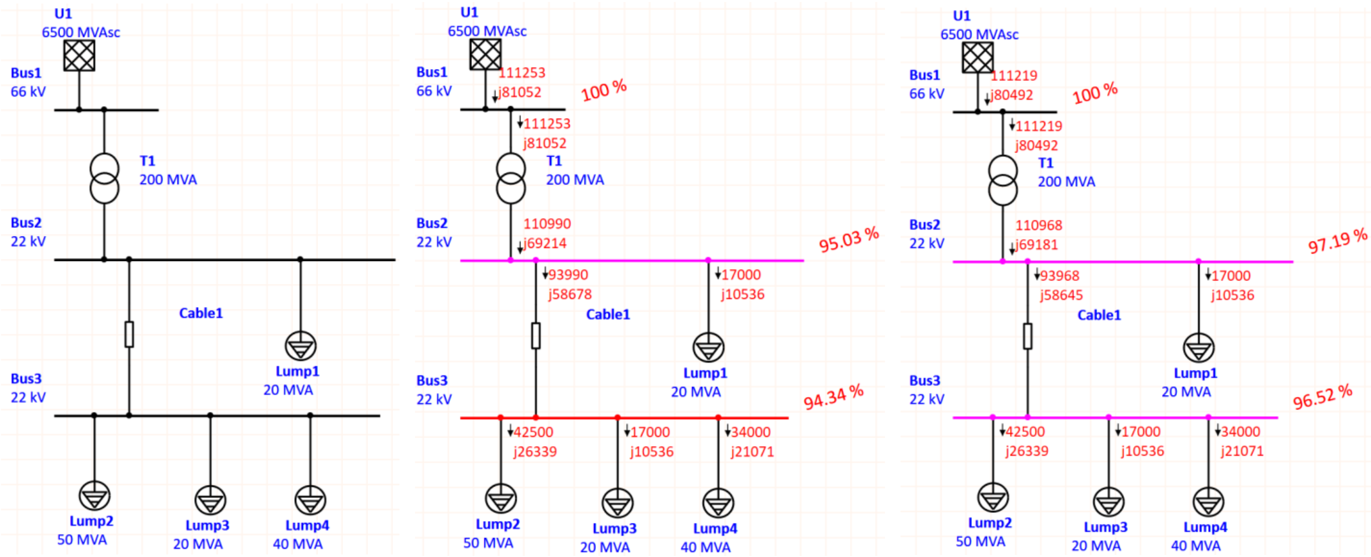
- Current Transformer Ratio (CTR):
  - According to IEEE and ANSI standards: The fault (short circuit) current must not exceed 20 times of the CTR:

$$I_{sc} < 20 * CTR; CTR > I_{sc}/20$$

  - Example: nominal current is 200A, and short circuit current is 2000A
    - According to the standards: $CTR > Isc/20$ and $CTR > Inominal\ or\ Irated$, so here CTR can choose 300

OCR and CTR ETAP examples

- The system used for analysis is shown below



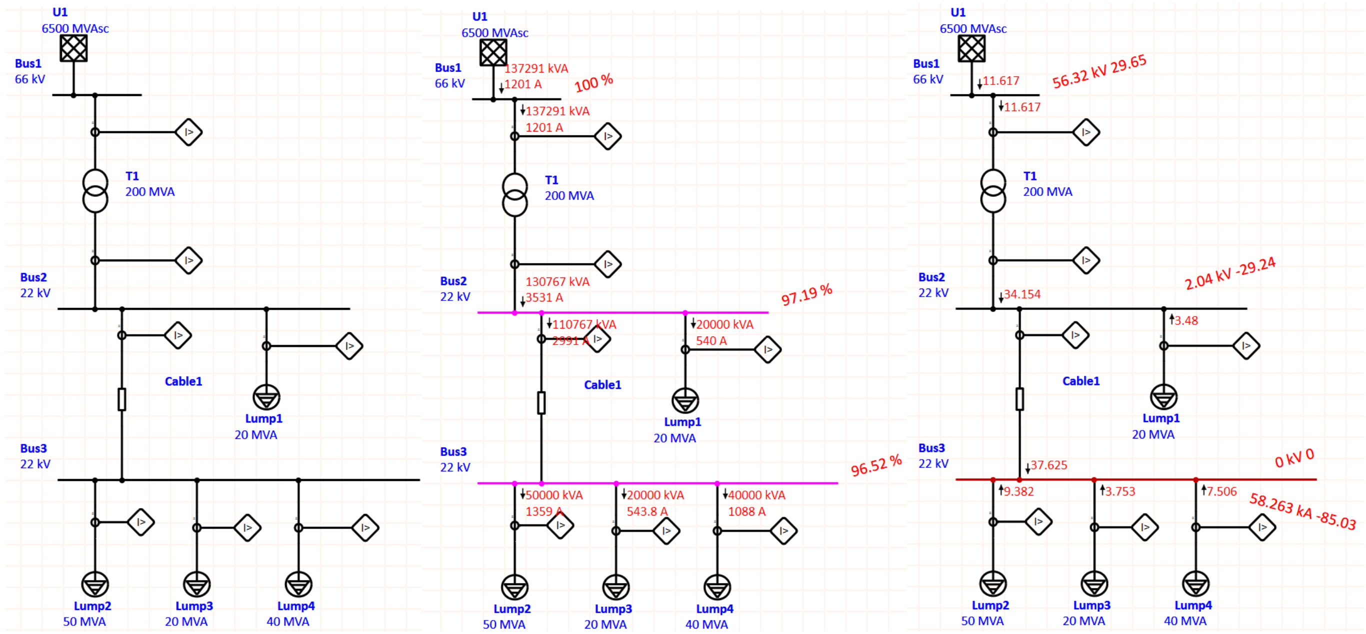
- Then running load flow analysis to adjust the parameters of the components
  - Increase the cable numbers and lower the transformer primary-side voltage (lowering the tap setting) to:
    - Improve the power factor and undervoltage problem at the downstream buses
    - Lower tap of the transformer is reducing the reactive power comes from the upstream. Real power wont be changed when the tap is adjusted.
- Add current transformer (CT) and overcurrent relay (OCR) on the system
  - Edit the rating of CTs. The rating of CT should be five times less of CTR where CTR depends on two parts $CTR > Isc/20$ and $CTR > Inominal\ or\ Irated$.

$$rating\ of\ CT = CTR/5$$

  - $I_{nominal}\ or\ I_{rated}$ can be found from load flow analysis, while I_{sc} can be found from short circuit analysis
  - Example: from below load flow analysis, the nominal current of the lump load 4 is 1088A, and the short circuit current of lump4 when bus3 is on fault is 58.263kA
    - $CTR > Isc/20$ and $CTR > Inominal\ or\ Irated$, so CTR should be greater than 2913.15A. The rating of CT on lump load 4 should be as follows:

