ELEC7021 Dissertation
Final Presentation

Supervisor: Dr. K.H. LAM

AC/DC Interface & DC Link Fault, Stability & Control

Karl M.H. LAI (3035273084)

SEPA Report

Integrated Distribution Planning:
A Framework to the Future

Core Elements

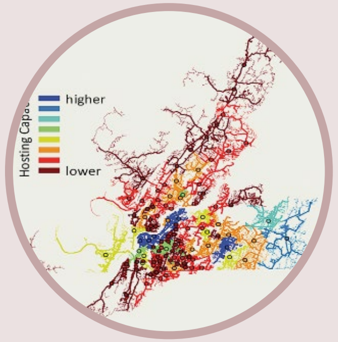
Forecasting

Sourcing

TDG Planning

Additional Elements

Info Sharing



Hosting Capacity

Stakeholders

"The utility may need to overcome internal cultural challenges, as distribution engineers adjust to the idea of trusting DERs to meet system needs"

Goal of Dissertation:

Identify ways to rebuild "**trust**" and bridge the **gap** between academic and utilities – in terms of system planning and network assessment

Section 2 | **Behaviour** & **Modelling** of PV, WTG, BESS & DC link → Discussed in Mid-Term Present

Section 3 | **Fault**, **Stability** and **Power Quality** Issues In RE Connected Systems

AC/DC Interface & DC Link Fault, Stability & Control

Section 4 | **Hosting Capacity** and **Optimizations** in Network Configuration

Section 5 | **Hierarchical Control** and **Supporting Systems** In Network Operation

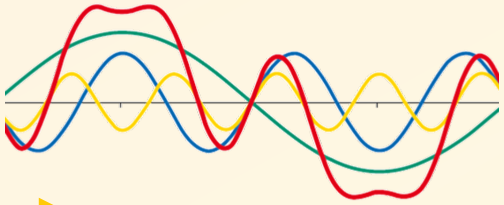
Section 6 | **Evaluation** in Hierarchical Control in Network Operation

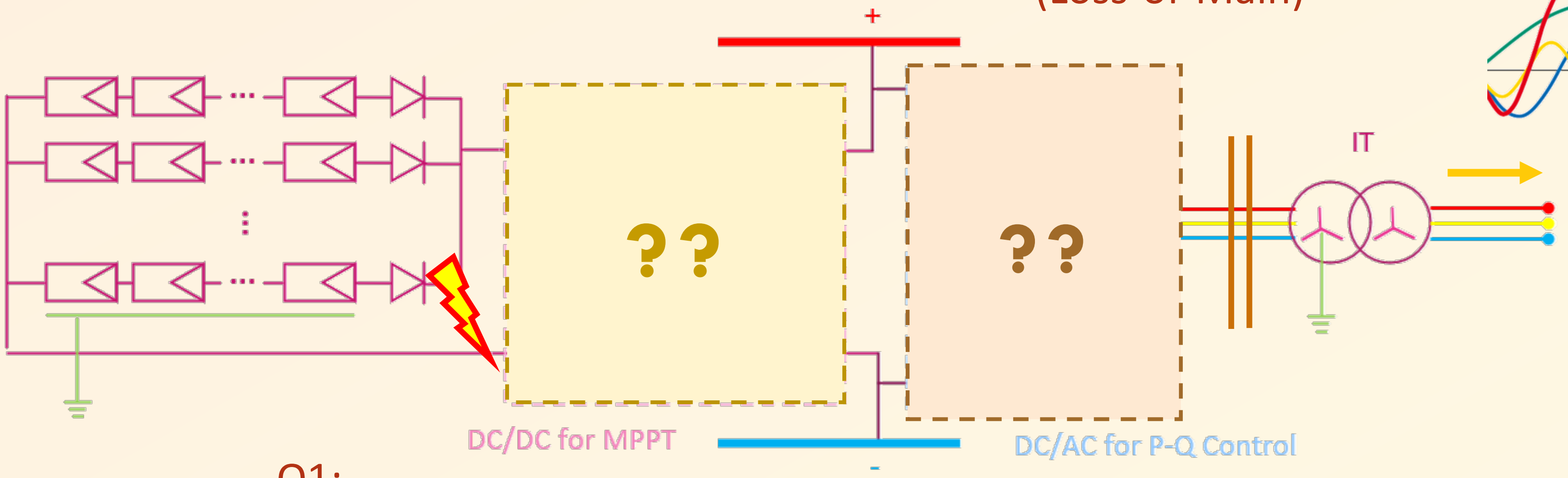
Dissertation Content

Question:
If the inverter itself is in fault, is it able to disconnect itself?

O3:
Anti-Islanding (Loss-of-Main)

O4:
Reconnection



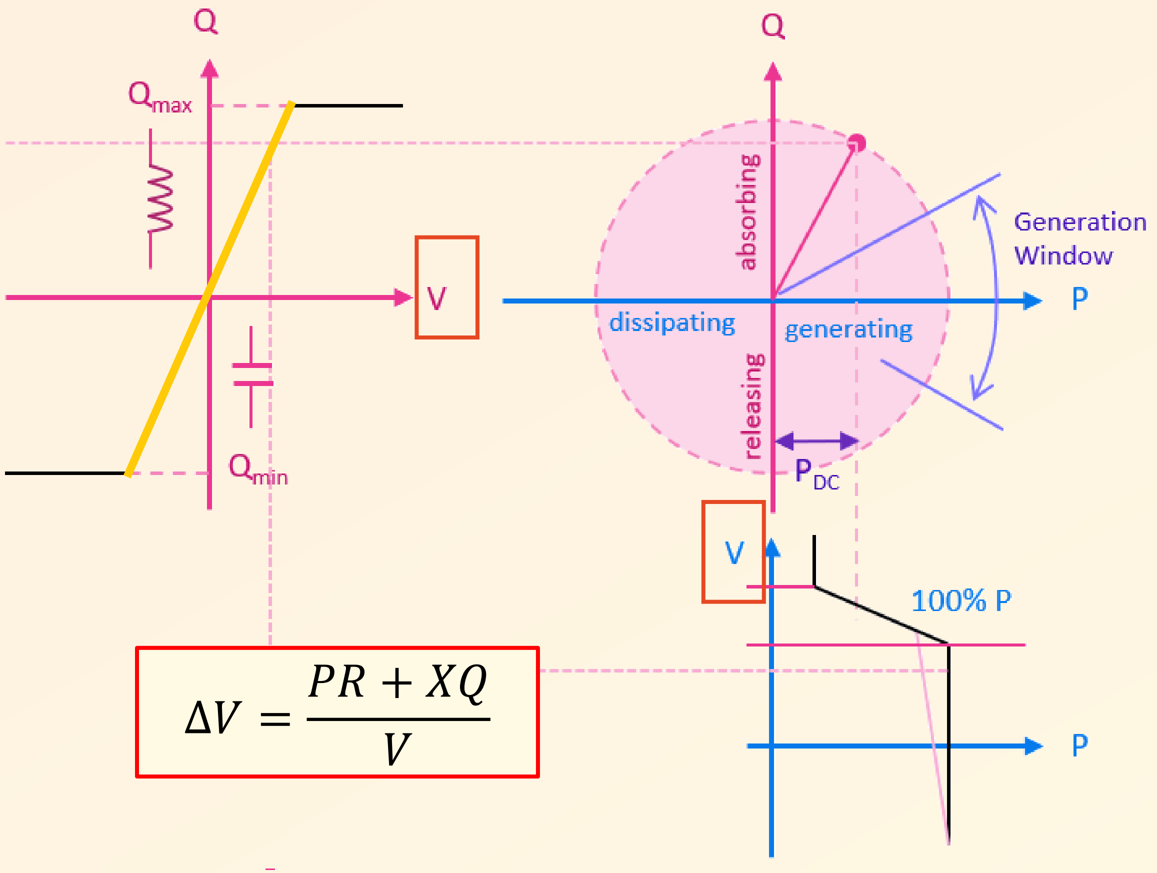


O2:
Harmonic Distortion

O1:
Earth Fault Loop Impedance

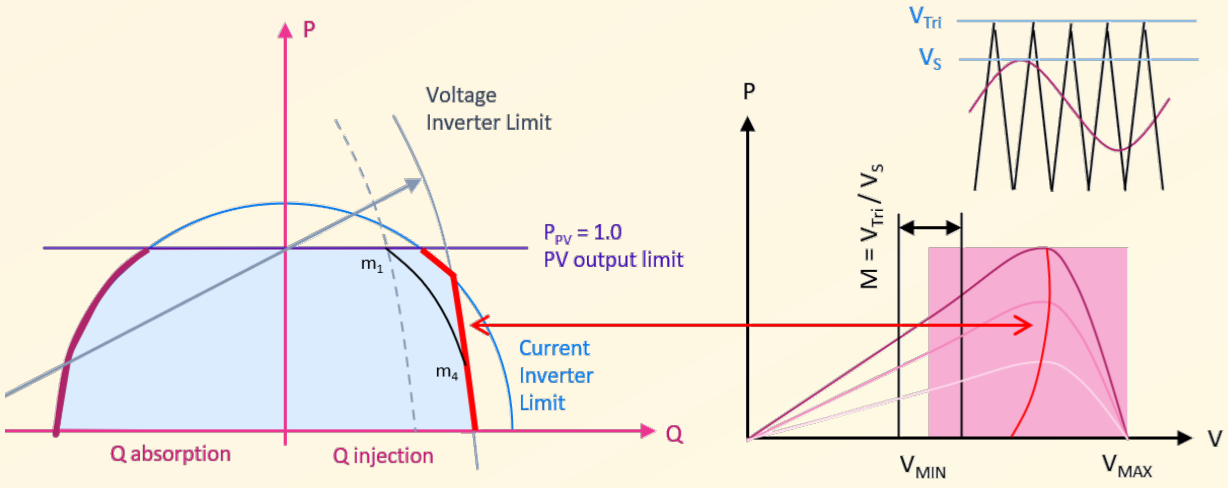
Question 1:
How should I set the basic requirement on PV specification?

Possible Requirements for PVs



$$\Delta V = \frac{PR + XQ}{V}$$

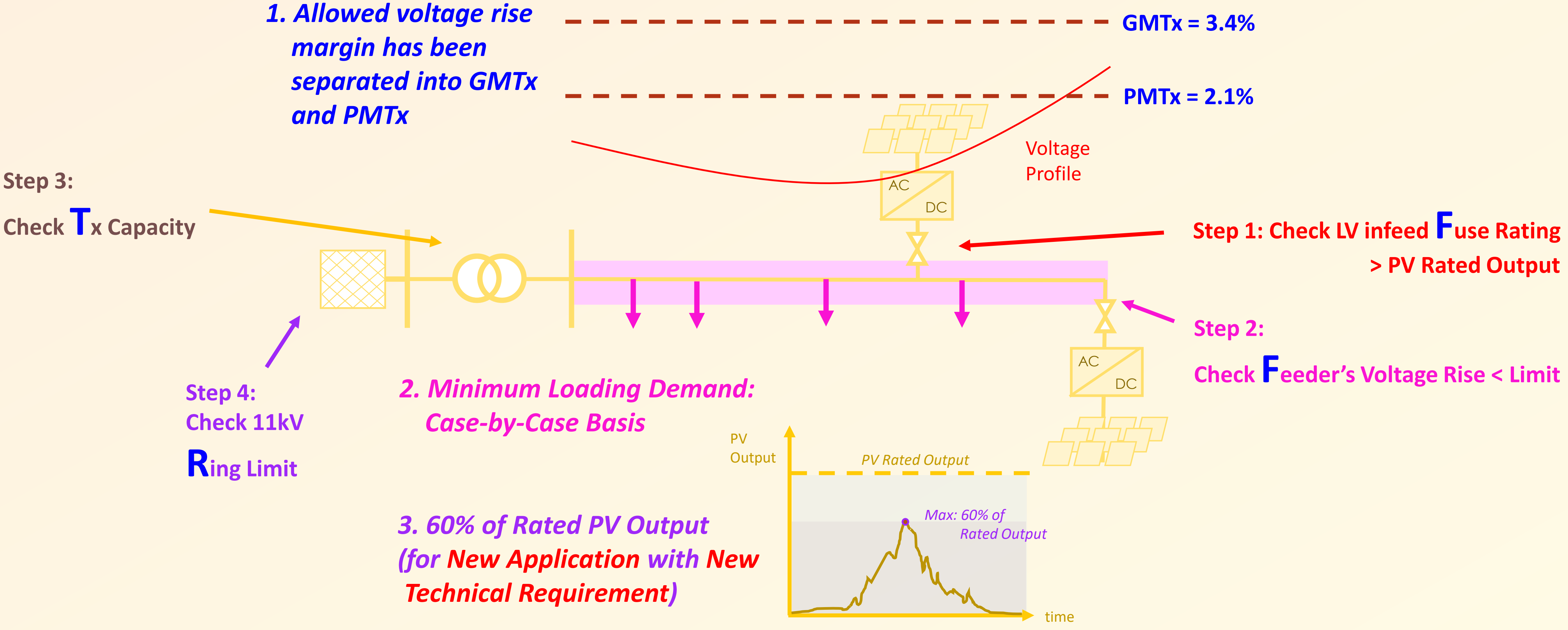
Requirements
- Dynamic Voltage Regulation
- Fault-Current Limiting
- Ride-Through Capability
- Power Exchange
- Low Power Disconnection
- Reserves Requirement
- Simulation Model



Roles of Utilities

1) Allow more integration 2) Coordinate it with its Functionality 3) Control with other grid components

Updated Assumptions in Network Assessment



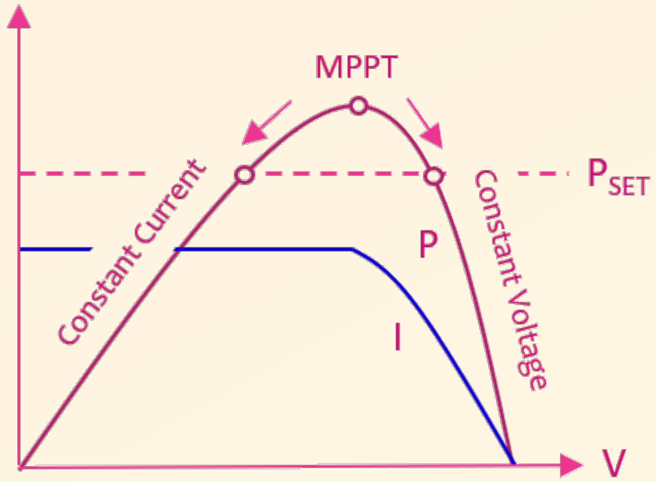
Flexible Power Point Tracking (FPPT)

Problem:

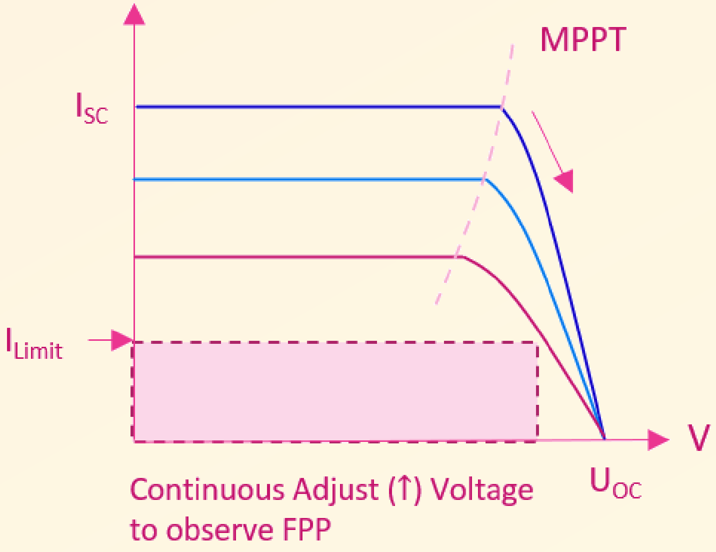
How to know the **maximum**?