一次側		二次側		电流比	匝数比
2950	A	5	A	2950 : 5	590 : 1

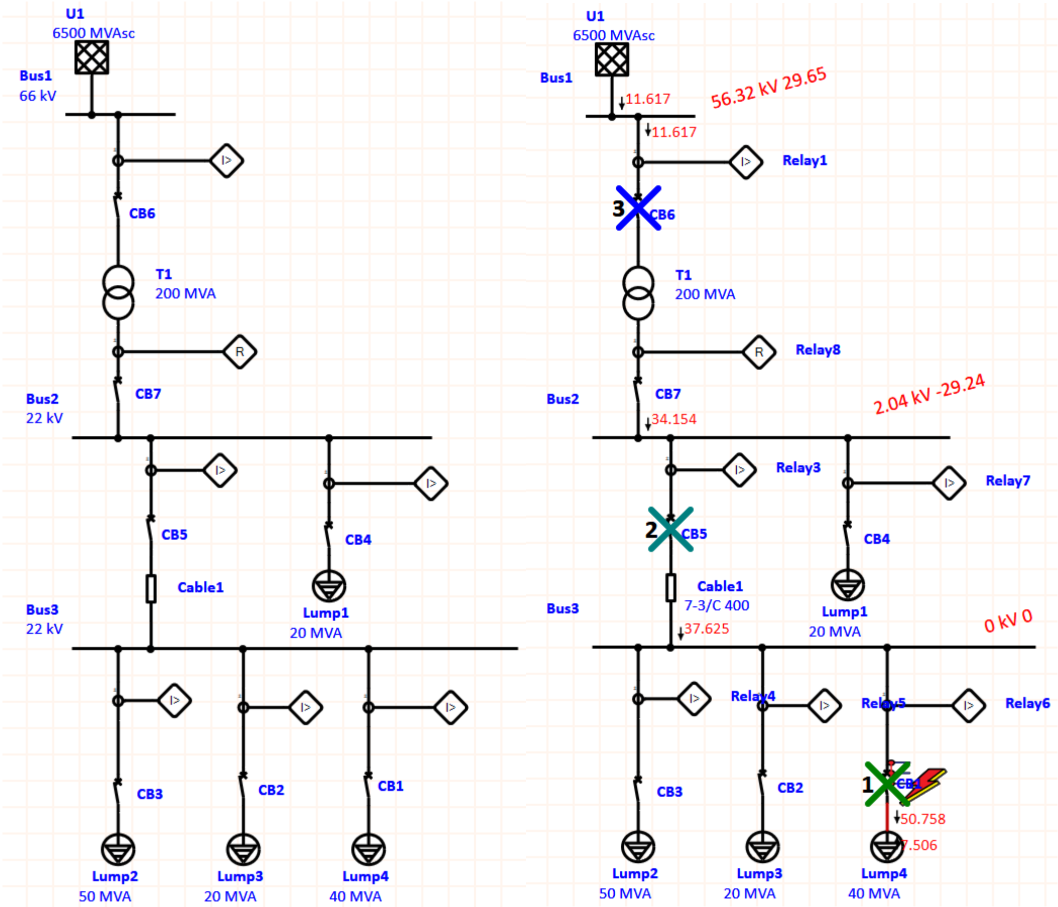
    - Same calculation procedure for the other CTs



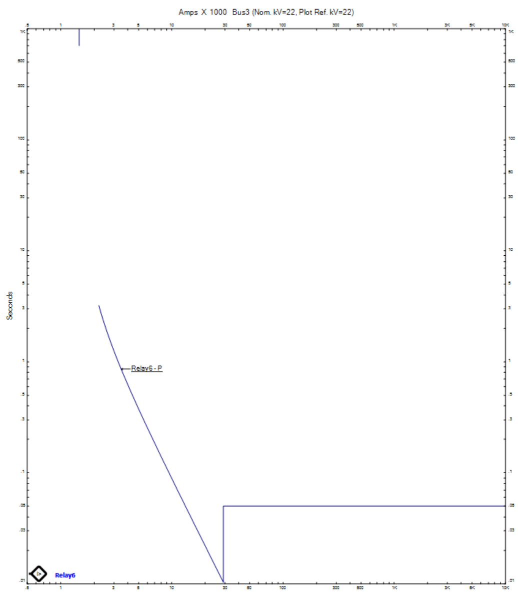
- The function of current transformer (CT): the CT scales down high current so the OCR can measure the current safely, since OCR can not measure the huge current during fault. So the CT reduces the current to a small safe value.
- OCR design for each CT
  - To design OCR, the tripping unit (inverse tripping unit for overload, and instantaneous tripping unit for short circuit) and key current values should be decided
  - To set the inverse tripping unit of OCR: Normally, the nominal current of OCR is 1.5 times of the line nominal current
  - To set the instantaneous tripping unit of OCR: the short circuit current value used in OCR is selected as 0.5 times the maximum short circuit current. For example, the short circuit current of bus 3 is 58.263kA, then the short circuit current in the OCR of lump load 2 to lump load 4 should be 0.5 * 58.263kA.

Coordination

- Add circuit breaker to trip due to any overcurrent relay in the system. The one line drawing system with CT (Current transformer), OCR (Overcurrent Relay), and circuit breakers is shown below
- To connect OCR and circuit breaker, the 'output action' should be defined in the OCR components
- Under the analysis of 'Production & Coordination', users are able to see which circuit breaker will open under any fault. As shown below, when the fault is happened on lump load 4. The short circuit operating order is like CB1 -> CB 5 -> CB 6



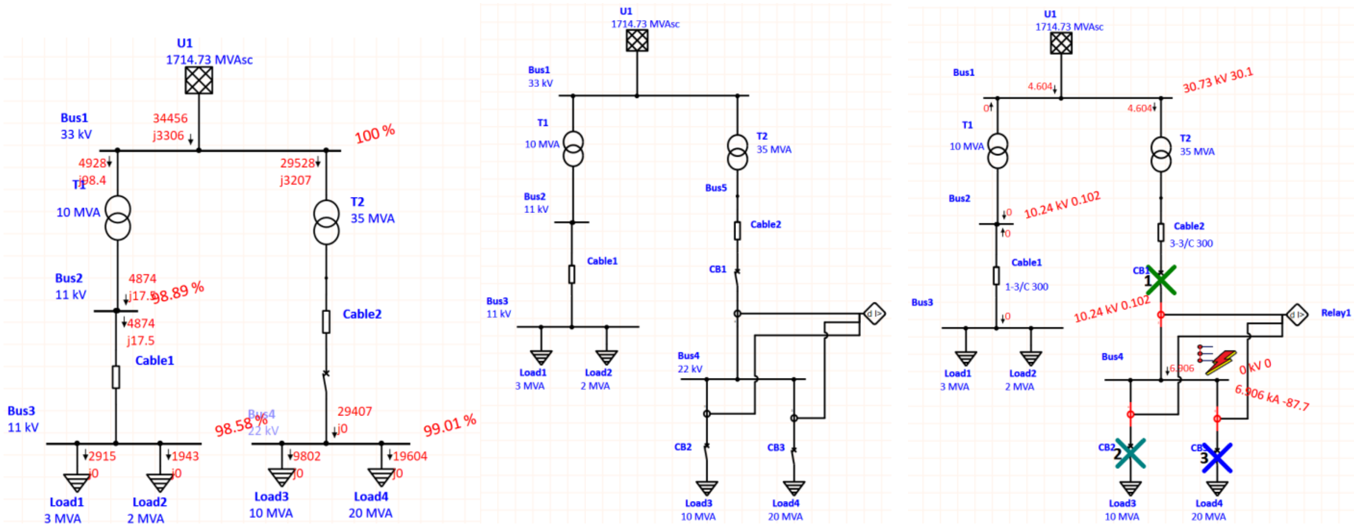
- The OCR tripping unit curve can also be visualized through 'production & coordination' analysis. The below curve shows the relay tripping unit curve of the OCR 6.



- To check the overlay OCR curves to make sure there has no intersection of each curve, which ensures the downstream circuit breaker will operate first.

Differential relay

- Differential relay checks if the current going into the system equals to the current coming out. A fault is inside if the two values doesn't match, so the differential relay trips to protect the equipment.
- Compared to overcurrent relay, the differential relay needs current transformer (CT) at both input and output sides of the component. There will be current flows through the differential relay once the current of the input is greater than the current of the output, it will then trip the circuit.
- ETAP simulation example
  - The one line drawing used for differential relay applications purpose is shown below. And the load flow analysis is performed to ensure the system is running correctly.