- Forecasted with historical data
- Measured with release FPPT to MPPT
- Modelled with G and T
- Correlated with voltage output
- Coordinated with small PV in MPPT

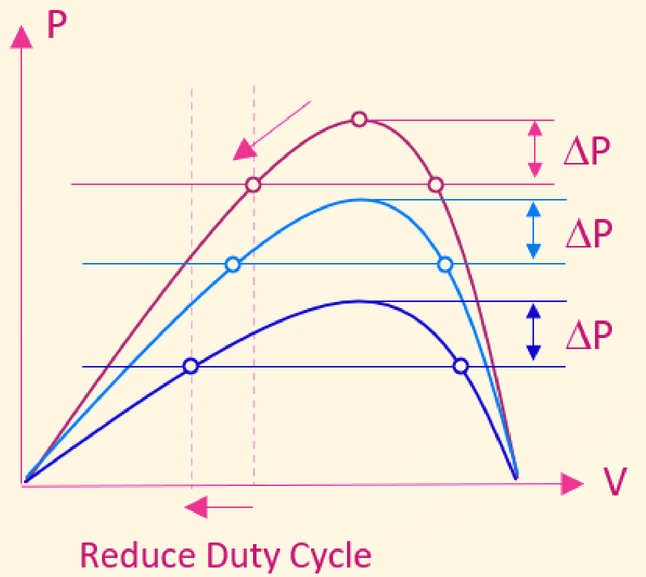
1. MPPT



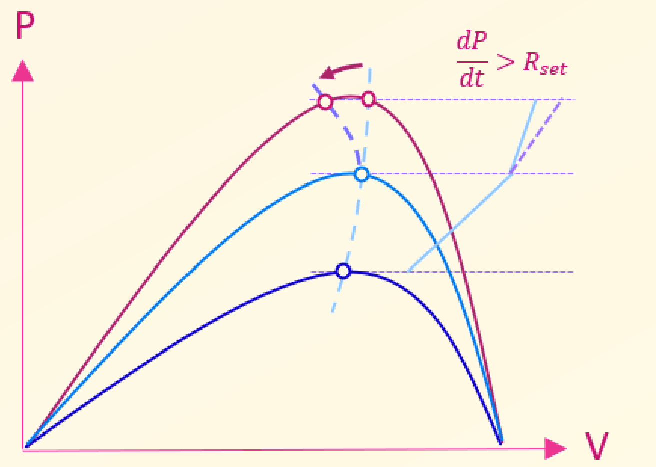
2. Power Limit



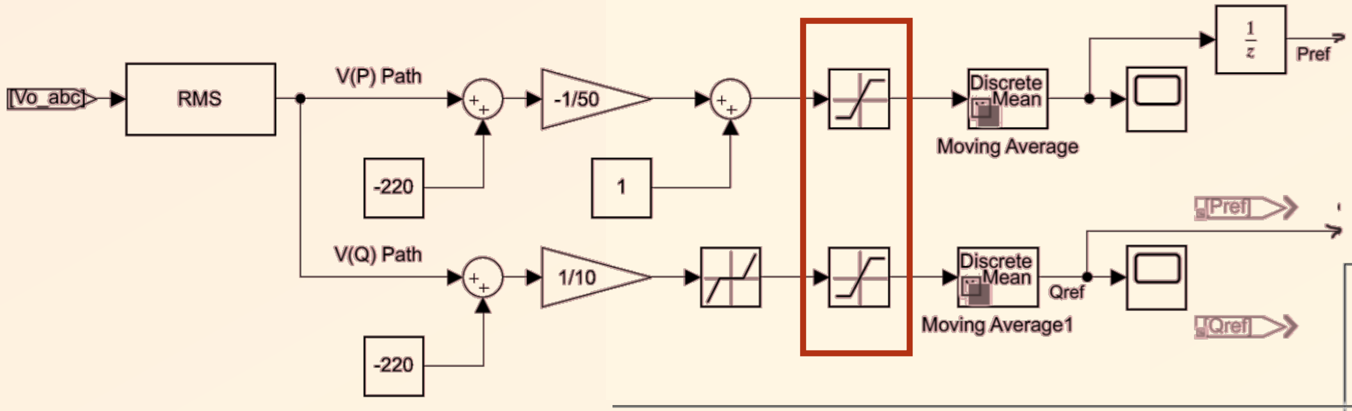
3. Power Reserve

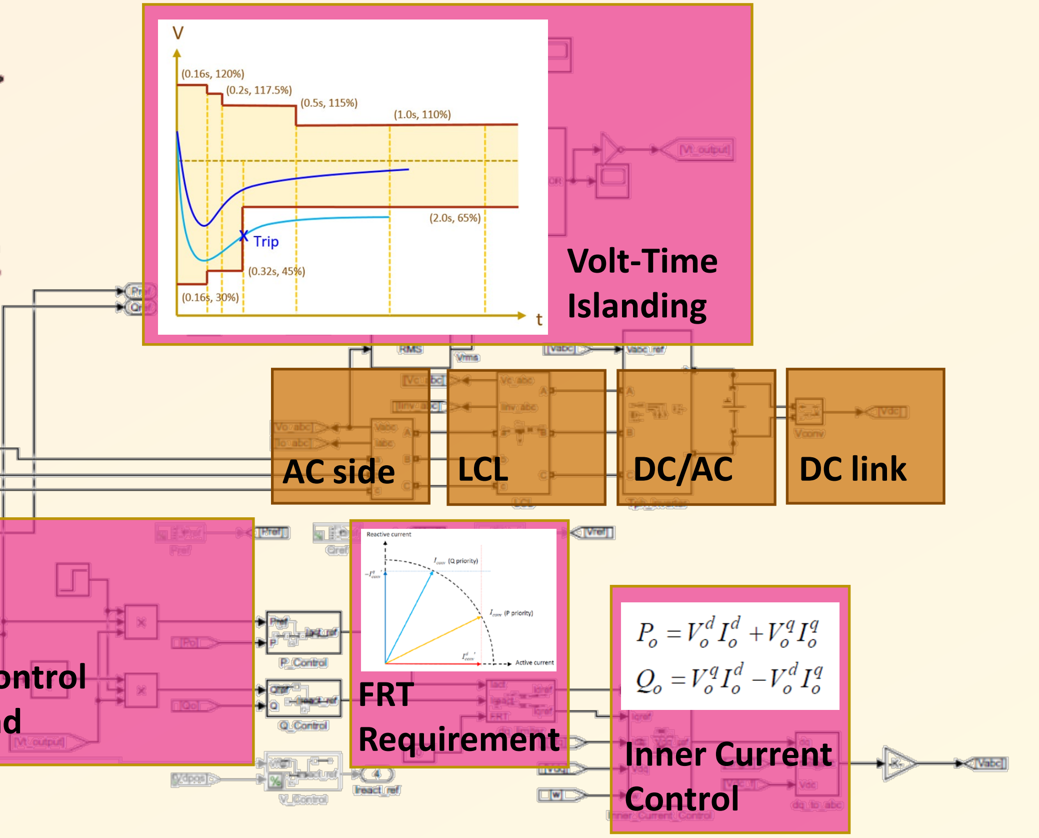


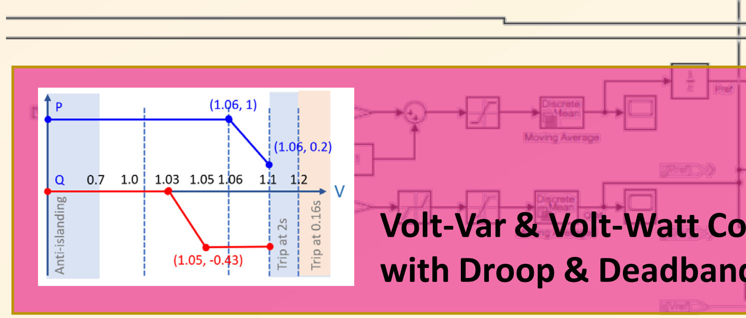
4. Ramp Limit



Slope & Max-Min *can be set accordingly.* → ***Can be coordinated.***







Outer Voltage *must be slower than* ***Inner Current*** *such that voltage can be considered as* *<u>constant</u>* *during switching.*

Inner Current Control

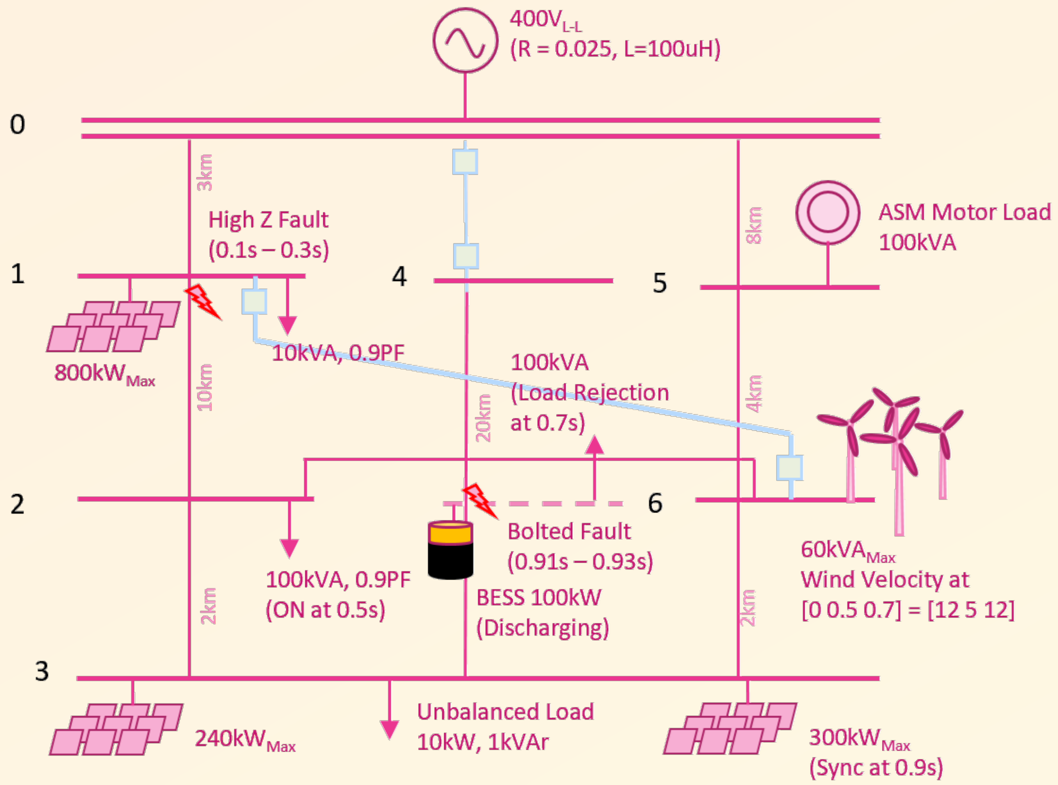
How can PV provide grid support under disturbance?

$$P_o = V_o^d I_o^d + V_o^q I_o^q$$

$$Q_o = V_o^q I_o^d - V_o^d I_o^q$$

$$V_c^q = 0 \longrightarrow P_c = V_c^d I_{conv}^d \quad Q_c = -V_c^d I_{conv}^q$$

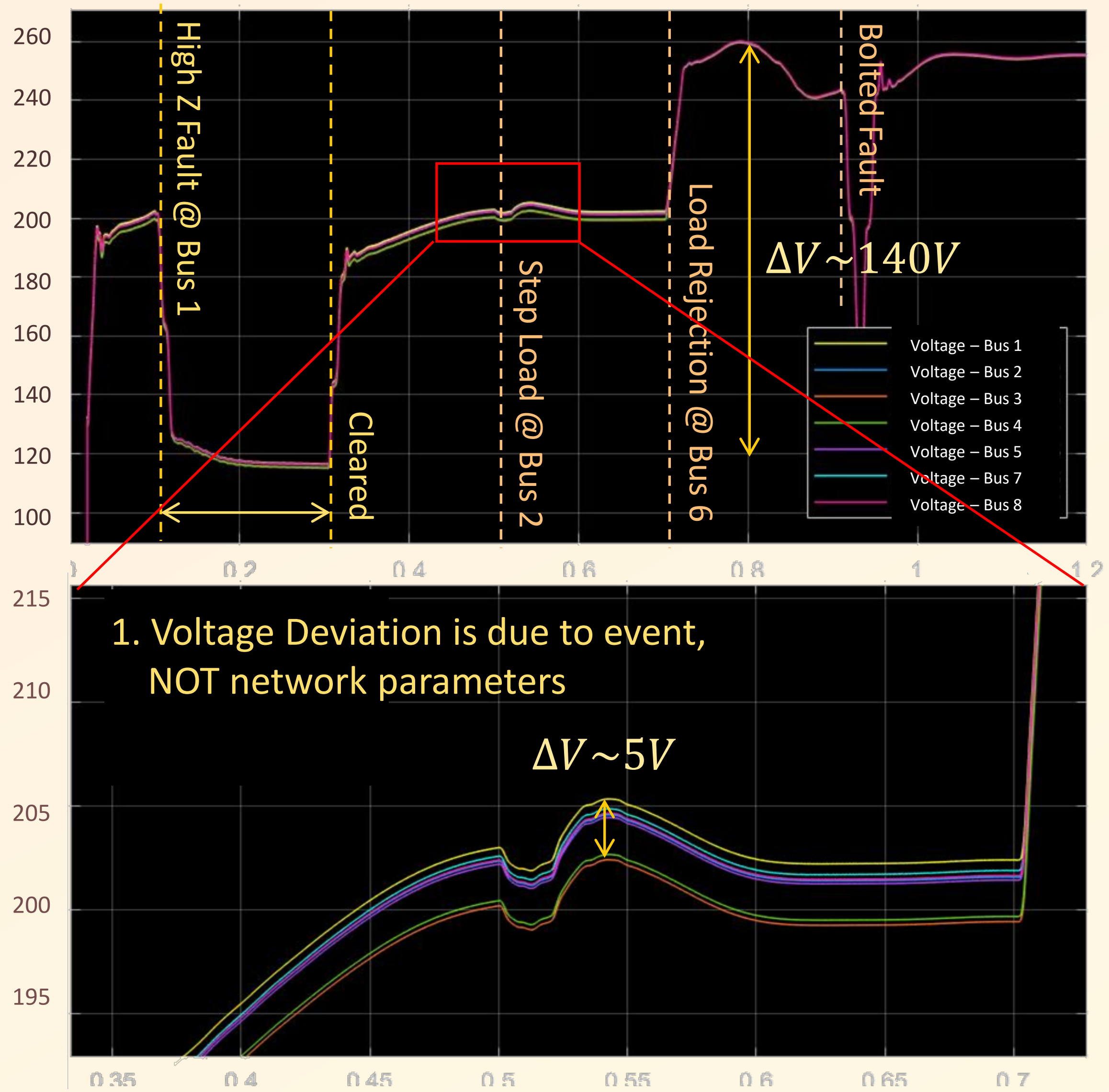
Sample Grid - Sample Event
A Prototype to Test Hierarchical Control

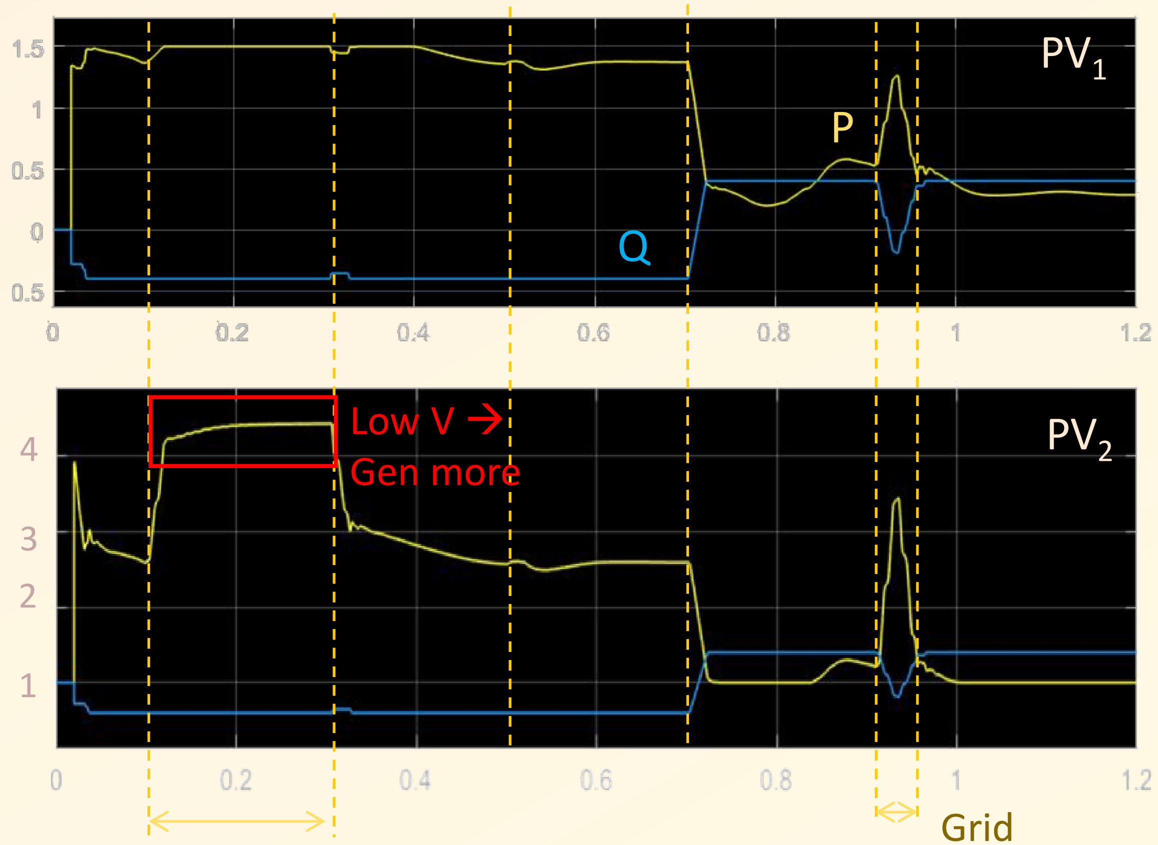


Assumptions

- Deterministic Transient Condition (NOT statistical transient ~ voltage flicker study)
- 300mm^2 cable with X/R = 0.625 is employed.
- PV and Wind Farm are balanced generation, as grid code requires all RE > 10kW must be in 3 phases.
- Grid voltage is stepped down to 400V, as 11kV network has much smaller voltage deviation effect.
- The effect of wind power fluctuation is not valid in nature, as it has a large time constant.
- Volt time islanding requirement (i.e. FRT / HVRT) and Volt-Var / Volt Watt Control follows the requirements in technical requirement at HK.
- Circuit Parameters and PV Parameters follows sampled network, with round off in numbers.

Sample Grid - Sample Event
A Prototype to Test Hierarchical Control



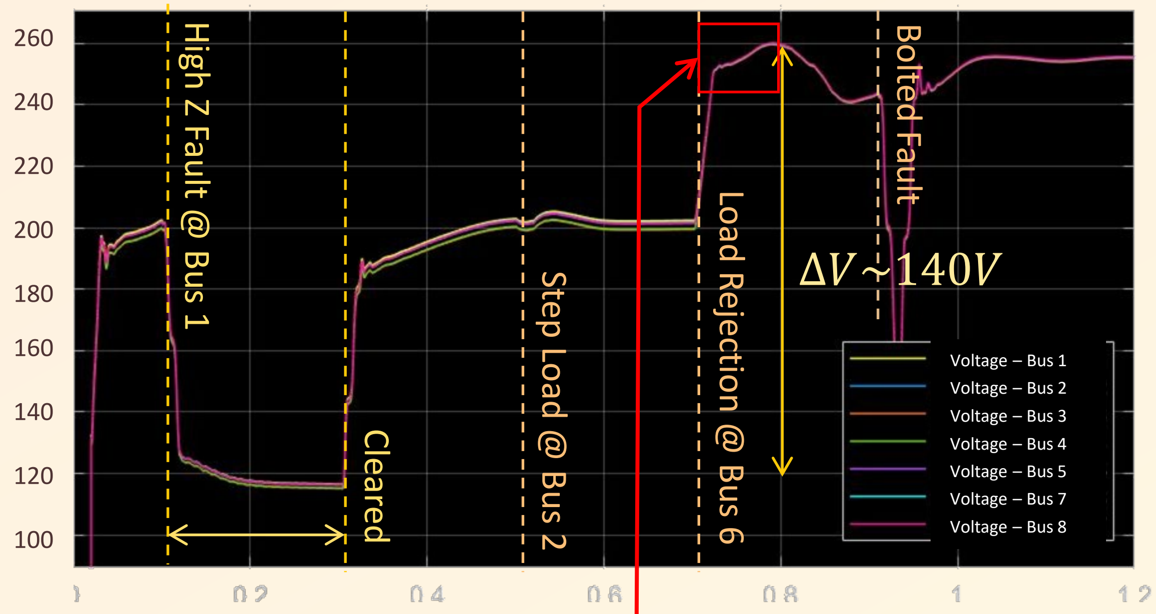


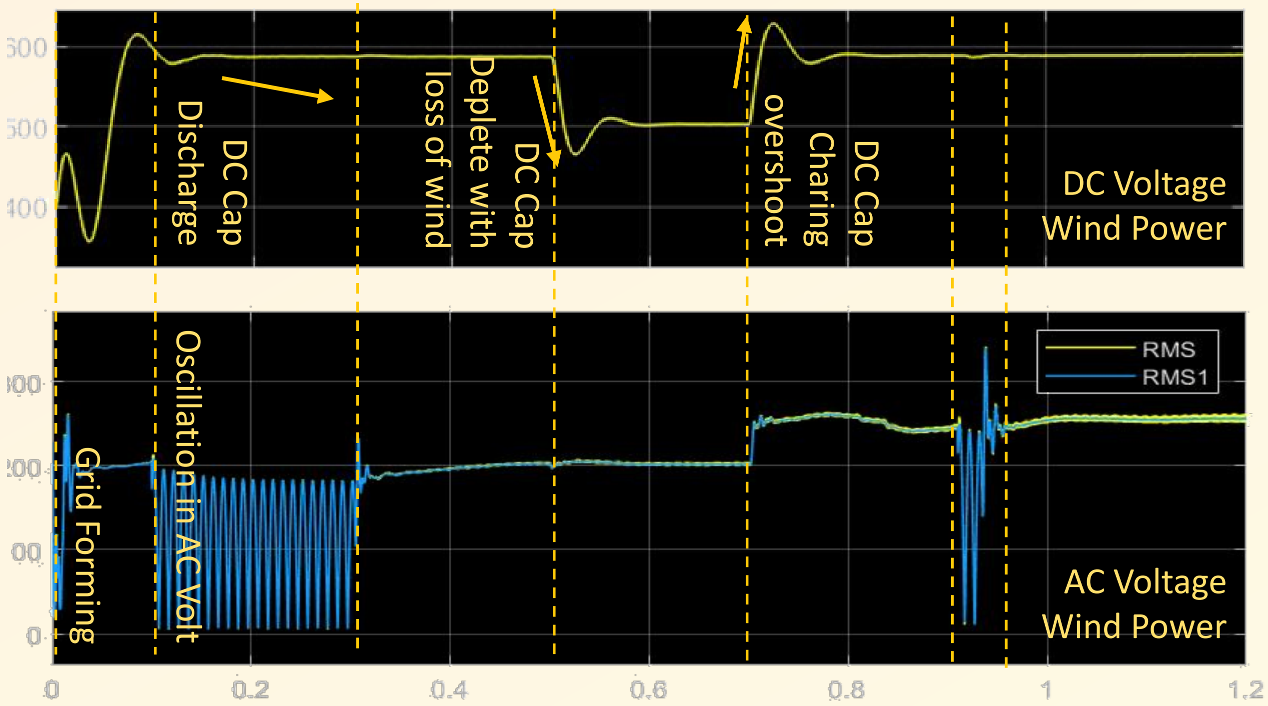
Both NOT disconnected due to LVRT

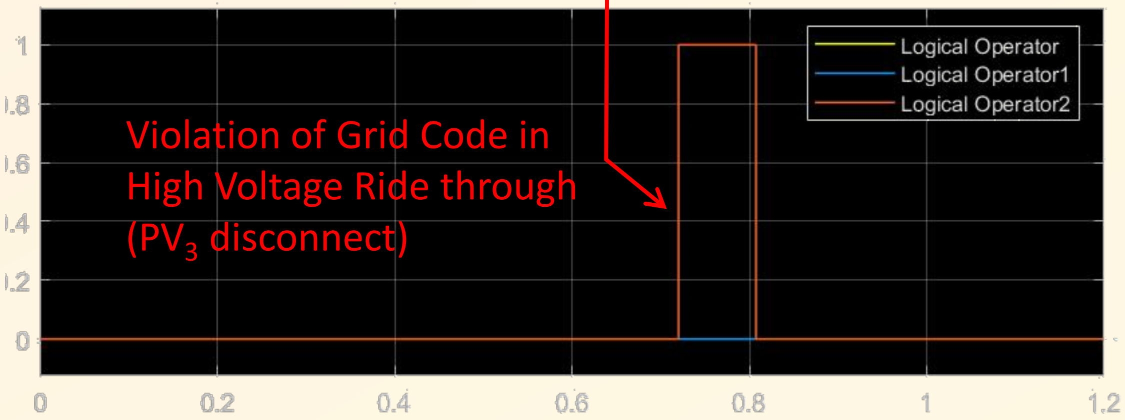
Grid Supporting

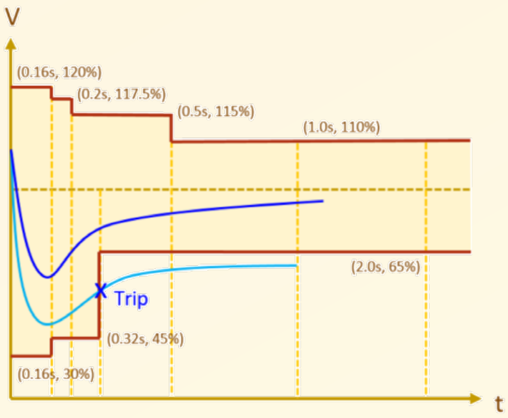
2. P and Q are generated according to the setpoint from grid code if the DC cap is large enough.

Sample Grid - Sample Event
A Prototype to Test Hierarchical Control





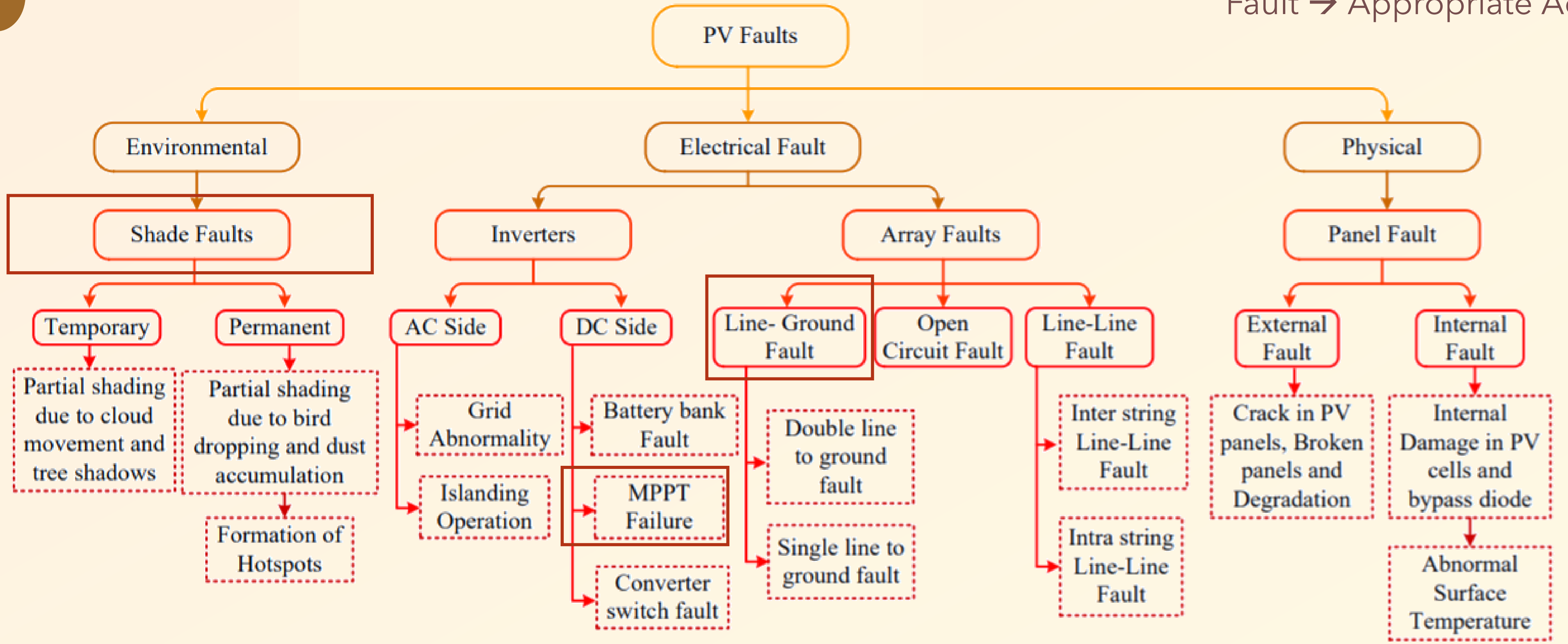




4. Interaction of Cap Voltage & Grid Voltage with DFIG

3. Fault Ride-through Requirement is NOT stringent. High Voltage disconnection is stricter in use.

Fault → Appropriate Action



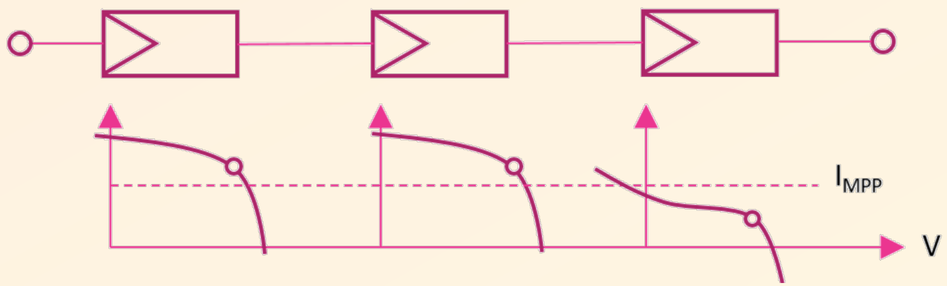
Question 2:
What are the possible faults in PV? Does it affect grid performance?

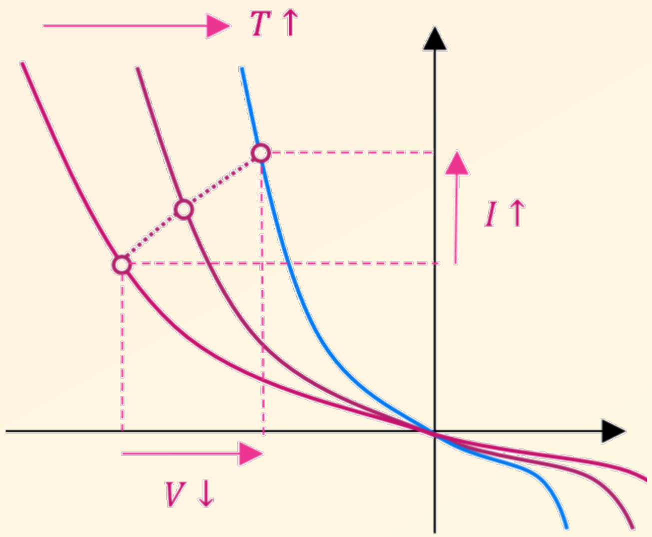
- PV Topology (e.g. Elastic PV Structure)
- Fault Current (e.g. IT Earthing System)
- Fault Characteristics (e.g. Persistent Melting)

Note:
PV has a **limited** output.

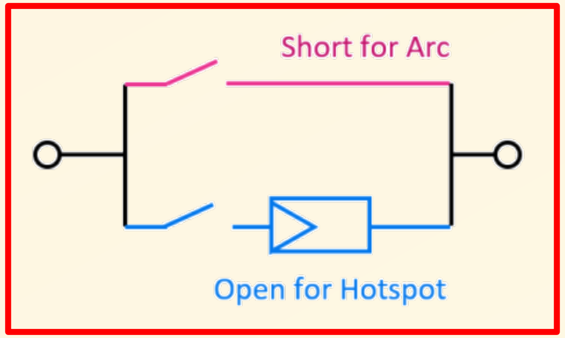
Hot Spotting & Arc Fault

Shading as Temporary Fault

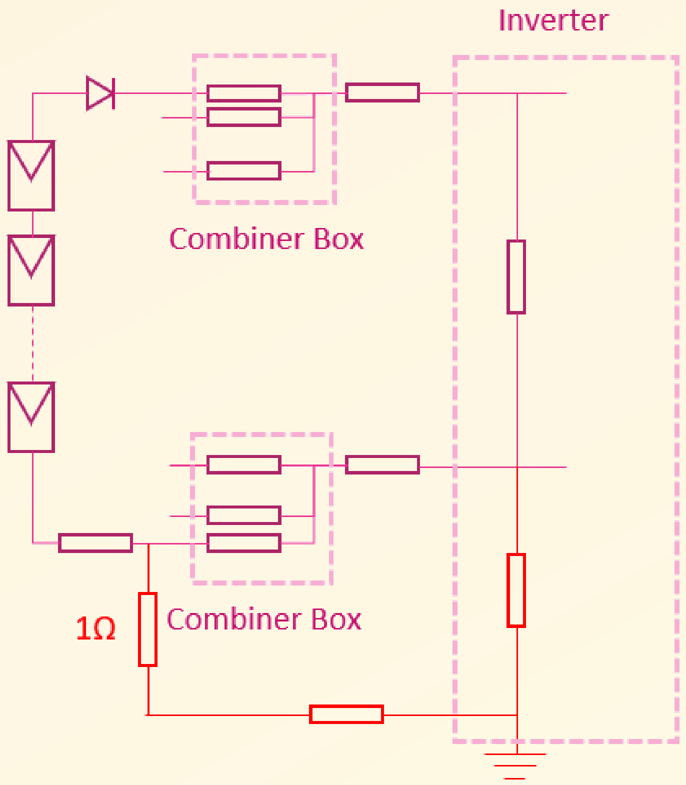




Solution:



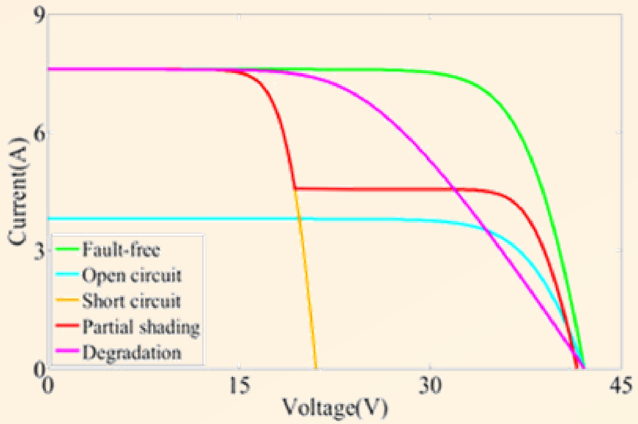
Arc Fault as Blind Spot Fault

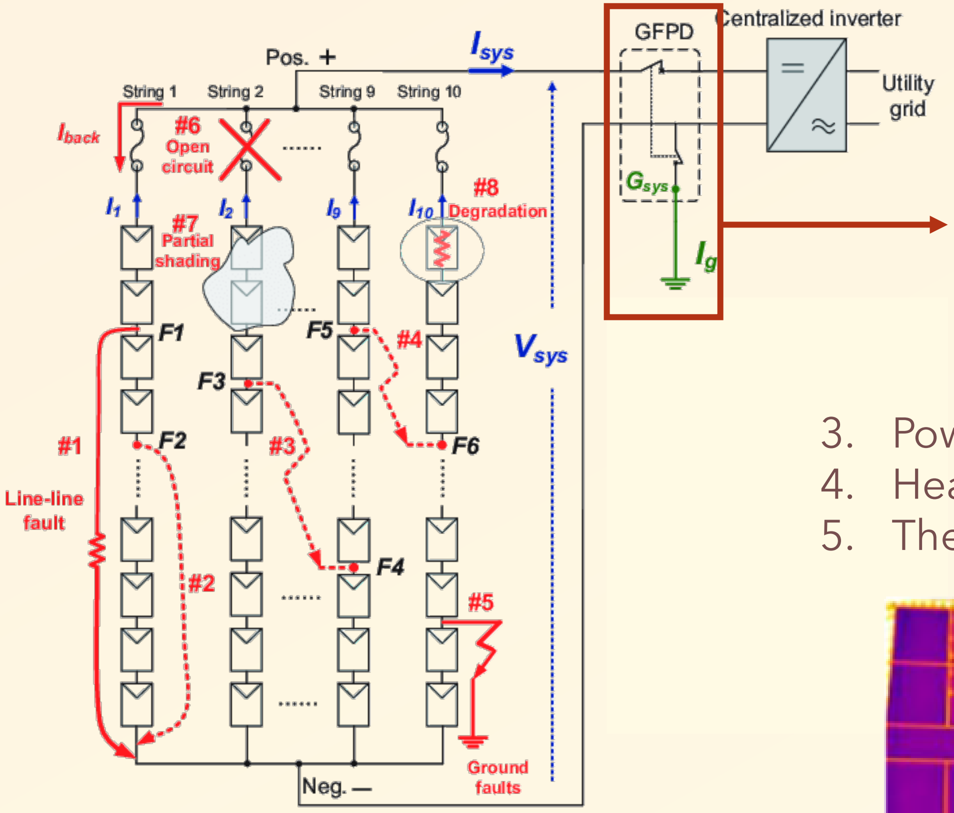


Note:
Requires **Arc Fault Detector** Logic.