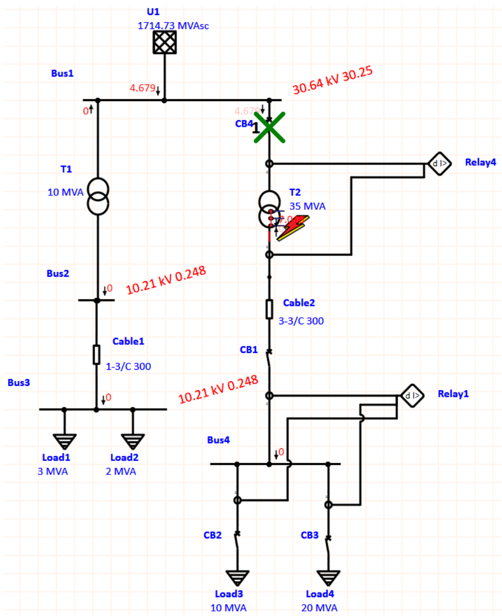
  - Target: add differential relay on bus bar 4.
    - The Alstom CAG 14 is selected as the differential relay for protecting bus bar 4
    - One thing to be attention is that the Current Transformer on the upstream of the bus bar 4 should be 'Reverse Polarity'.
    - Set the input and output actions in Differential Relay
    - Running the simulation 'Production & Coordination' to check the circuit breaker operation order when there has a fault happened on bus bar 4.
    - As shown in the graph above, the circuit operating order is CB1 -> CB2 -> CB3 when the fault is happening on bus bar 4
  - Target: add differential relay on transformer
    - The main formulas for transformer differential relay design are:

$$i_{primary} = \frac{I_{primary}}{CTR_{primary}}$$

$$i_{secondary} = \frac{I_{secondary}}{CTR_{secondary}}$$

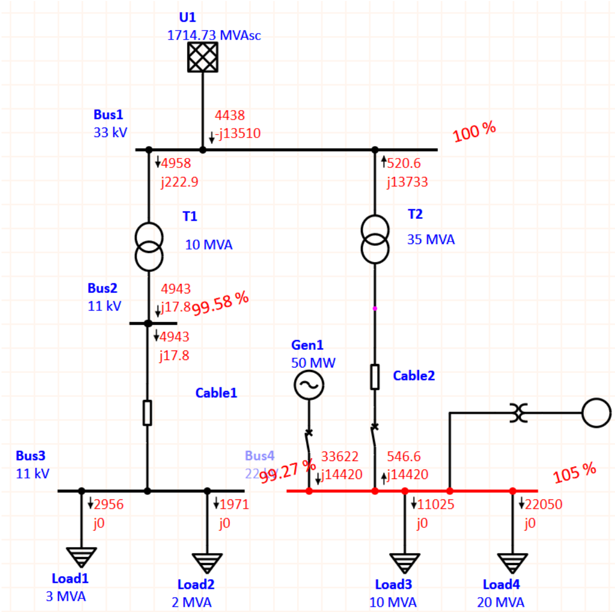
$$CTR_{secondary} = a * CTR_{primary};\ I_{primary}a = I_{secondary}$$

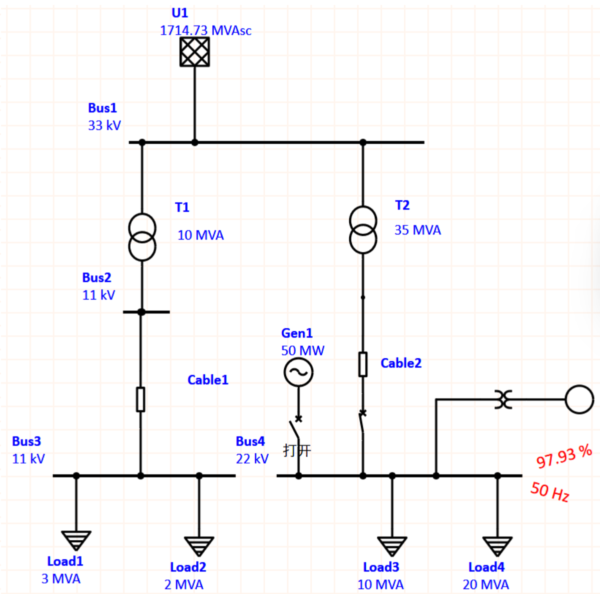
    - After setting the values in current transformers and the actions in differential relay. The simulation result of the transformer fault is shown below:



Voltage Relay (Over/Under Voltage Relay)

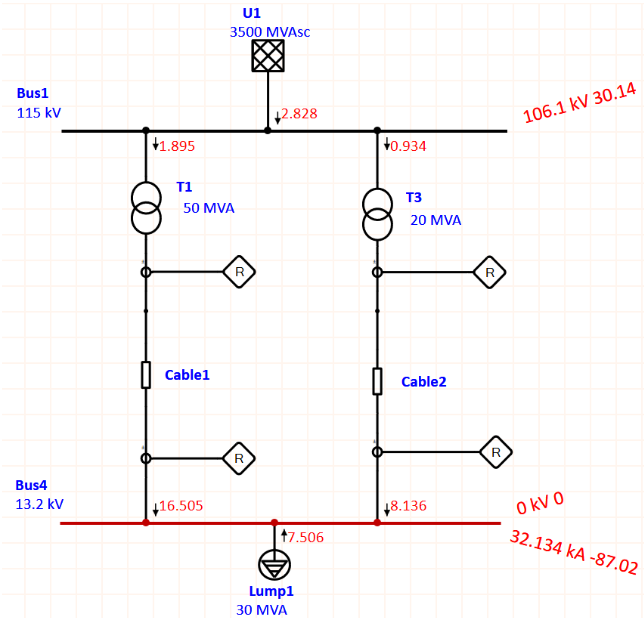
- When the voltage of the target component is too high or too low, the voltage relay will open the circuit breaker. 59 relates to over-voltage relay, while 27 relates to under-voltage relay.
- The voltage relay operates with potential transformer
- Operate over-voltage relay when the voltage on bus bar 4 is too high. From the transient stabilioty simulation result shown in the below right graph, the circuit breaker has been open when the bus bar 4 voltage is too high.

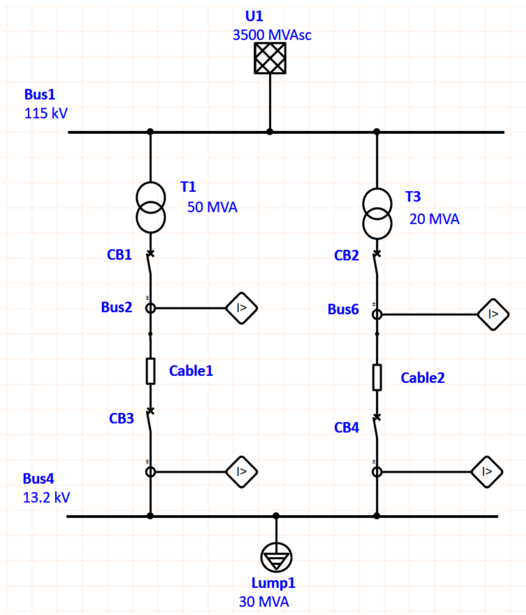




Directional Overcurrent Relay (DOCR)

- It's a type a overcurrent relay that also checks which direction the fault current is flowing. It requires the input and output current to determine the direction of the fault. Compared to OCR, DOCR trips only the fault current is coming from the direction that is supposed to be protected.
- ETAP simulation with DOCR application
  - The one line drawing of a power system is shown below. The short circuit analysis is performed to assist designing the current transformer (CT) and OCR.