PV - Fault Detection Method

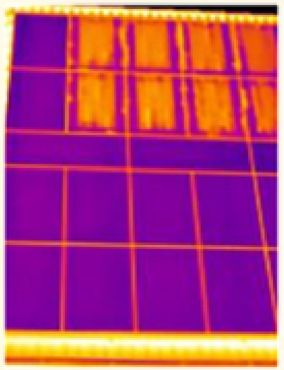
1. Localized I-V, R_{SH} Measurement
2. Modelling Based Comparison

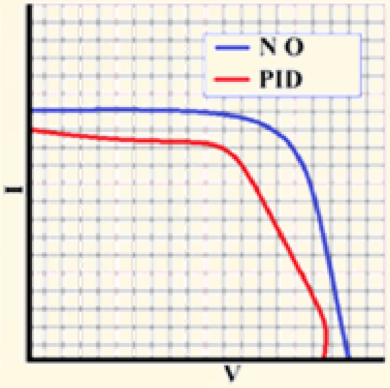




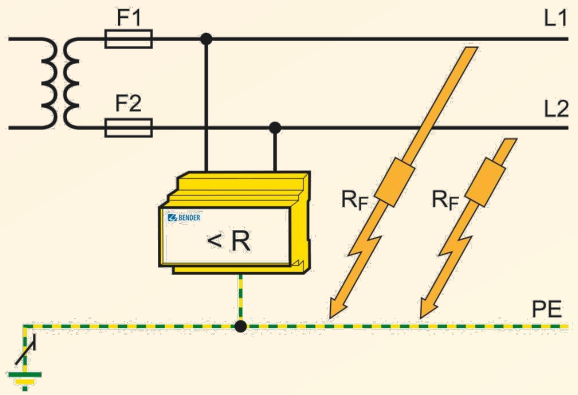
6. GFID / Fuse

3. Power Loss Method
4. Heat Exchange Measurement
5. Thermal Imaging



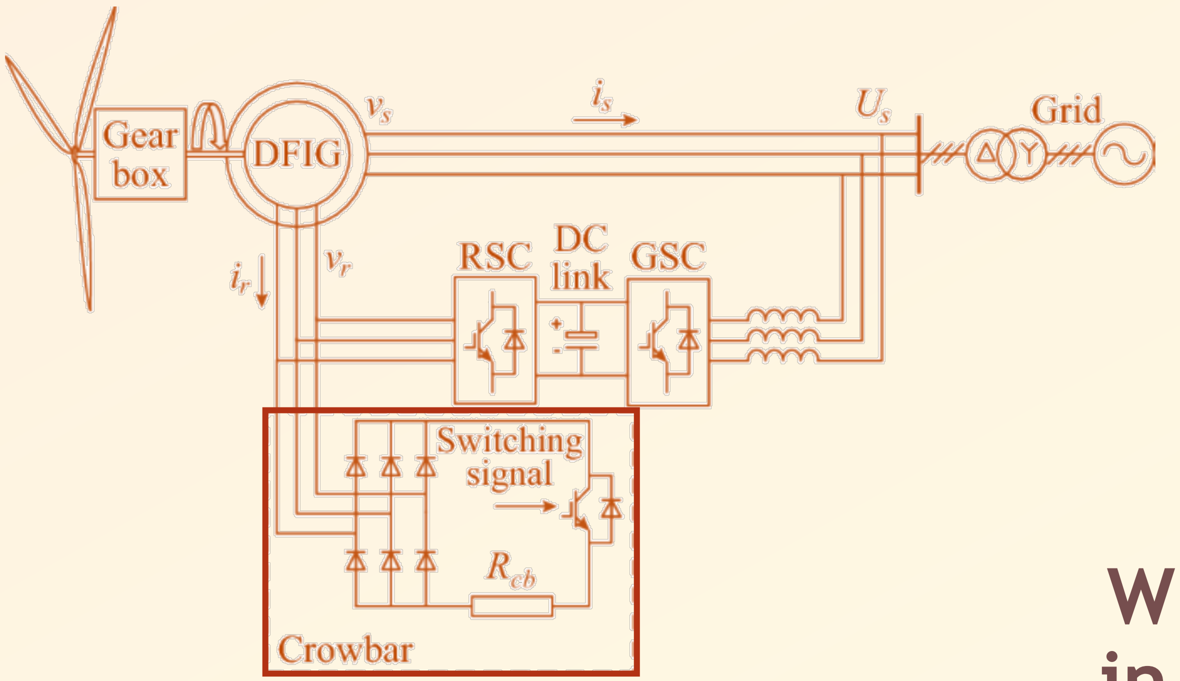


7. Insulation Monitoring Device



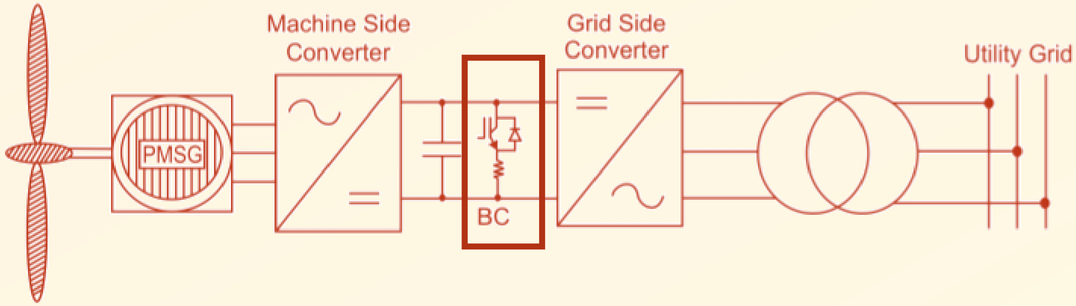
Type 3 - DFIG

- DFIG can supply **transient fault current** before depletion of field, i.e. DC link cap voltage.



Type 5 - PMSG

- AVR is employed to provide constant excitation. It means continuous fault current can be generated if not cut off by crowbar or relay tripping.

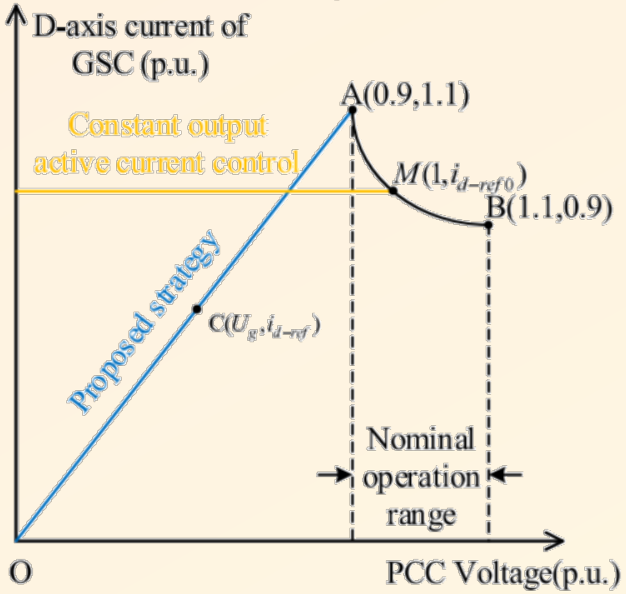


Question 3:
What are the Fault Characteristics in Wind Turbine Generation (WTG)

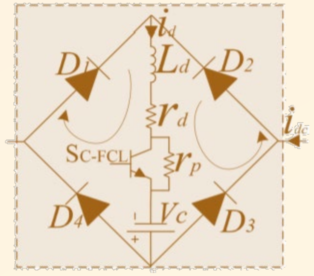
Fault Characteristics of Wind Turbine Generation

1. Fault Current is Controllable

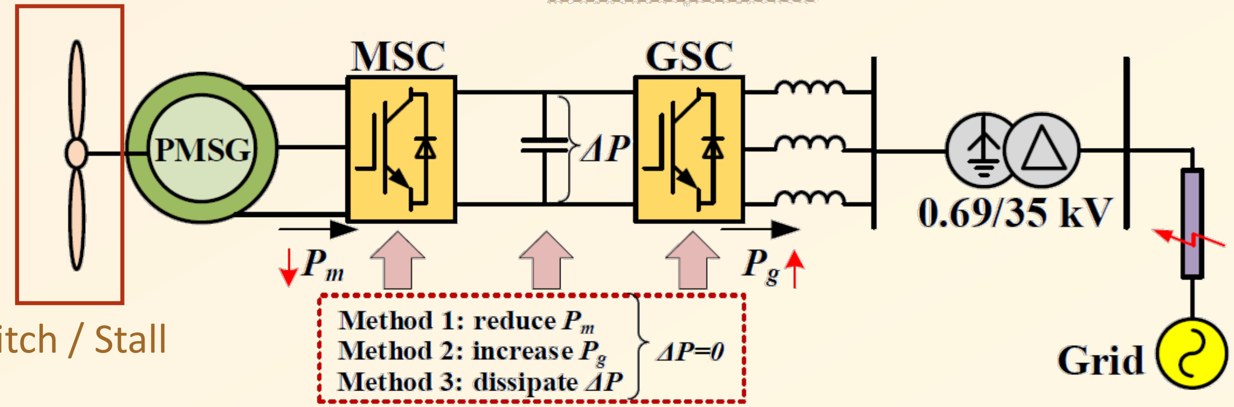
$$\begin{cases} i_d = K_p U_g \\ i_q = -1.5(0.9 - U_g) \end{cases}$$



2. Fault can be ride-through.



- Fault Current Limiter
- DC Chopper
- Crowbar Circuit
- Static Dynamic Resistor



Pitch / Stall

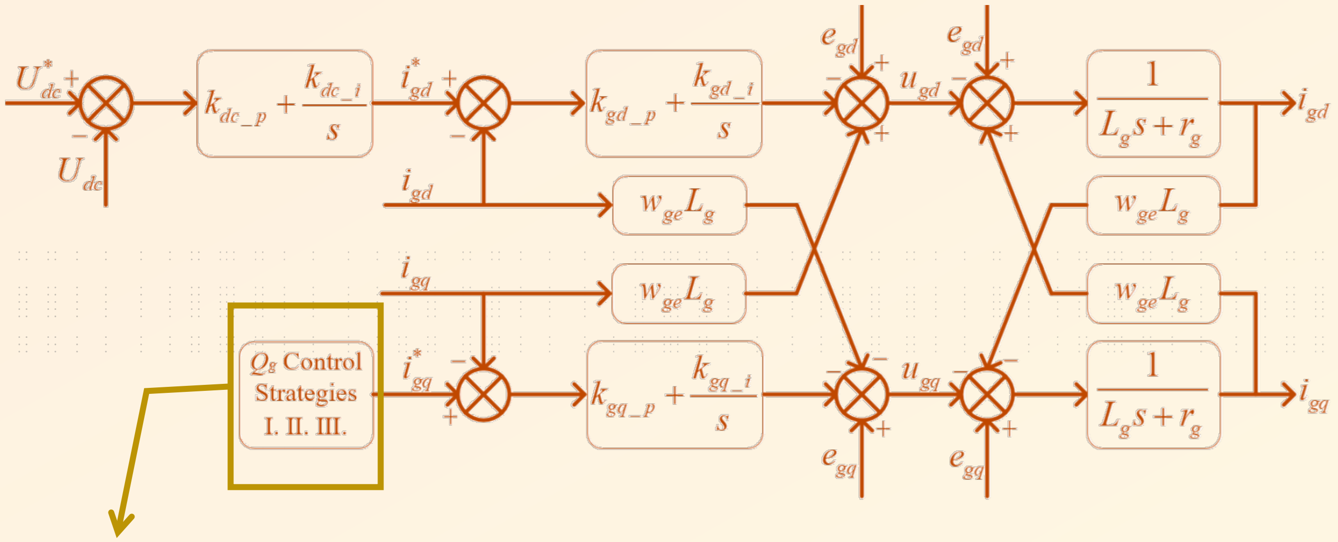
3. Fault is both control and machine dependent.

$Ae^{-at}\sin(\omega t)$ ✕

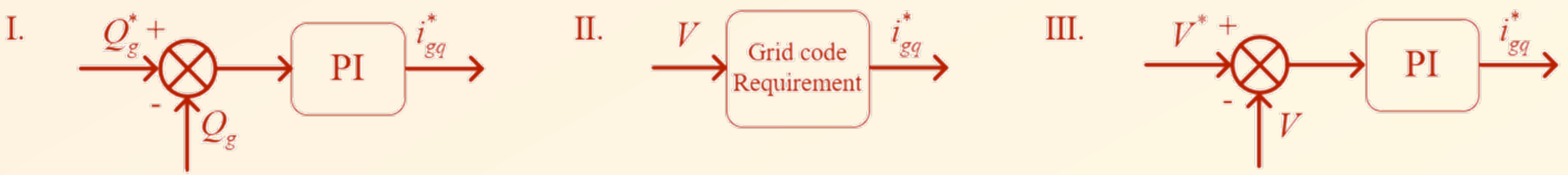
$Ae^{-at} + B\sin(\omega t)$ ✓

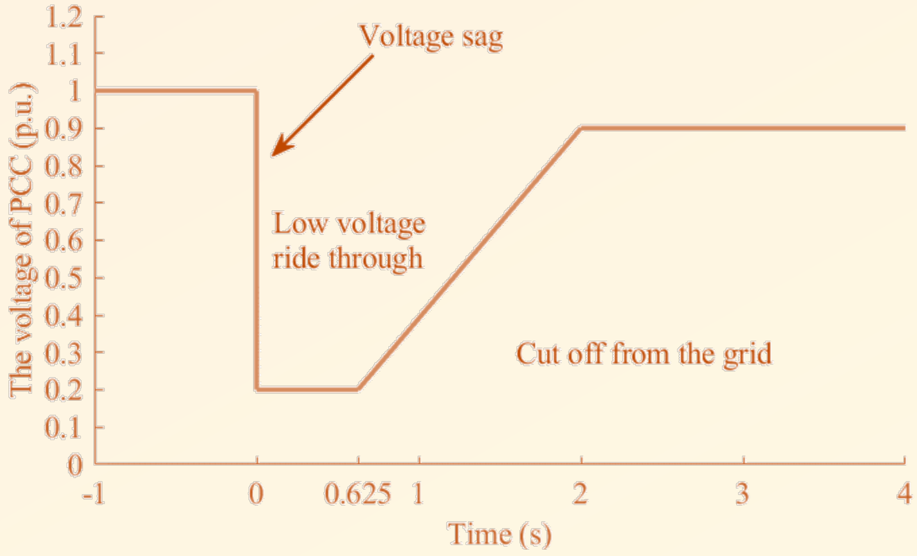
For DFIG:

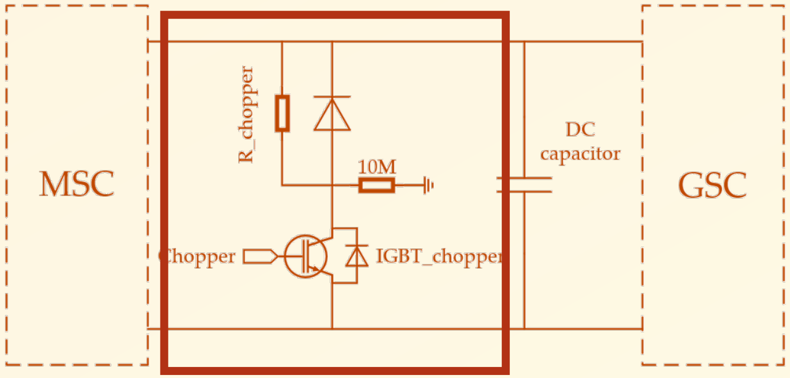
- Inner rotor current controller = Second order → **rotor current** constant before and after fault
- **Stator Fault Current** has only damped DC + fundamental fault current (NO damped fundamental)
- **Damped DC** depends on **depth of voltage dip** (volt stiffness + earthing), **time constant** depends on **stator RL circuit** only (independent of rotor)
- **d-axis component** is nearly zero in fault



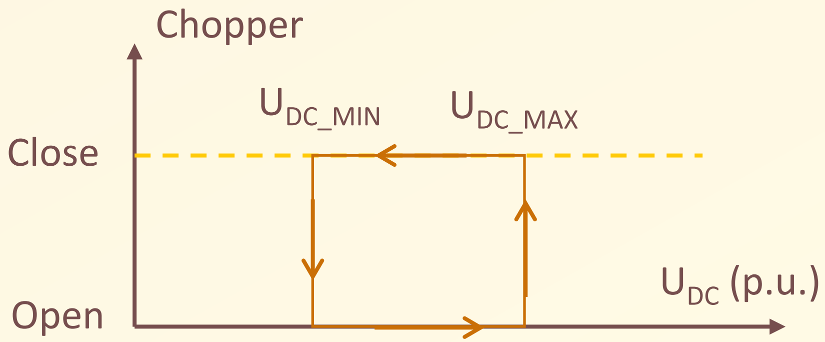
The Q_g Control Strategies of the GSC q-axis are shown as follows.



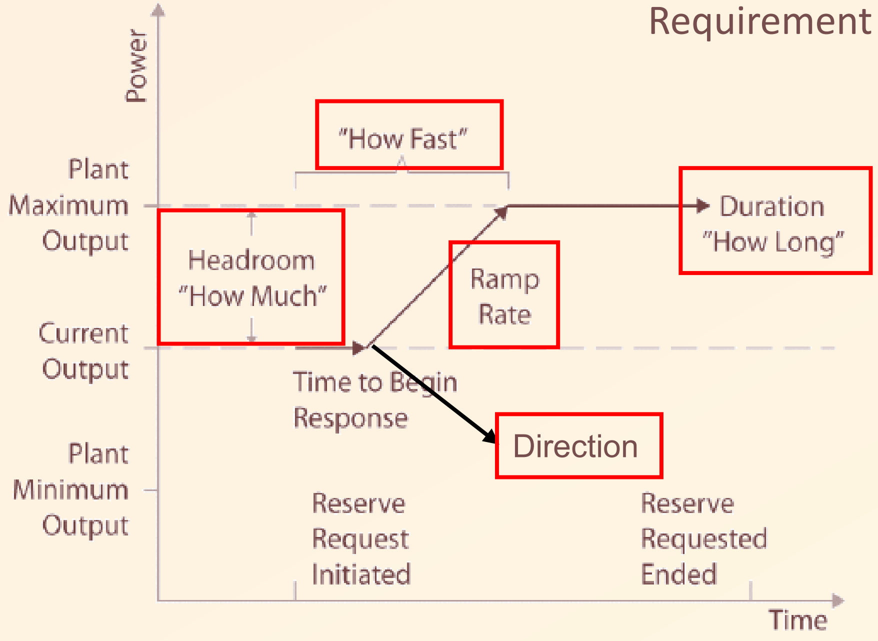


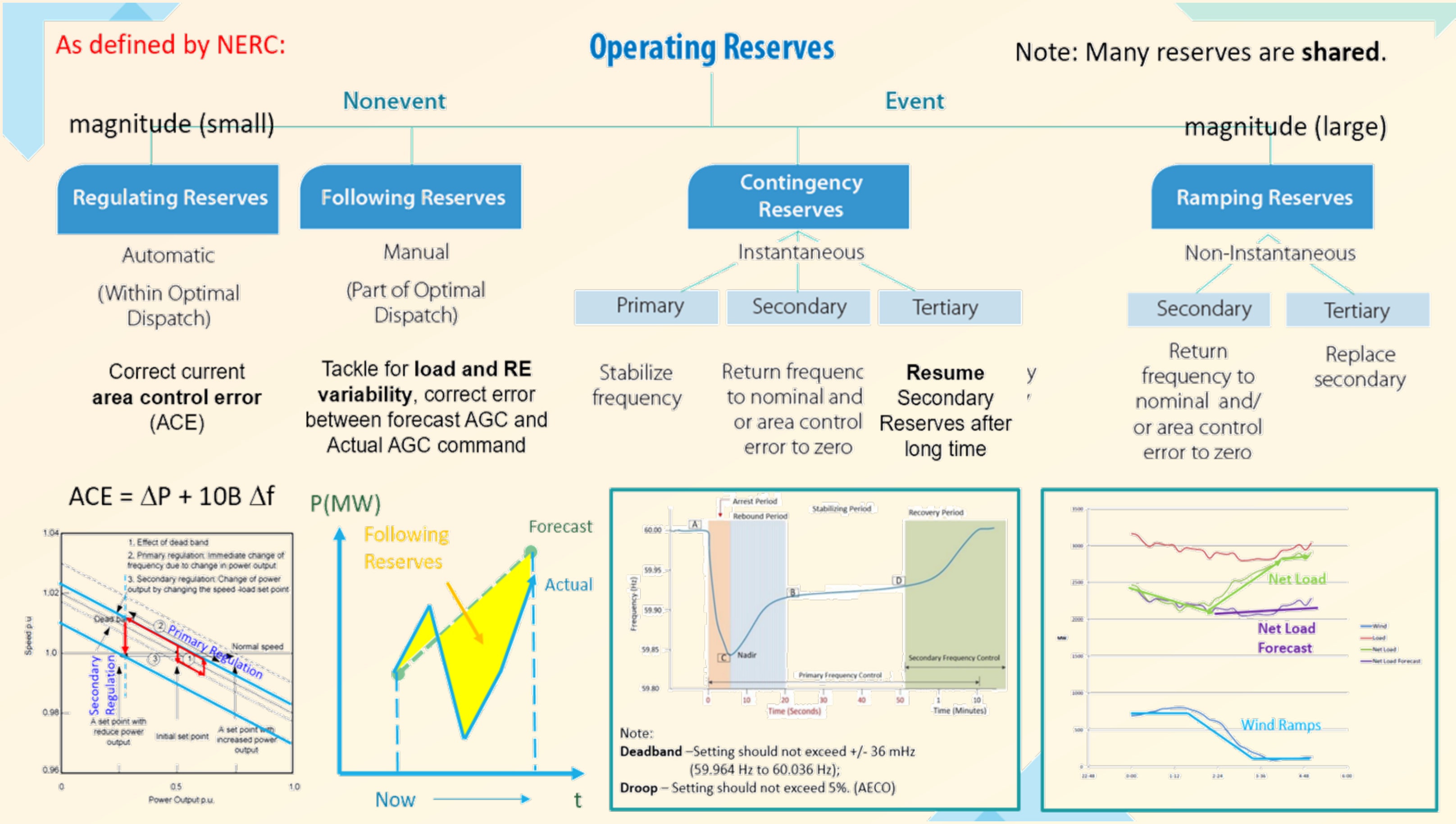


Wind Power Output Control & Low Voltage Ride Through



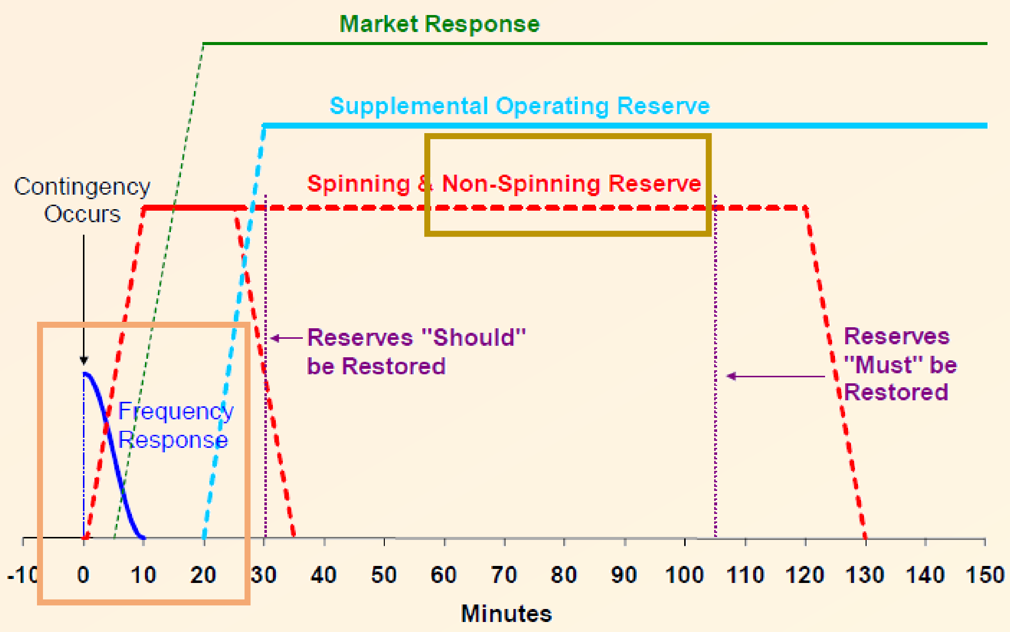
Operational Reserves Requirement

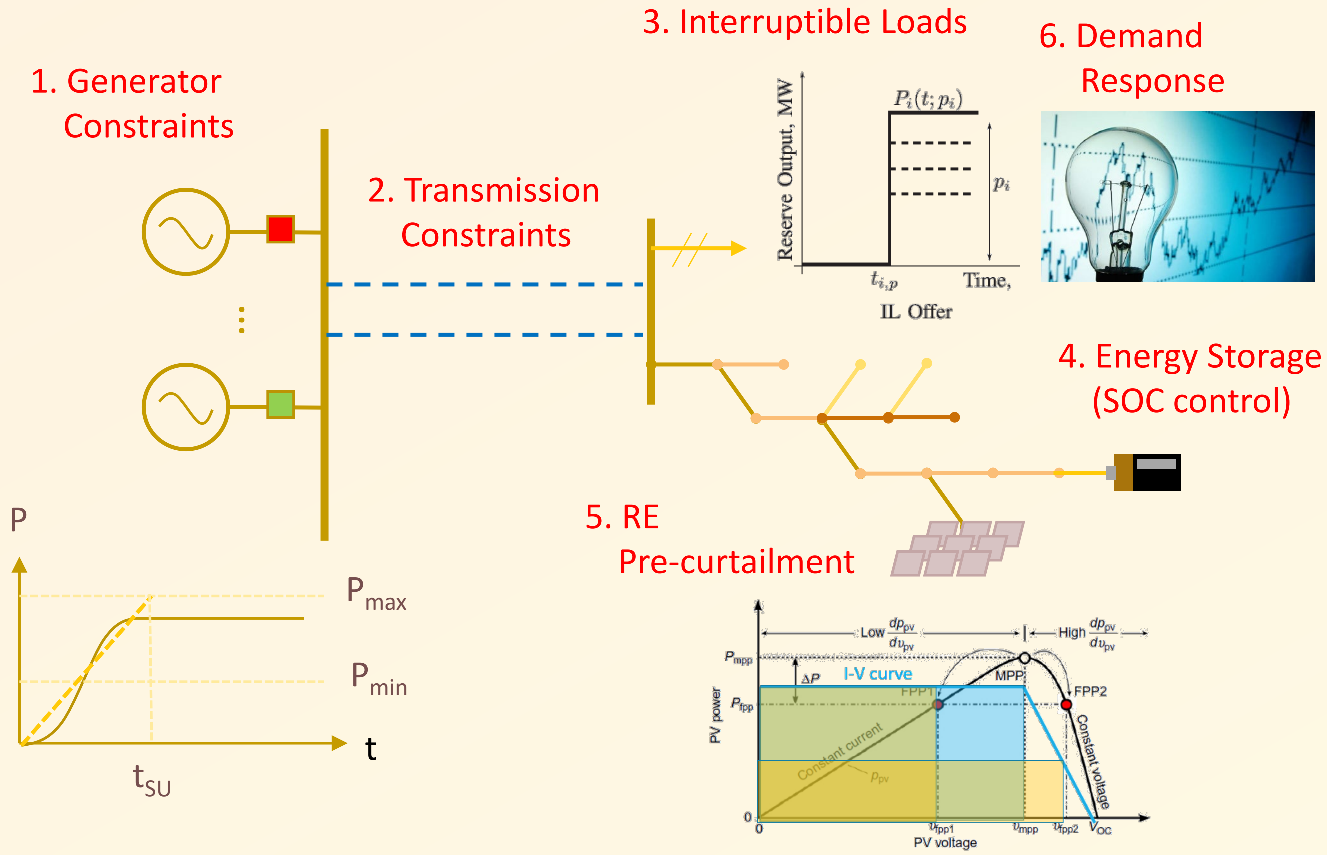


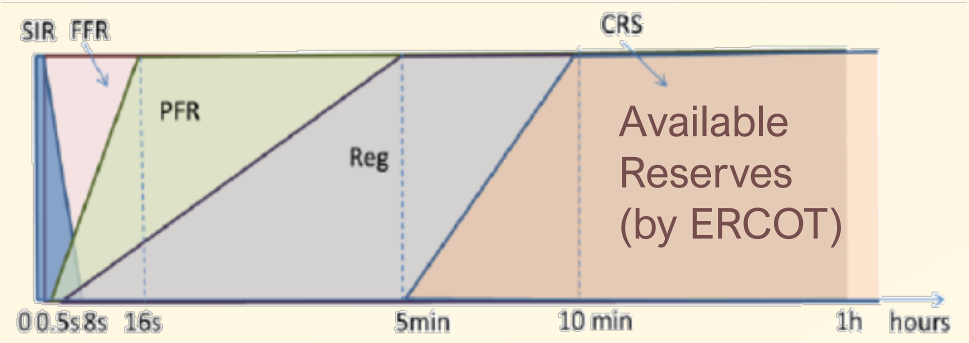


Question 4:
How to adjust current Spinning Reserve Requirement?

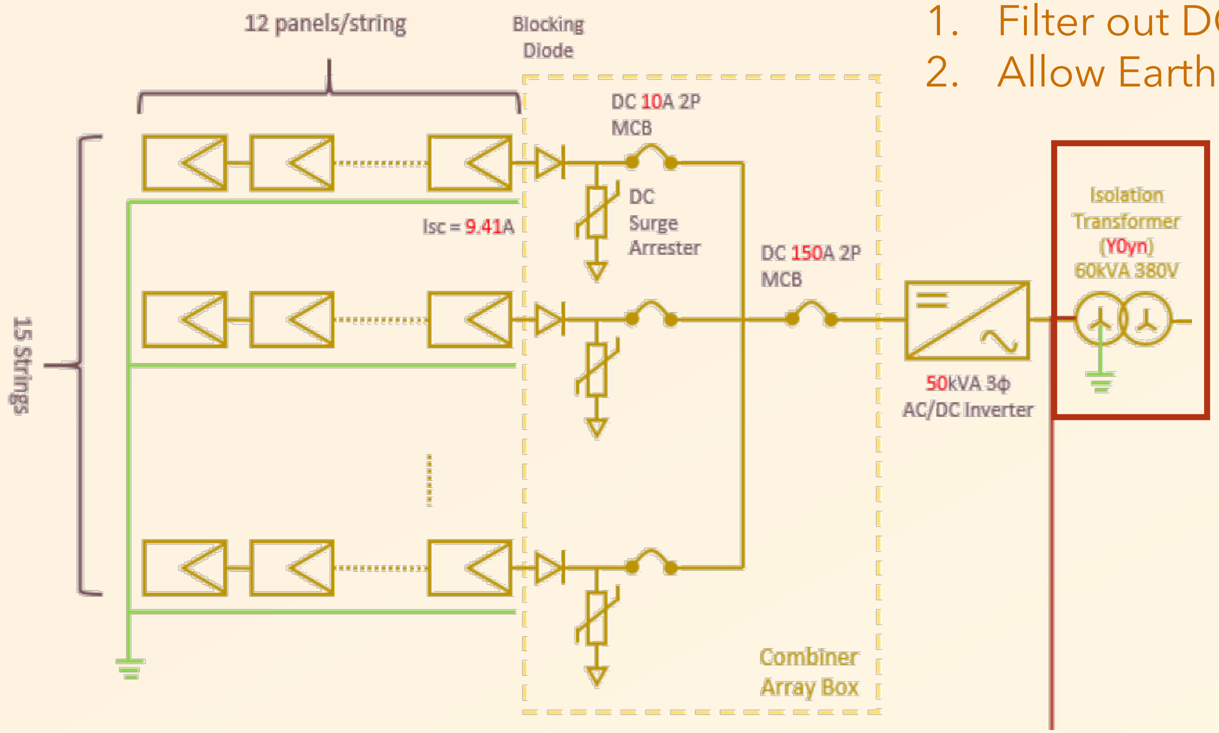
Problem:
What is the cost of reserves or value of loss of reserve?



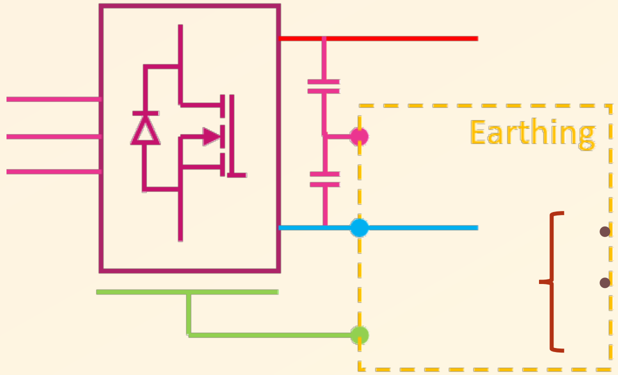




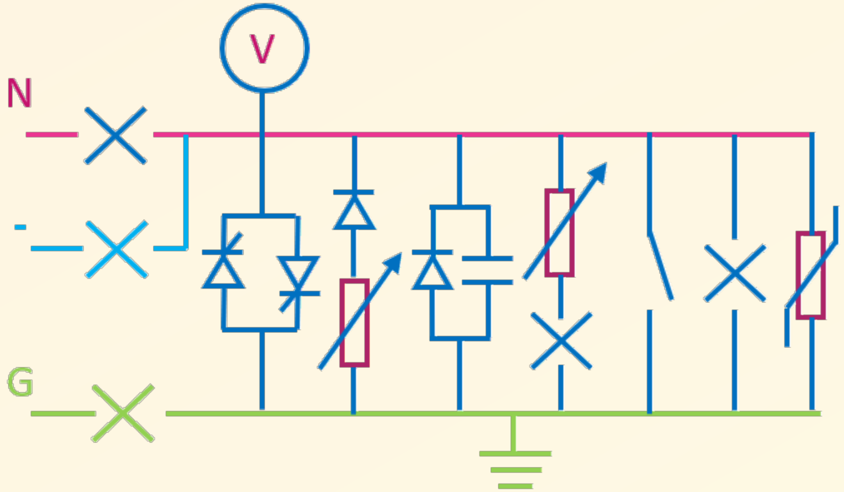
Spinning & Non-Spinning What to "Subscribe"?



IT:
1. Filter out DC
2. Allow Earthing



- Device
- Configuration
- IT / TT / TN



Question 5:
Where and How should be Earthed in the system?

Consideration:
- Earth Continuity (even during CB open)
- Fault Current for Fault Detection
  (All parts in fault must provide enough fault current for fault detection, location and isolation)
- Common Mode Voltage

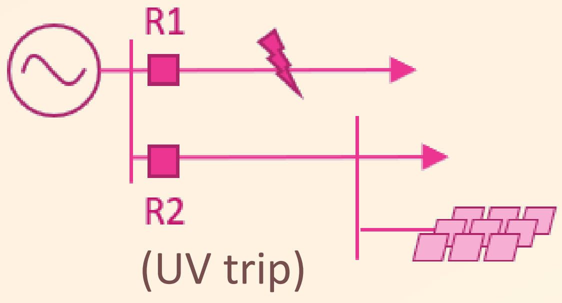
Earthing System Comparison

Earthing Device	Ungrounded	High R Grounded	Low R Grounded	Solid Grounded	Diode Grounded	Thyristor Grounded	Capacitor Clamped [1]
Common Mode Voltage at Normal Condition	**High**	**High**	Low	Low	Moderate/Low	Moderate/High	Low
Transient OV under Fault or Disturbance	**High**	**High**	Moderate	Low	Moderate	Moderate	**Moderate/High**
PG Fault Current	Low	Low	Moderate	**High**	**Moderate/High**	Moderate/Low	High
Leakage Current	Low	Moderate	Moderate	**High**	**Moderate/High**	Moderate/Low	Low
Relay Protection	**Hard**	Moderate	Easy	Easy	Easy	Easy	Moderate
Service Continuity	Yes	Yes	Yes	**No**	**No**	**No**	Yes/No [2]
Insulation Level	**High**	**High**	Low	Low	Moderate/Low	Moderate/High	High
Safety	**Low**	High	High	High	Moderate/High	Moderate/Low	A
Grounding Power Loss	No	**Yes**	No	No	No	No	No

[1] Capacitor Clamped is to earth with a capacitor clamped with a diode. It enables passive transfer from ungrounded system to solidly grounded system without injection for fault location.