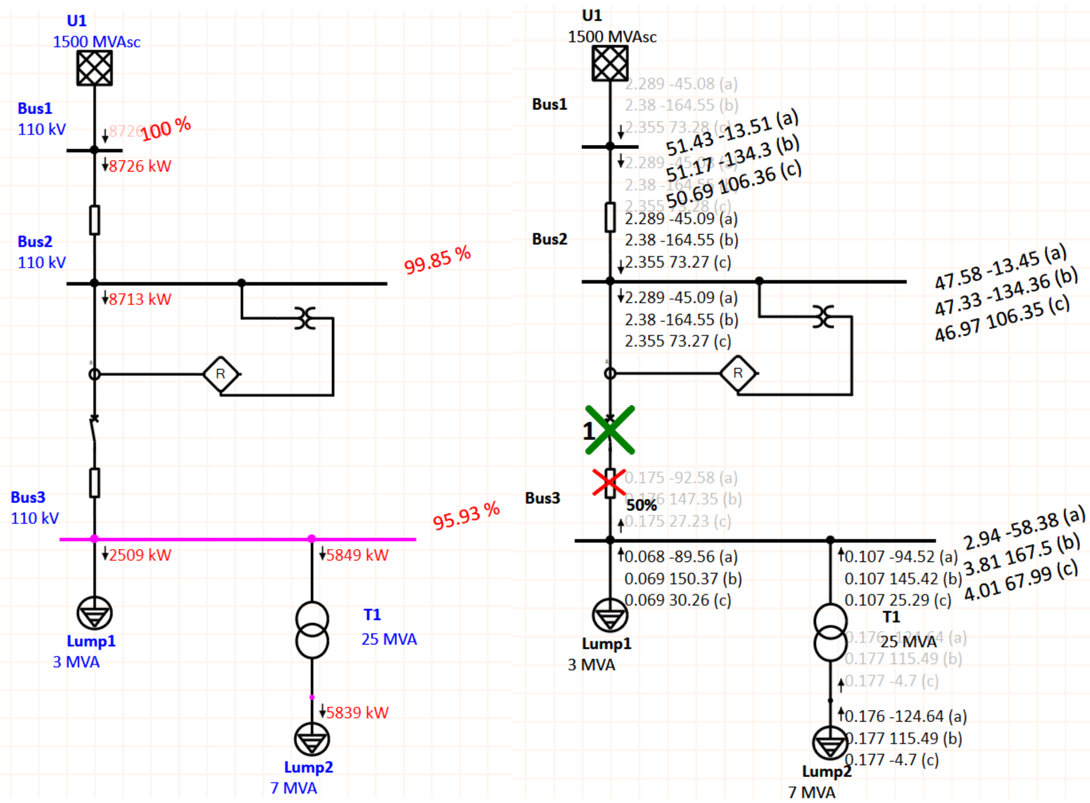
- Target: operate the left circuit breakers (CB1 and CB3) when the fault is happened at the left side. Operate the right circuit breakers (CB2 and CB4) when the fault is happened at the right side.
- Operate DOCR by adjusting the polarity direction of CT and OCR

Distance Relay (Impedance Relay)

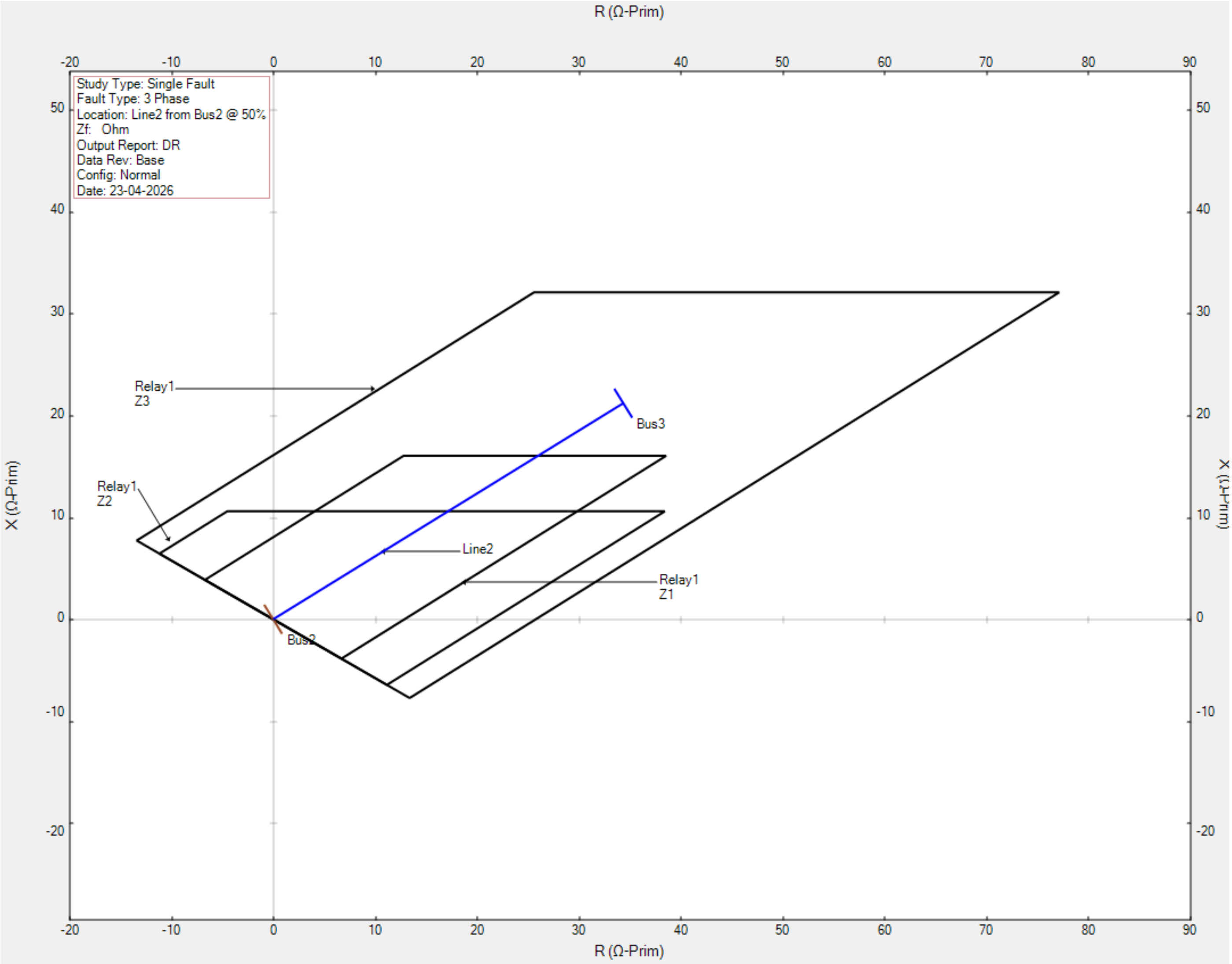
- It's used to protect transmission line against fault, it works by measuring the line's impedance that increases with the distance. If the measured impedance becomes small, the relay knows the fault is nearby and trips.
- The distance relay can detect how far the fault on a transmission line is.
- Normal impedance normally equals the summation of line impedance and the load impedance

$$Z_{normal} = Z_{line} + Z_{load} = V/I$$

- If $Z_{normal} < Z_{line}$, it means there is a fault inside the transmission line, then it gives signal to the relay to trip the circuit breaker.
- The values needed to design the distance relay:
  - Current Transformer (CT) ratio
  - Voltage Transformer (VT) ratio
  - Line impedance
  - Line length
  - Zero sequence compensation factor, $k_0 = \frac{1}{3}(\frac{Z_0 - Z_1}{Z_1})$
  - Arc resistance
- Example
  - The one line drawing of the power system with distance relay is shown below. And the load flow analysis is performed to assist checking if the power system is operating correctly.



- Set the value of distance relay based on the manual of selected relay component. Here the Schneider P441 is selected as the distance relay for the simulation.
- The value needed for design the distance relay (the StarZ | Distance section):
  - CTR = 200/1
  - VTR = 1000/1
  - Z ratio = 200/1000 = 0.2
  - Line length for transmission line = 50km
  - Cable impedance:
  - Zero compensation factor
- Add three-phase fault on downstream transmission line, and running the ‘StarZ Protection & Coordination’ Simulation. The simulation result shown in the above right graph shows the circuit breaker is operating properly.
- The below graph shows the StarZ plot of the downstream transmission line under the application of the distance relay. From the plotting, we can see:
  - The transmission line 2 is covered by zone 1 about 80%, by zone 2 about 50%, and it’s entirely covered by zone 3


R (Ω-Prim)
Study Type: Single Fault
Fault Type: 3 Phase
Location: Line2 from Bus2 @ 50%
Zf: Ohm
Output Report: DR
Data Rev: Base
Config: Normal
Date: 23-04-2026
Relay1
Z3
Relay1
Z2
Bus3
Line2
Relay1
Z1
Bus2
X (Ω-Prim)
X (Ω-Prim)
R (Ω-Prim)

Circuit Breaker

- According to IEC 60947-2 (molded case CB) and IEC 60898-1 (Miniature CB), there are two types of circuit breakers:
  - Category A: fixed setting
    - Mniature CB: protects low-current circuit that used in residential and commercial panels. It has fixed settings
  - Category B: adjustable setting
    - Molded case CB: protects higher-current circuit that used for feeders, and industrial systems. It has adjustable thermal and magnetic trip settings
- The fundamental characteristics of a circuit breaker:
  - Rated voltage: voltage where the CB has been designed to operated under normal condition
  - Rated current (In): maximum value of the circuit breaker
  - Overload relay current (Ir): the current that the CB operates under inverse tripping
  - Short circuit relay trip current (Im): instantaneous tripping type
  - Rated short circuit breaking capacity (Icu or Icn): maximum fault-current a circuit breaker can interrupt safely for only one time. Afterwards, the CB should be replaced.