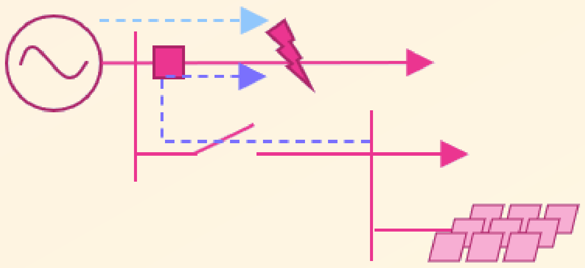
[2] Capacitor Clamped can be designed to transfer to solid earth with a lower clamping voltage, or NOT to allow service continuity.

1. **Sympathetic Tripping**
   due to DG type, location & capacity



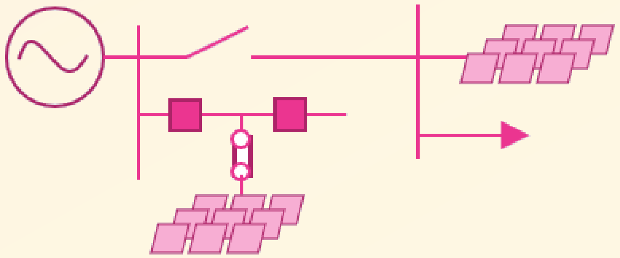
- Dynamic OC Setting
- Directionality for Blocking
- Transfer Trip

2. **Blinding**
   in Protection with DG



- Adaptive OC Setting with/ without DG
- Check CT Location
- Reduce source impedance dependent protection

3. **Auto Reclose Coordination**
   and loss of fault discrimination

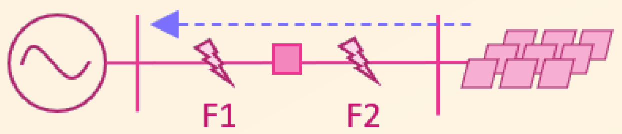


- Replace fuse / recloser with adaptive relay
- Delay reconnection time (= 5 min)
- Avoid leading asynchronous operation of machines

Question 6:
How does RE integration affect current protection practices?

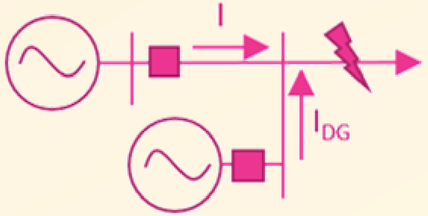
RE integration and Current Protection Practices

4. **Bidirectional** Fault Current due to DG (> Load)



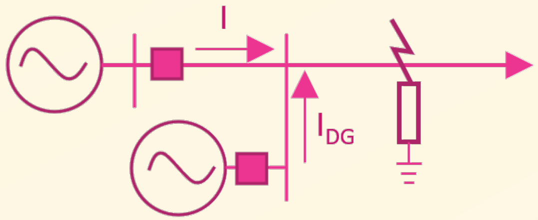
- NOT necessary from downstream to upstream, can be **Random flow** in graphs
- **Directional** with interlock
- Current Differential/ Permissive Overreach (Unit Protection)
- **Nodal & Zonal Protection**

5. **Reach Setting** in Distance Element

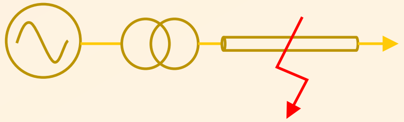
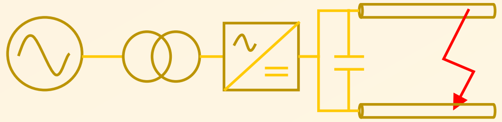
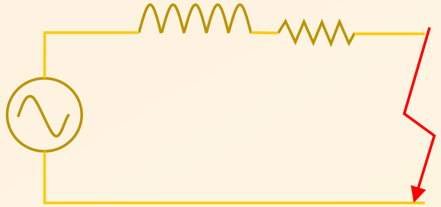
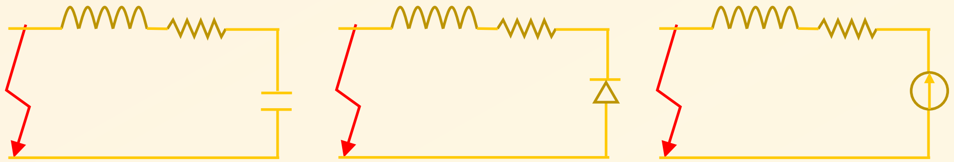
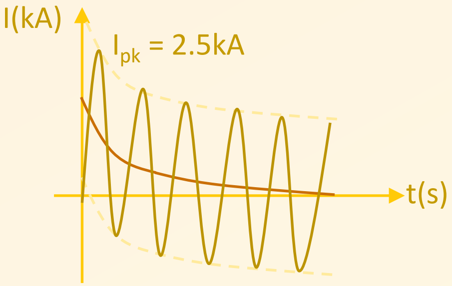
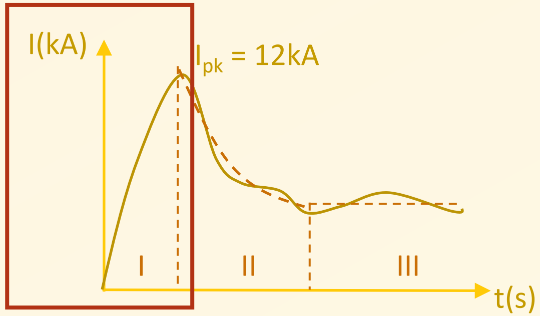


- $Z_{seen} = \frac{V}{I} = R_L + \left(1 + \frac{I_{DG}}{I}\right) R_F$
- **Overreaching Effect** and Delayed Tripping
- **Admittance + IDMT** or **Directionality** to identify internal/external fault

6. **High Impedance Fault** due to insulation failure



- Possible causing **thermal fault**
- Arc Fault by **arc fault detector**
- **Asymmetric** in current waveform due to breakdown voltage
- Current magnitude escalates gradually until reaching constant

	AC Fault (LLLG)	DC Fault (LL / LG + LG)
Schematic of Faulty Feeder		
Equivalent Circuit		
Fault Current Waveform		

Question 7:
What are the differences between AC and DC fault?

I. **Capacitor Discharge** Current (under-damping condition):

$$i_c(t) = \frac{V_0}{Lw_d} e^{-at}\sin(w_d t) + I_0 e^{-at}\left(\cos(w_d t) - \frac{a}{w_d}\sin(w_d t)\right)$$

II. **Cable Discharge** Current:

$$i_L(t) = I_0 e^{-\frac{R}{L}t}$$

III. **Rectified Grid Side Current:**

$$i_{grid}(t) = i_{ga}(> 0) + i_{gb}(> 0) + i_{gc}(> 0)$$

AC Vs DC Fault

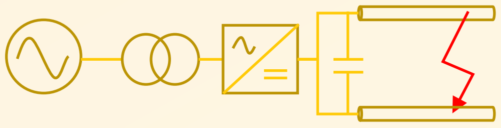
Fault at DC side?

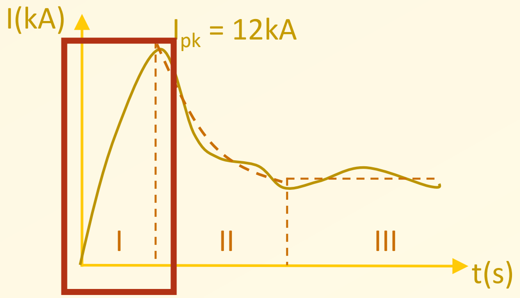
1. **DC CB Design**
   Requires MOV to clamp voltage, resonant circuit to create zero, SCR + Coupled Inductor to drain out energy with alternate path.

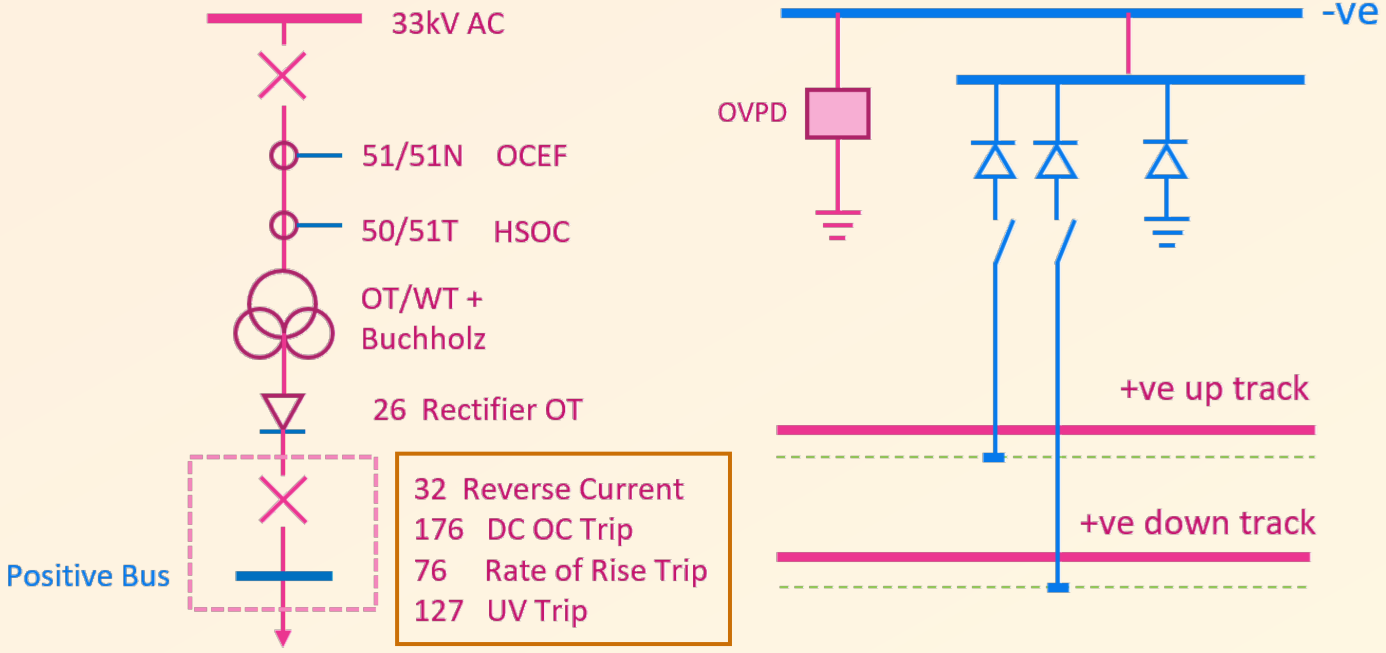
2. **CB Location**
   Inc. converter blocking, AC side CB, DC side isolator + DC CB in series with cap bank

	AC Fault	DC Fault
Zero Crossing Time:	Based on **Rated Frequency**.	No Zero Crossing Point, hence it chops current anyway.
Max Fault Current:	Related to **Voltage and Source Impedance**	Related to the **size of Capacitor**, DC link voltage stiffness and Fault Impedance.
Effect of **Source Impedance**	Changes the **amplitude** of fault current	Changes the **characteristics** of fault current (under/ critical/ over damped)
Ideal time for Fault Clearance	First **Zero-Crossing Point** (within 10ms)	Before **Capacitor Discharge** reaches its maximum point.

3. **Ability of IGBT to take fault current**
   Noted that IGBT cannot take such a large current even in short time.

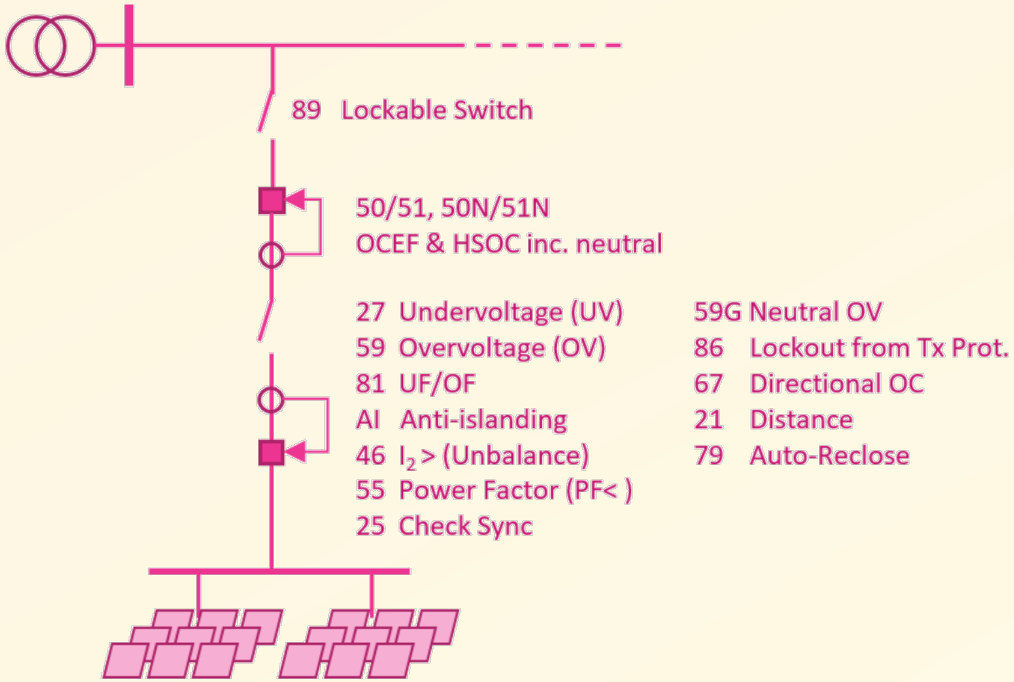






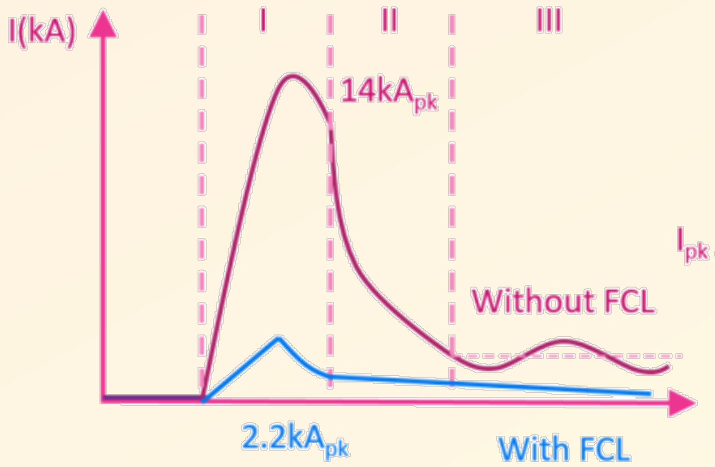
MTR Protection Items:

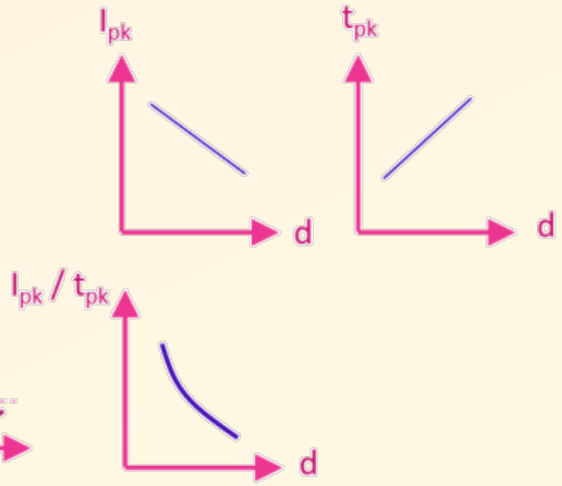
- Reverse Current (DOC, 32)
- DTL – OC (Setting = 8kA, Peak Load = 7.2kA)
- IDMT – OC (Setting = 3kA, 25s – OHL)
- Rate of Rise of Current (200kA/s + ΔI)



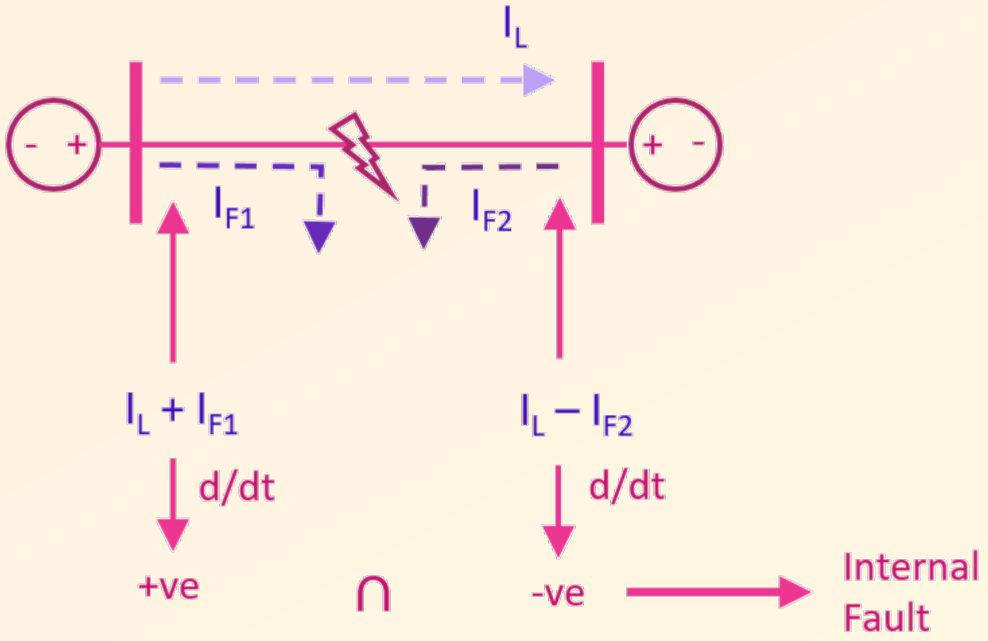
Question 8:
How to protect system from a DC fault?