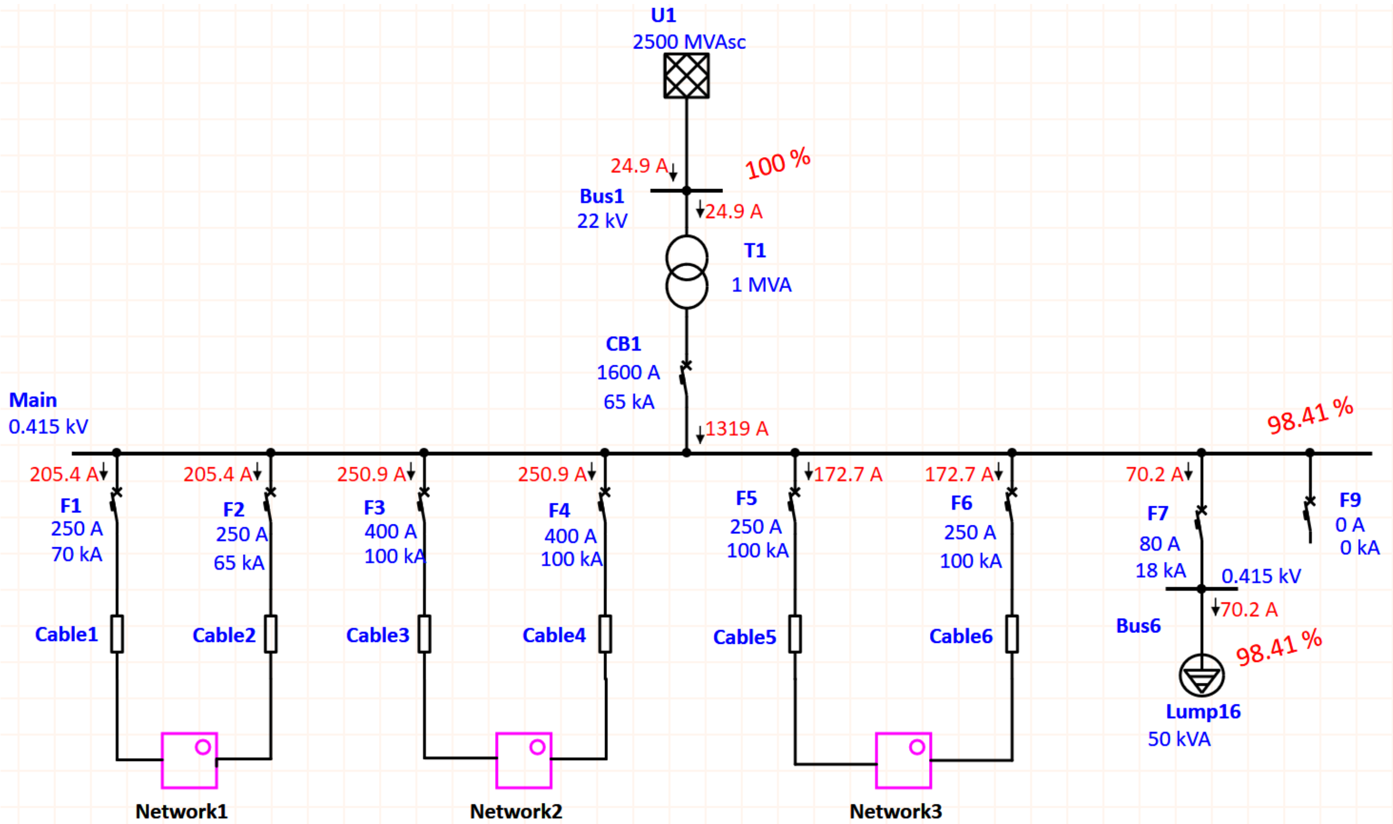
Type of protective relay		Overload protection	Short-circuit protection		
Domestic breakers IEC 60898	Thermal- magnetic	Ir = In	Low setting type B 3 In ≤ Im ≤ 5 In	Standard setting type C 5 In ≤ Im ≤ 10 In	High setting circuit type D 10 In ≤ Im ≤ 20 In[a]
Modular industrial circuit-breakers	Thermal- magnetic	Ir = In fixed	Low setting type B or Z 3.2 In ≤ fixed ≤ 4.8 In	Standard setting type C 7 In ≤ fixed ≤ 10 In	High setting type D or K 10 In ≤ fixed ≤ 14 In
Industrial circuit-breakers IEC 60947-2	Thermal- magnetic	Ir = In fixed	Fixed: Im = 7 to 10 In		
		Adjustable: 0.7 In ≤ Ir ≤ In	•Adjustable:Low setting: 2 to 5 In •Standard setting: 5 to 10 In		
	Electronic	Long delay 0.4 In ≤ Ir ≤ In	Short-delay, adjustable 1.5 Ir ≤ Im ≤ 10 Ir Instantaneous (I) fixed I = 12 to 15 In		

- CB sizing
  - 1st step: confirm rated current In, a CB is designed and evaluated to carry 100% of its rated current
    - 80% rated circuit breaker calculation:
      - Ex. A power system has one 50A continuous load and one 60A noncontinuous load, the rated current of the circuit breaker is: 60 + 1.25*50 = 122.5A, the In will be selected as 125A
    - 100% rated circuit breaker calculation: In = 60 + 50 = 110A, the In is selected as 125A
    - 80% rated CB is cheaper than 100% rated CB
  - 2nd step: selectivity – energy or logic
- CB coordination
  - Selectivity coordination: it means the downstream breaker's ability to trip independently without affecting the upstream breaker, enabling a more secure system by isolating faults

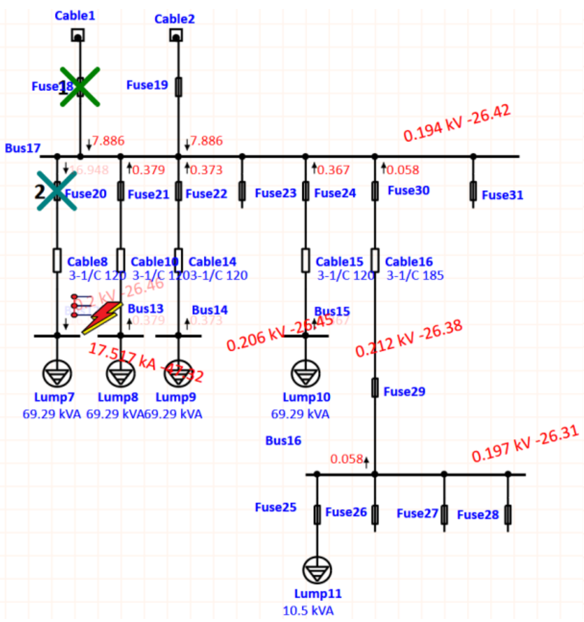
effectively.

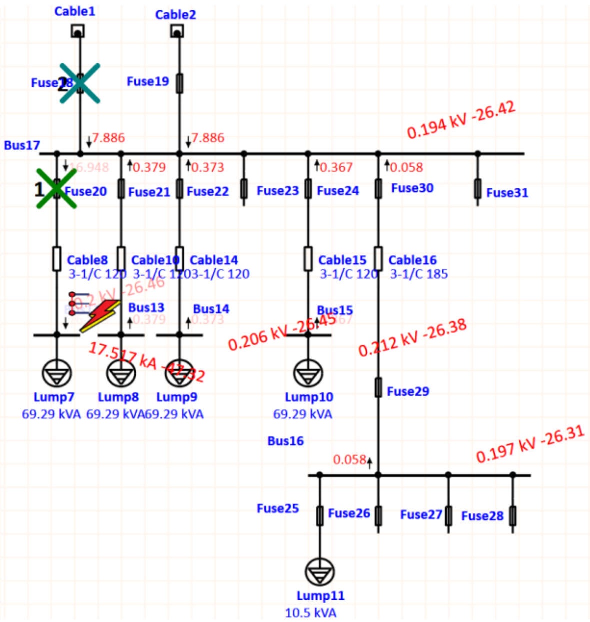
- After confirming the short circuit current, make sure all panel breakers can withstand this value of short circuit current (Icu >> Isc)
- All down stream breakers are selective with the main breaker by value more than Isc
- Cascading: it's used when you can not find any selectivity between upstream and downstream CB. When we can not use downstream CB with enough Icu, then the upstream CB is needed to protect the downstream breakers.

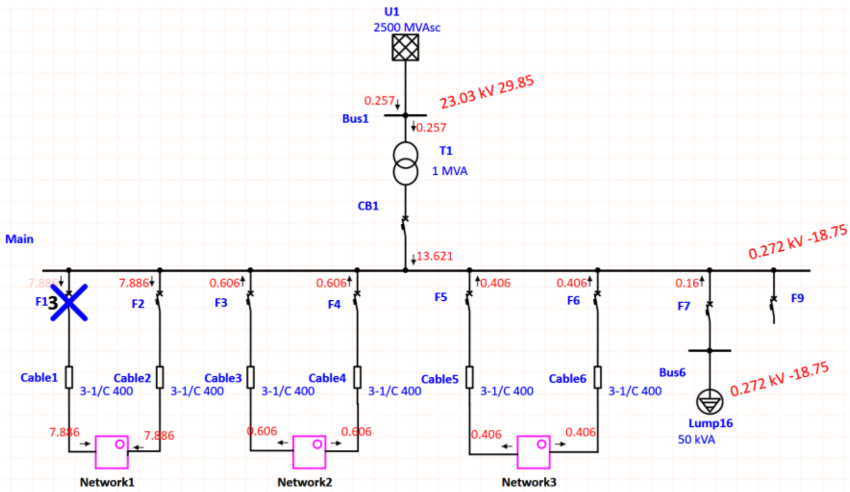
- CB selectivity and coordination simulation on ETAP
  - The one line drawing of the power system for CB selectivity and coordination action is shown below:



  - Entre the data for each circuit breakers
    - Each CB contains two parts: the frame design of the circuit breaker and the trip device
    - The Schneider circuit breakers are used for the simulation
    - CB1: the current from load flow analysis is 1319A,
    - F1 CB: the current from load flow analysis is 205.4A, the CB NSX250-H is selected
    - Check the selectivity of fuses and CB are working properly by running simulation shown below and the breaker open sequence (assists to check if the breakers are designed properly). The operation order is: fuse 18 -> fuse 17 -> F1, the fuse type of fuse 18 should be changed based on StarZ plot, as the order should be fuse 17 -> fuse 18 -> F1



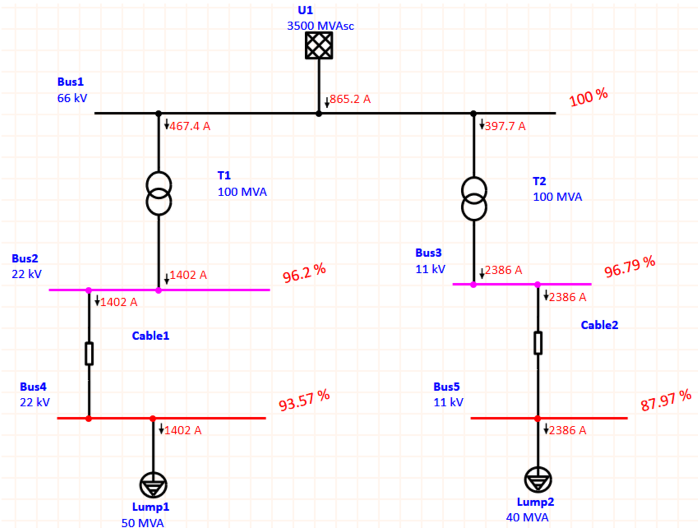


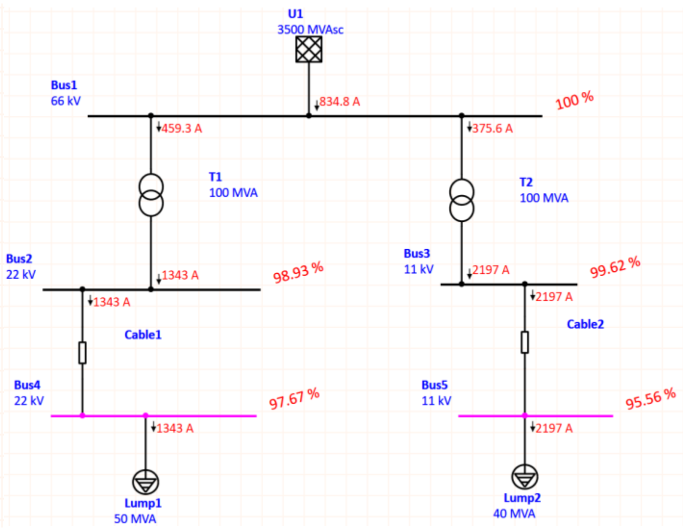


ID	If (kA)	T1 (ms)	T2 (ms)
Fuse30	5.977	< 0.1	
Fuse29	5.977	< 0.1	
Fuse18	2.729	1.3	
Fuse19	2.729	1.3	
F1	2.729	14.9	80.0
F2	2.729	14.9	80.0
CB1	4.714	1385	1748

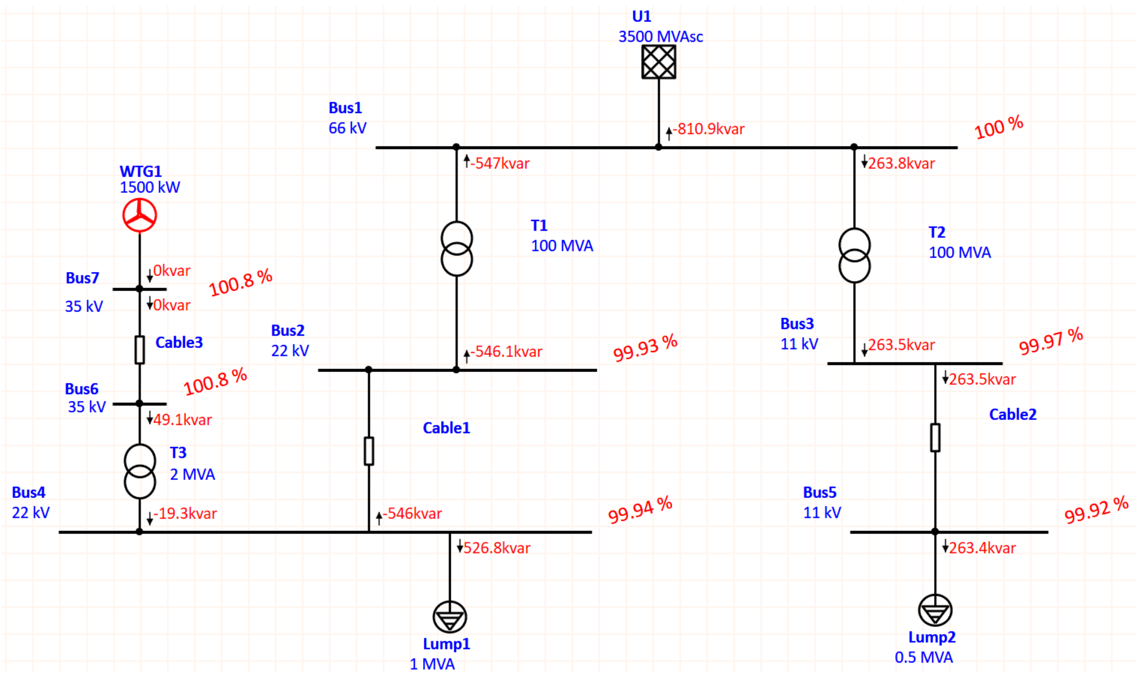
13 Renewable Energy Resource (Wind turbine source)

- Build a power system first and operate the load flow analysis to check each component. After checking the load flow analysis, the bas bar 4 and bus bar 5 are under voltage.
  - Under voltage may due to the over resistance of the cables, bigger size or paralleled cable may reduce the voltage drop.
  - If increasing the number of the cable does not reduce the voltage drop obviously, then the transformer needs to be adjusted. Reducing the tap% of the primary side of the transformer.
    - It increases the voltage of the secondary side of the transformer.
  - The load flow analysis result after adjusting the components is shown in the below right graph.