2. Fault Current Limiter (FCL) to Clamp Cap Current

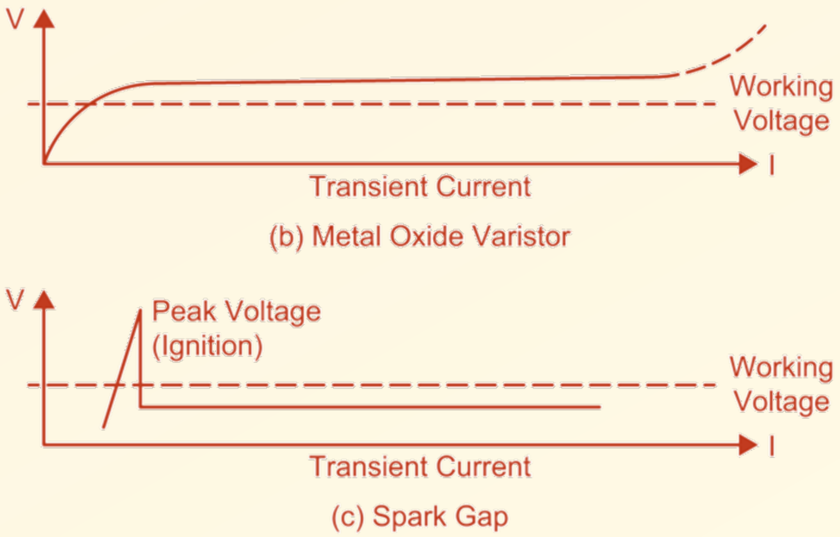




1. Directionality

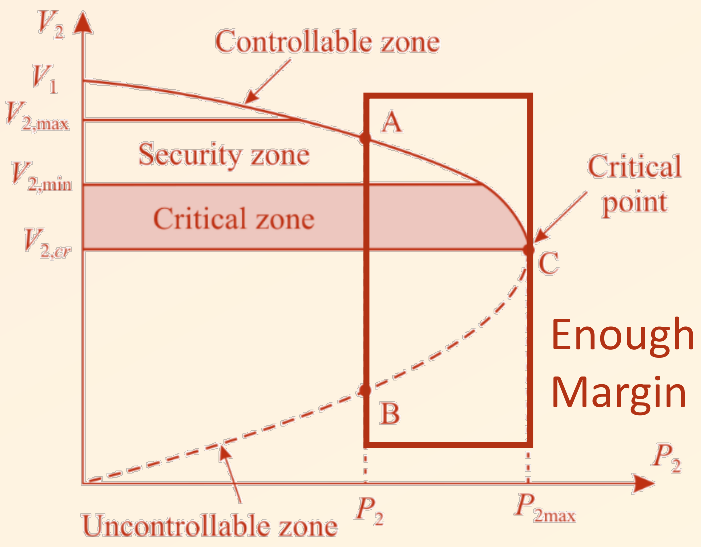


3. NOT just current protective device

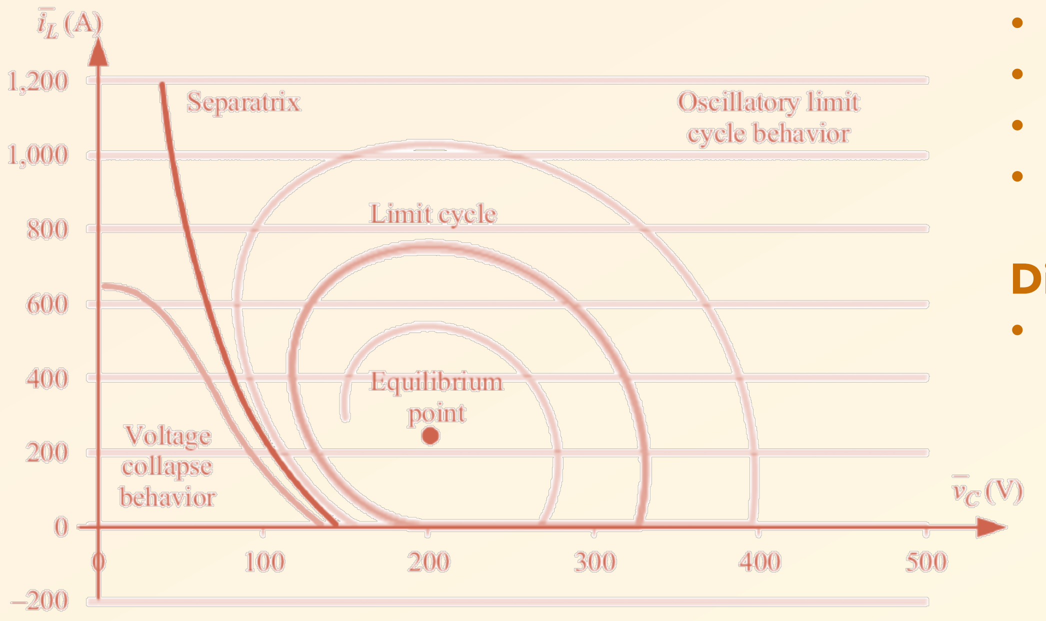


DC Protections

1. Voltage Stability still exists.



2. Constant Power Load (CPL) Issues



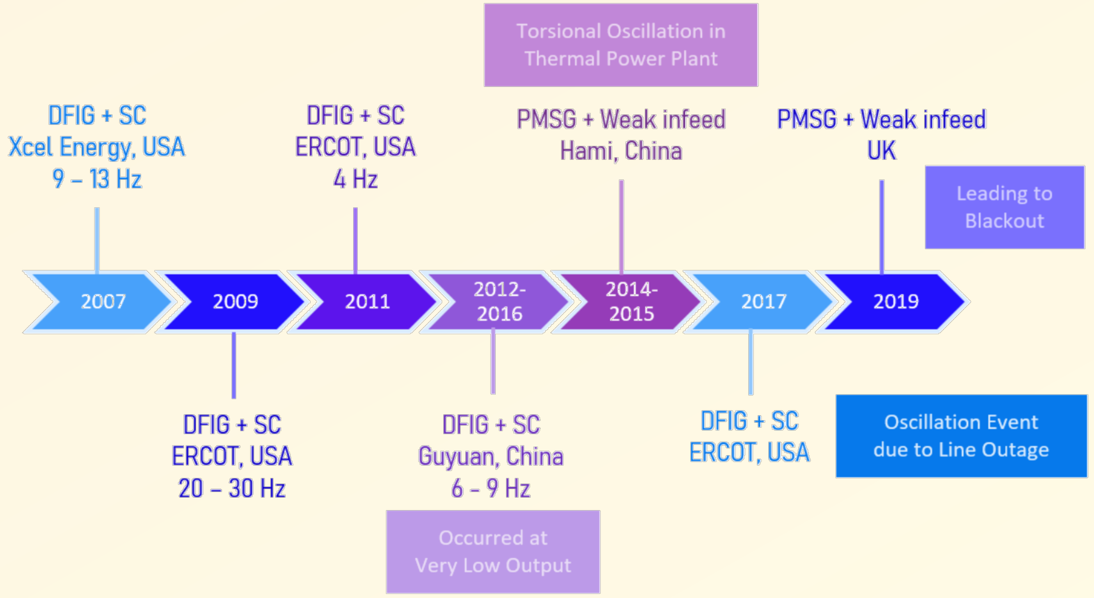
Suggestion

- Virtual Impedance
- Avoid Overcompensation
- Work within Constraint
- Check Frequency Coupling

Difficulties

- Do NOT have model

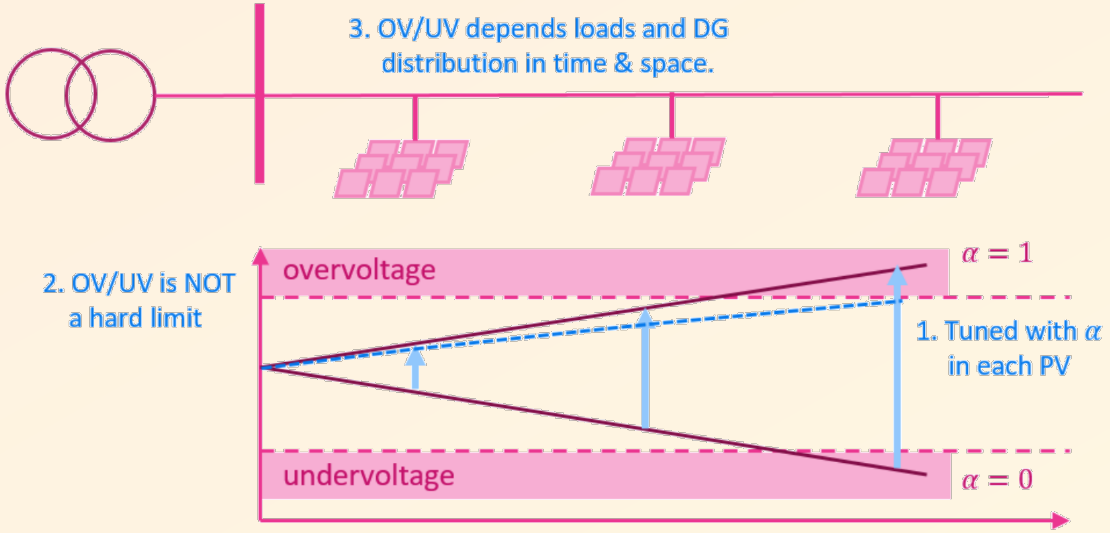
3. PMSG + Weak Infeed / DFIG + Series Cap

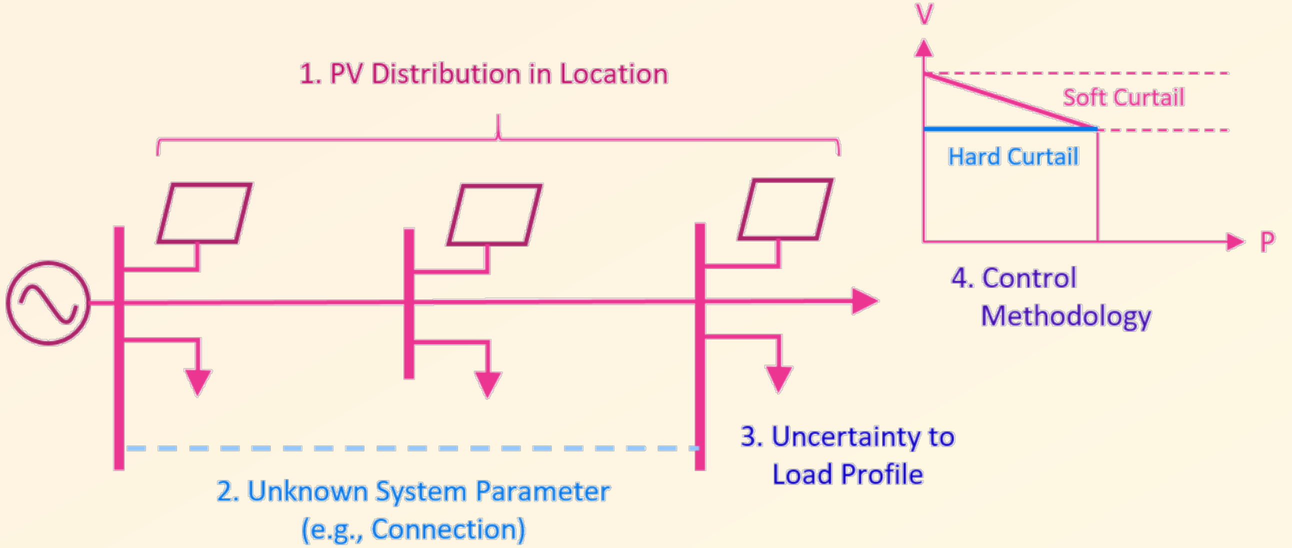


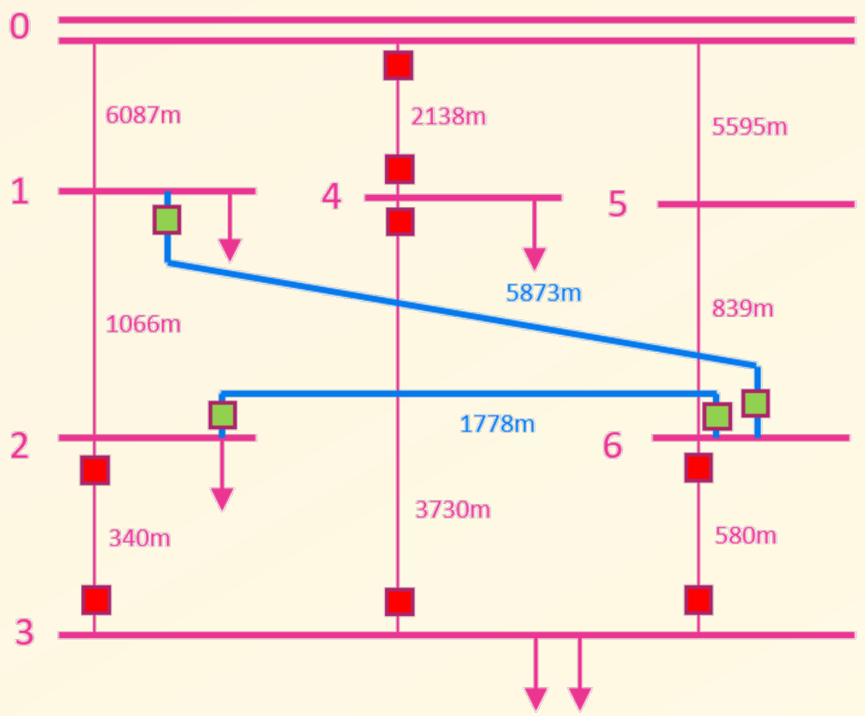
Question 9:

"DC is better than AC as it does NOT have stability issues."

- Is it correct?



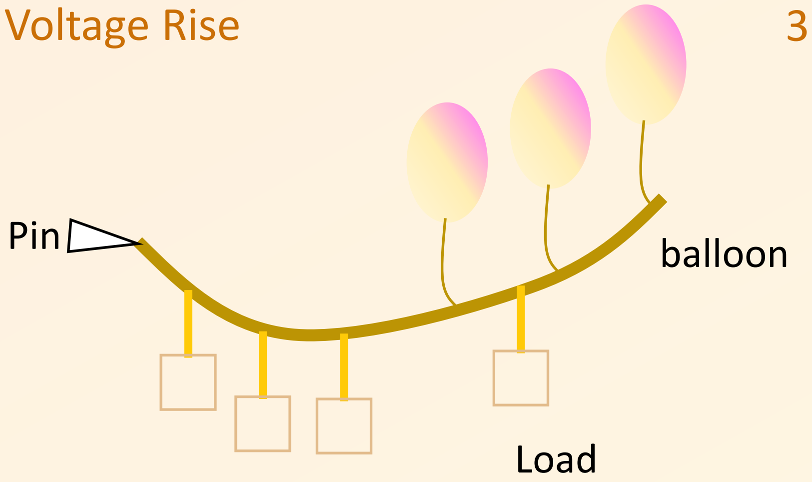




Question 10:
What are PV penetration issues and how to solve them?