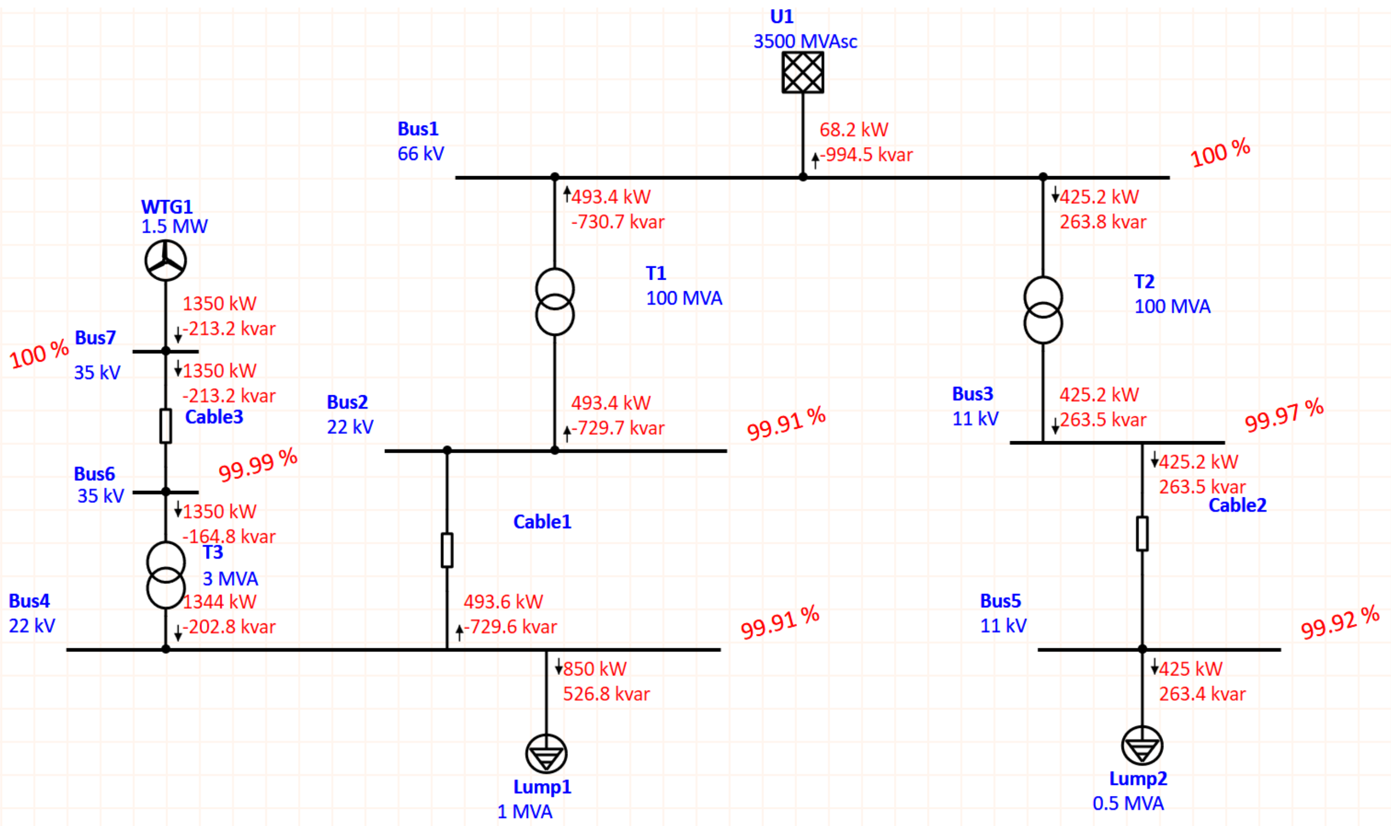
- Add a wind turbine to bus bar 4
  - Bus bar 4 becomes a generation bus after the wind turbine is added on the bus bar
  - After adding the load at bus bar 4, the lump load 1 will be supplied locally, upstream current will decrease, bus 4 voltage increases while the bus 1 and bus 2 current decrease.
  - If the wind turbine generates more power than the power grid U1, the power will flow from bus 4 backwards to bus 2. In this case, cable 1 becomes a bidirectional feeder



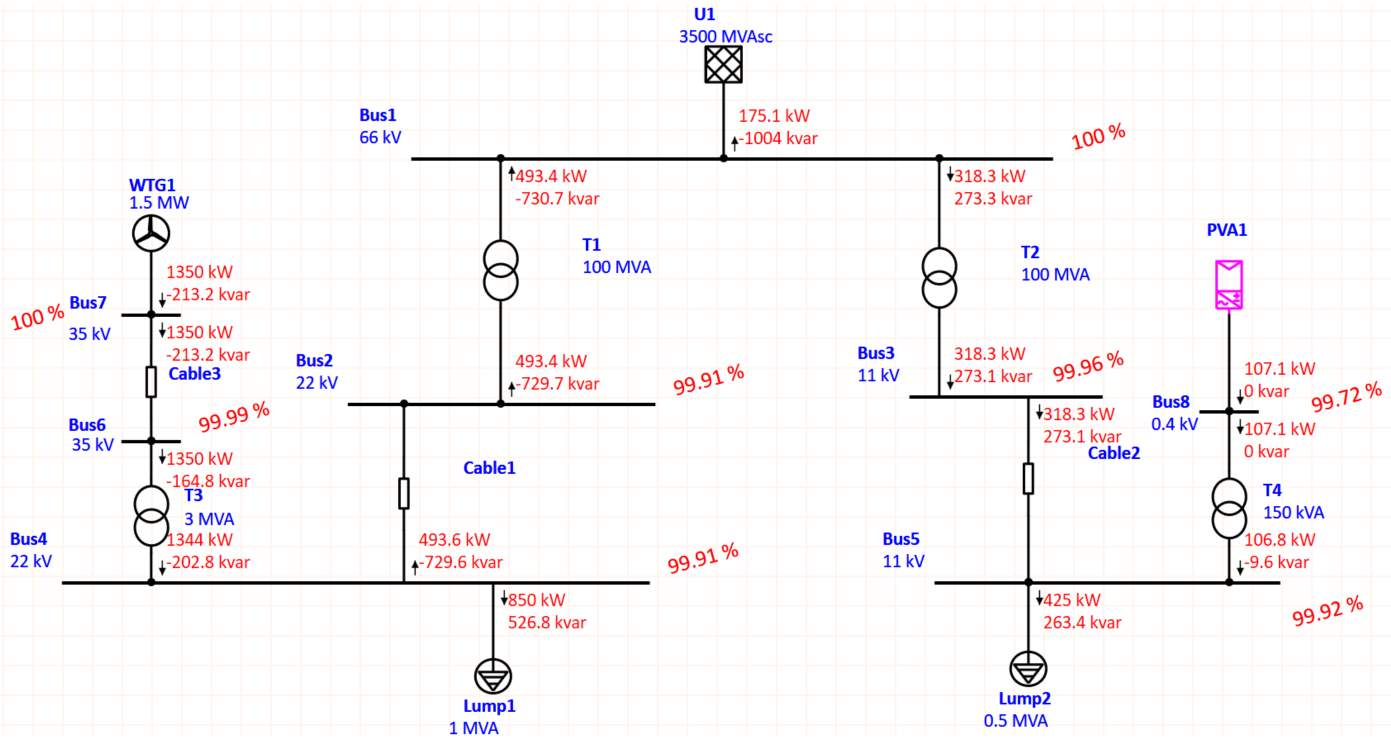
  - To simulate a bidirectional power system, the capacity of lump loads are adjusted. The power grid U1 is receiving the power from the WTG as seen in the above power flow analysis. The

WTG is operating under its 100% capacity.

- To ensure the WTG is not overloaded, cap the real power supply under 1.5MW.



- Add solar array to the system
  - Based on the load flow analysis, most of the real power for the loads is actually supplied by the WTG and the PV panels, so the grid import is relatively small and mostly reactive power. The transformers and cables are operating with high efficiency. The power system demonstrates how bidirectional renewable energy can lightens the loading on the upstream system while keeping the efficiency of the entire system.



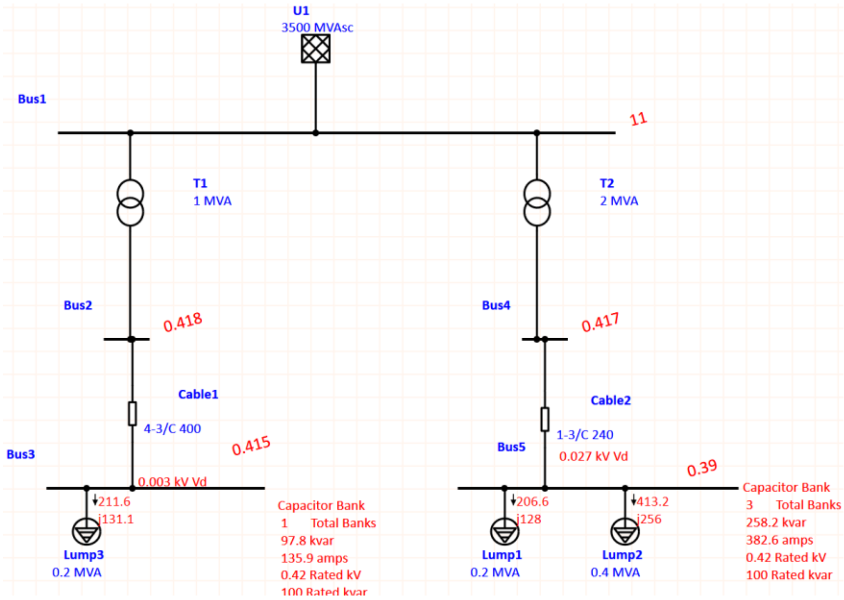
12 Optimum Capacitor Bank Selection (Power Factor Correction)

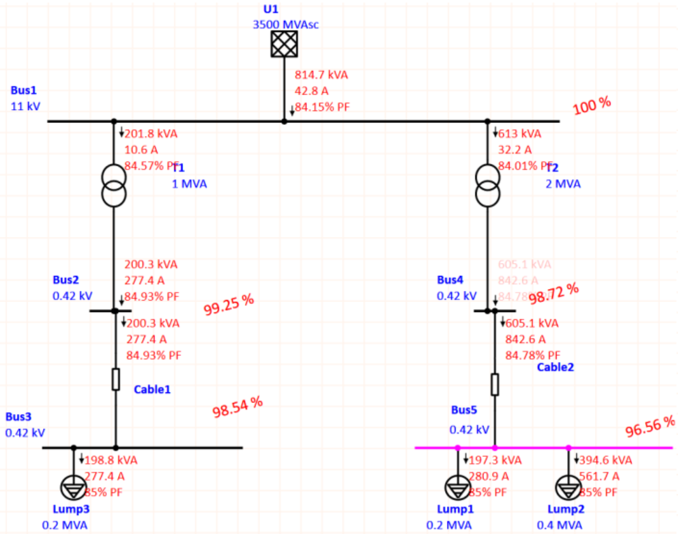
Power factor: how much we can benefit from the total power generated

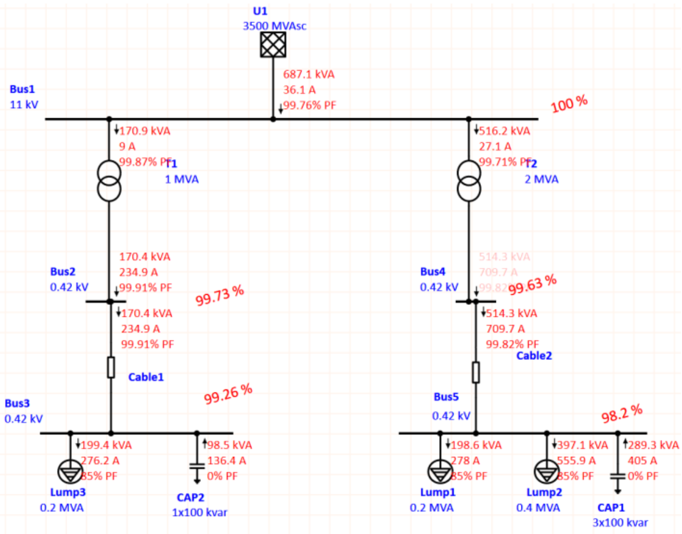
- P: Active power or real power
- Q: reactive power
- S: apparent power
- Q: When load needs to absorb Q?
  - Magnetic field which is responsible for producing rotational mechanical power in electrical motors requires reactive power. Reactive power assists transfer active real power to mechanical power.
- $S = \sqrt{P^2 + Q^2},\ PF = P/S$
- Disadvantage of low power factor:
  - Higher equipment rating
  - Higher cable power losses: $I = \frac{P}{\sqrt{3} * V * PF};\ P_{cable\ losses} = 3 * I^2 * R_{cable}$
  - Higher cable voltage drop: $V_{drop} = I * Z_{cable}$
- Power Factor Improvement
  - Adding reactive power through another way such as capacitor bank. Then the reactive power needed from the upstream source is decreased while the real power maintain the same. In this way, the power factor can be increased PF = P/S
  - Capacitor bank is usually connected through delta connection: $C = \frac{Q_C}{3V_{phase}^2(2\pi f)}$

Optimum Capacitor Bank Selection Example

- After load flow analysis for the below one line drawing power system.
  - Target: adding capacitor bank to increase the power factor of bus bar 4
  - Running Optimal Capacitor Placement to improve the power factor. From the load flow results. The PF of the cable 2 has been greatly improved from 84% to 99%.




U1
3500 MVAsc
814.7 kVA
42.8 A
84.15% PF
Bus1
11 kV
100 %
201.8 kVA
10.6 A
84.57% PF
T1
1 MVA
613 kVA
32.2 A
84.01% PF
T2
2 MVA
200.3 kVA
277.4 A
84.93% PF
Bus2
0.42 kV
99.25 %
200.3 kVA
277.4 A
84.93% PF
Cable1
Bus3
0.42 kV
98.54 %
198.8 kVA
277.4 A
85% PF
Lump3
0.2 MVA
605.1 kVA
842.6 A
Bus4
0.42 kV
98.72 %
605.1 kVA
842.6 A
84.78% PF
Cable2
Bus5
0.42 kV
96.56 %
197.3 kVA
280.9 A
85% PF
Lump1
0.2 MVA
394.6 kVA
561.7 A
85% PF
Lump2
0.4 MVA


U1
3500 MVAsc
687.1 kVA
36.1 A
99.76% PF
Bus1
11 kV
100 %
170.9 kVA
9 A
99.87% PF
T1
1 MVA
516.2 kVA
27.1 A
99.71% PF
T2
2 MVA
170.4 kVA
234.9 A
99.91% PF
Bus2
0.42 kV
99.73 %
170.4 kVA
234.9 A
99.91% PF
Cable1
99.26 %
Bus3
0.42 kV
199.4 kVA
276.2 A
85% PF
Lump3
0.2 MVA
98.5 kVA
136.4 A
0% PF
CAP2
1x100 kvar
514.3 kVA
709.7 A
Bus4
0.42 kV
99.63 %
514.3 kVA
709.7 A
99.82% PF
Cable2
Bus5
0.42 kV
98.2 %
198.6 kVA
278 A
85% PF
Lump1
0.2 MVA
397.1 kVA
555.9 A
85% PF
Lump2
0.4 MVA
289.3 kVA
405 A
0% PF
CAP1
3x100 kvar