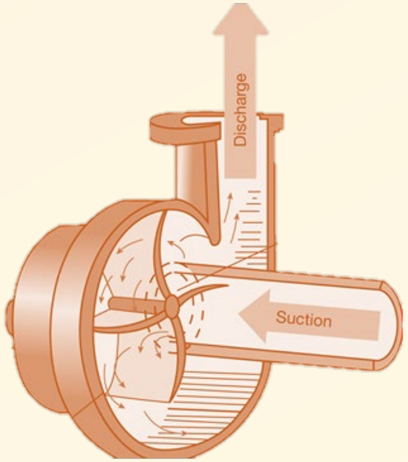
PV Related Issues and Solutions

1. Voltage Rise

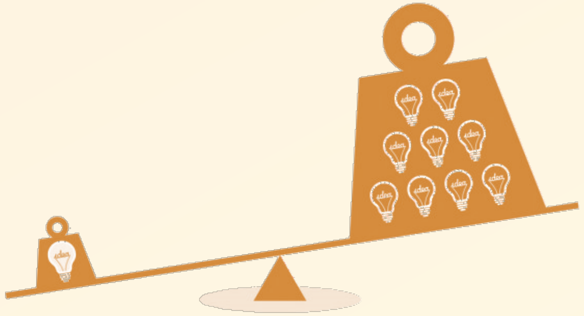


3. Voltage Flicker

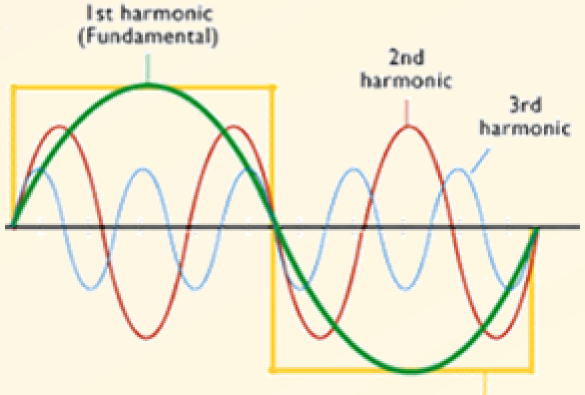
5. DC Injection



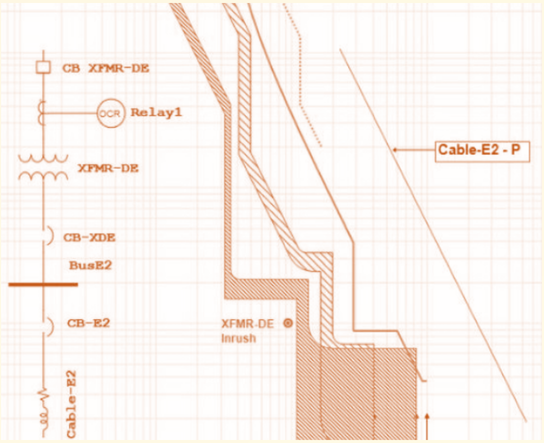
2. Unbalanced Current / Voltage



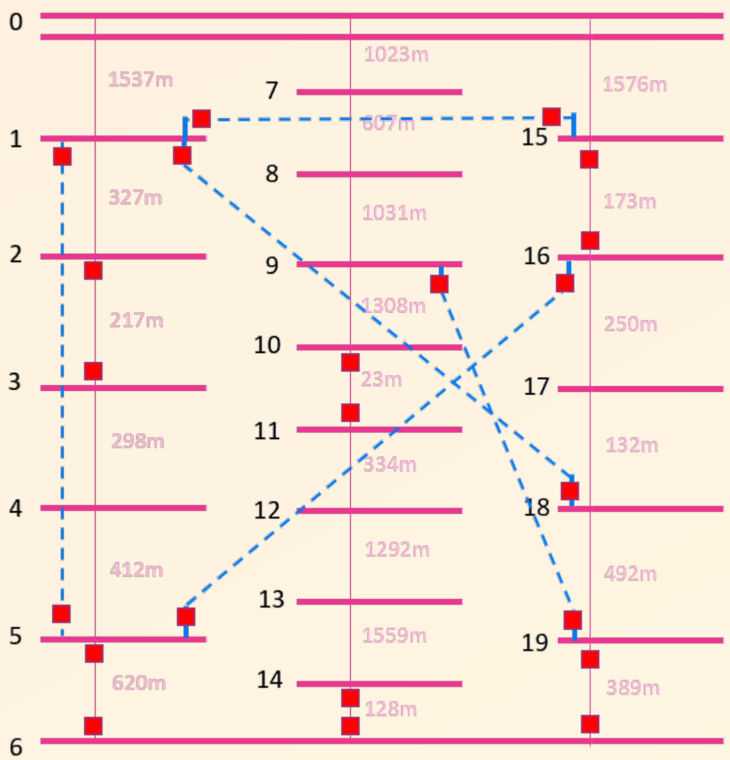
4. Harmonics



6. Protection Coordination



Sample Grid B - MPO



Constraint

Power Flow Constraint

$$P_k = |V_k| \sum_{j=1}^{N} |V_j| \left(G_{kj} \cos(\theta_k - \theta_j) + B_{kj} \sin(\theta_k - \theta_j) \right)$$

$$Q_k = |V_k| \sum_{j=1}^{N} |V_j| \left(G_{kj} \sin(\theta_k - \theta_j) - B_{kj} \cos(\theta_k - \theta_j) \right)$$

$$\rightarrow \Delta V = I|Z|$$

Voltage Constraint

$$\boldsymbol{V_{min} < V < V_{max}}$$

Thermal Constraint

$$\boldsymbol{I_{min} < I} = \frac{V_i - V_j}{Z_{ij}} < \boldsymbol{I_{max}}$$

Connection Constraint

$$s_i = \sum_{\substack{j=1 \\ i \neq j}}^{N} s_{ij} \geq 1$$

(Integer)

Objective Function

$$\max \sum_{i=1}^{N} P_{PV(i)}$$

$$\max \left(\alpha \frac{\sum_{i=1}^{N} P_{PV(i)}}{P_{PV\_max}} + \beta \frac{\sum_{i=1}^{N} c_i s_i}{c_{max}} + \gamma \frac{\sum_{i=1}^{N} (V - V_n)^2}{V_n^2} \right)$$

$$\alpha + \beta + \gamma = 1, \quad \alpha, \beta, \gamma \geq 0$$

(Non-Linear)

Can Reconfiguration help improve hosting capacity and voltage deviation?

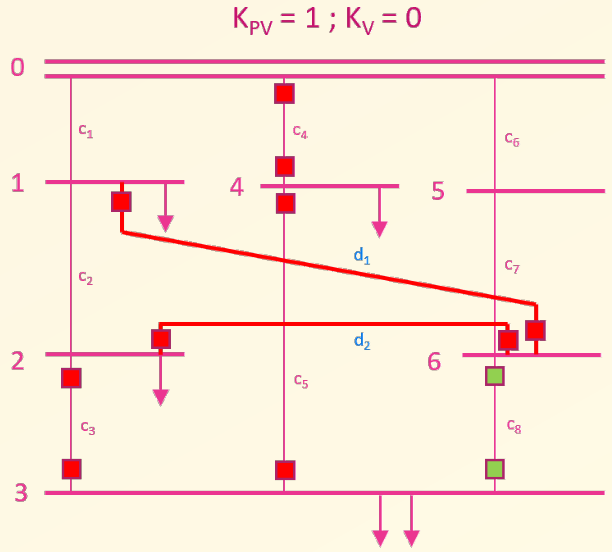
Optimization Tools

Assumptions

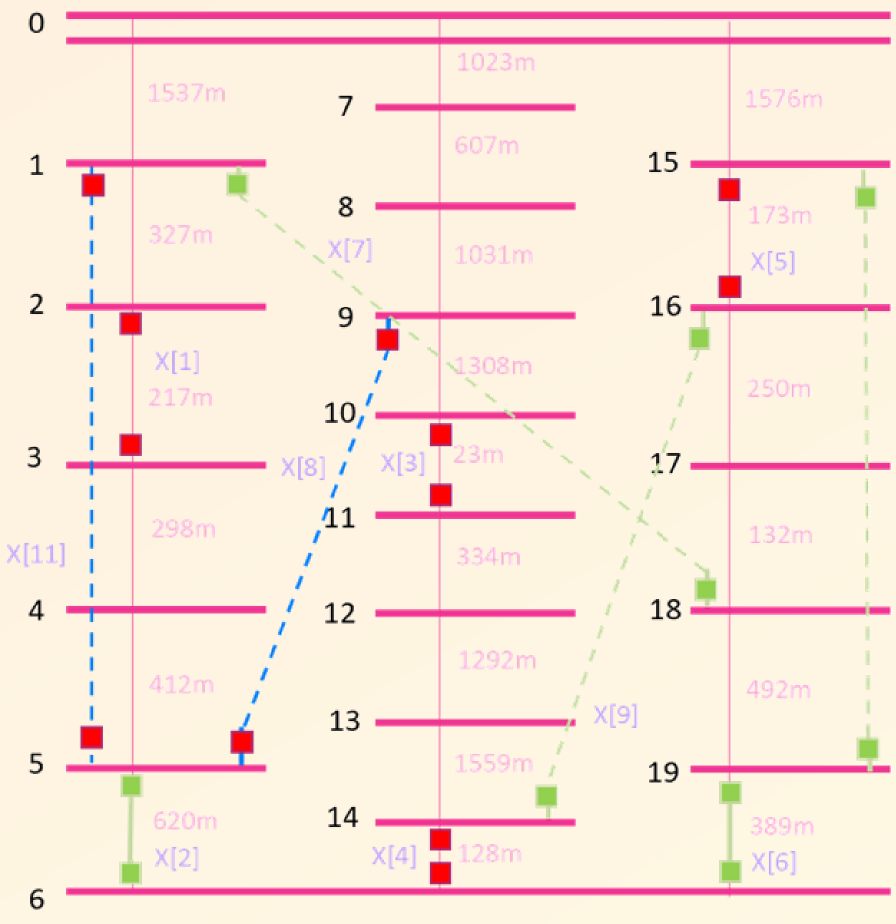
- Steady State Condition.
- Hard Margin for Voltage Deviation is used.
- Protection Constraint such as time coordination and selectivity can be solved by other means.
- 300mm² XLPE cables with X/R ratio = 0.625 is employed to apply simplified power flow equation.
- Balanced load flow with phase selector.
- Deterministic Approach, i.e. maximum output simultaneously

Optimization Case

1. min PV [-ve in nature]
2. min dV (voltage deviation)
3. min PV + dV
4. min 8PV + 9 dV
5. min 10PV + dV
6. min 8PV + dV + Cost

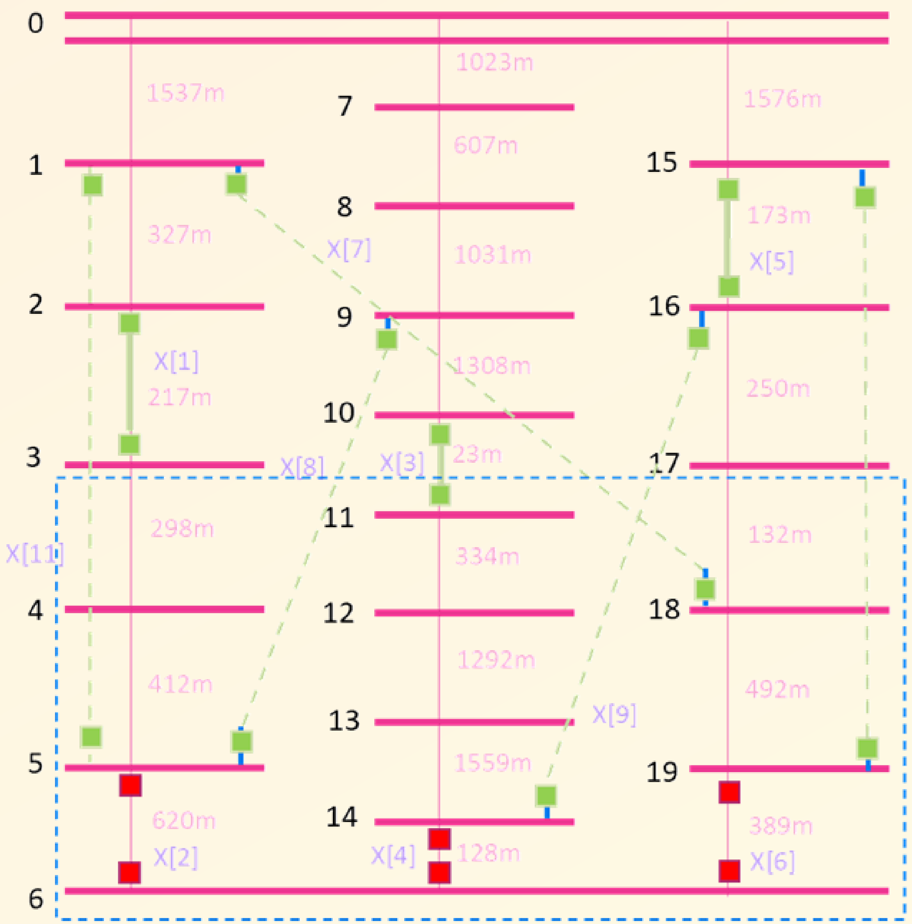


Results - Reconfiguration



dv	2.67MV^2
pv	42.2 MVA
hc	1.48

P4	7MVA
P10	1.57MVA
P14	0
P16	4.5MVA
P6	6.07MVA
P19	6.07MVA
P5	7MVA
P2	1.52MVA
P15	1.5MVA
P13	0
P7	7MVA

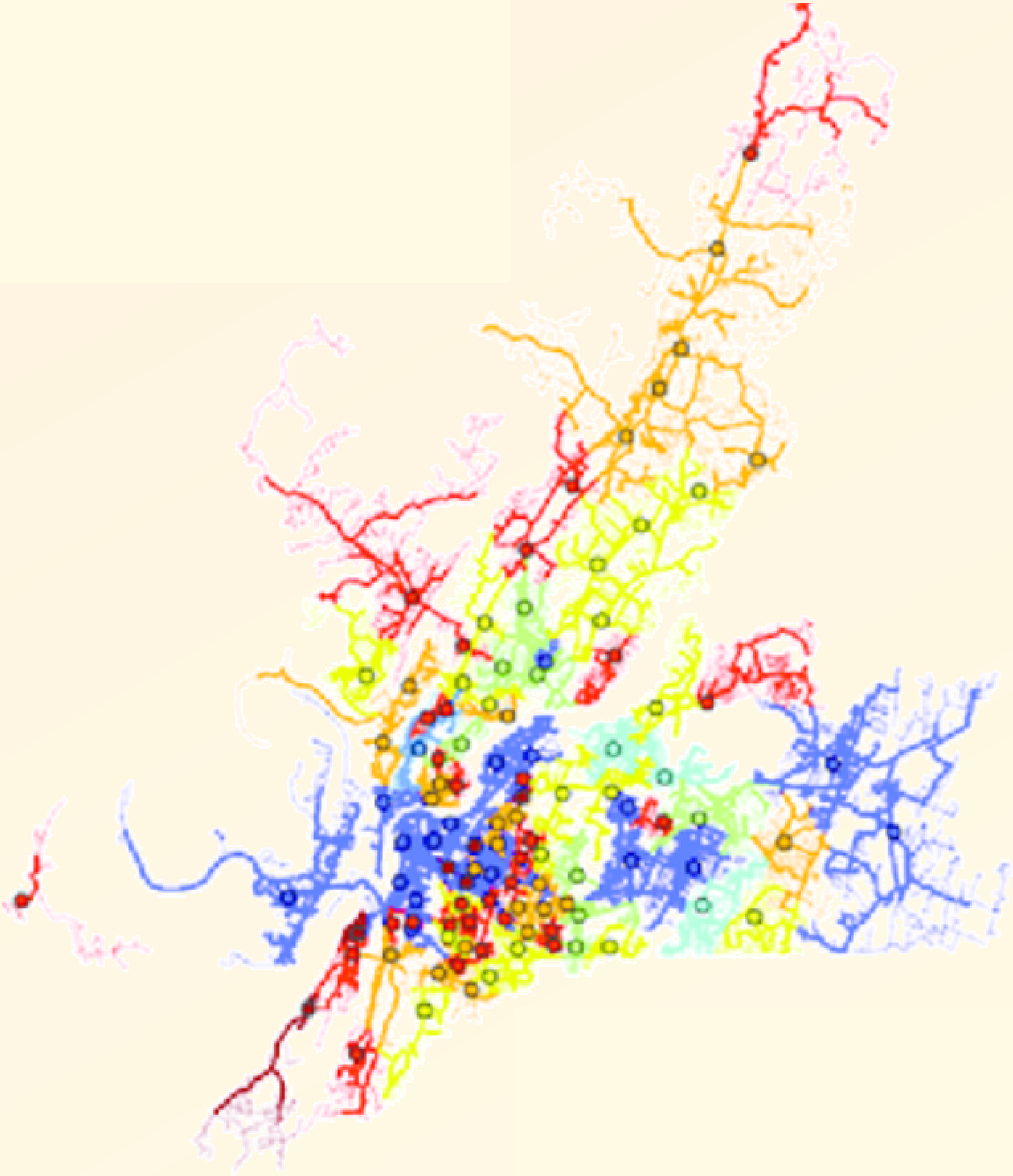


dv	0.34MV^2
pv	19.6MVA
hc	0.68

P4	3.7MVA
P10	30.5kVA
P14	0
P16	2.84MVA
P6	0
P19	4.71MVA
P5	56.3kVA
P2	0
P15	0
P13	6.21MVA
P7	1.5MVA

- Optimization in Hosting Capacity is never a single solution – It is an **efficient frontier**.
- Some interconnectors are identified as **useless** at any time, even if it is considered as useful for intra-ring support in the past.
- **Grid partitioning**, as a hot topic in this year, is often a good solution to reduce voltage deviation.
- This method, possibly with no newly added component, can effectively reduce voltage deviation with **P:Q = 4:1** effectiveness.

Hosting Capacity - Conclusion



Conclusion

1. This dissertation aims to bridge the gap between the academics and utilities in understanding of RE or IBR **fault**, **stability** and **control** to improve **distribution planning** and **network assessment process**.
2. To obtain the **voltage support functionality** from PV, Volt-Var and Volt-Watt control are often implemented in inverter. Yet, the utilities should have their control in the **slope** and **boundary setpoint** in order to coordinate the grid with other network elements.
3. Although **generator faults** (WTG / PV) can be cleared by grid with OV/UV or directional elements, and it should be isolated or located by plant operator, several generator faults (WTG / PV) are identified with solutions. Noted that the effect of generator fault is NOT large.
4. It requires NO **spinning reserve requirement** update, as contingency reserve is much larger than the others and actual load profile is known with double meter configuration in HK.
5. **Earthing system** with RE should be carefully considered, with common mode voltage, earthing coverage at all operation condition, permanent design fault or fault current. It is suggested to have a specification in converter topology to determine if the earthing system is appropriate.
6. For **DC fault**, in case a DC system is implemented, DC CB in series with cap + elements to constrain DC cap discharge current must be available (e.g. SFCL) + AC CB must be provided.

Conclusion

7. DC has its **stability issues**, inc. voltage stability in transmission constraint, constant power load issues, wind power coupling issues (DFIG + series cap / PMSG + weak coupling) and converter coupling issues. It is suggested to operate within constraint, introduce virtual impedance and perform impedance decoupling for the full response.
8. RE does affect **current grid protection** operation in terms of blinding of current source, overreaching distance, time coordination with fixed element such as fuse and recloser, directionality with meshed network.
9. DFIG and PMSG have their own **fault characteristics**. DFIG can create a larger volt dip with extraction of more reactive power to build up the field, but it damps down fast. PMSG can provide steady state fault current as soon as the AVR is not disconnected. Hence, chopper, crowbar and series resistance with thyristor are often applied in WTG.
10. Grid partitioning or Grid reforming are often solutions under **grid reconfiguration** to deal with increasing PV application with larger demand in network reserves and voltage quality.

This dissertation has obtained full support from Dr. K.H. LAM and Department of EEE, HKU. Here expresses appreciation to them.