Capacity Building on Advance & Innovative Transmission System Design and Optimization

General Principle and Recent Trends of Power System: Grid Architecture & Components (Day 1.1 A)

By

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Under SAARC Energy Center

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Agenda

1. Grid Architecture & Components
2. Basic Components of a Power System
3. Overhead Line
4. Cables
5. Substations
6. Loads

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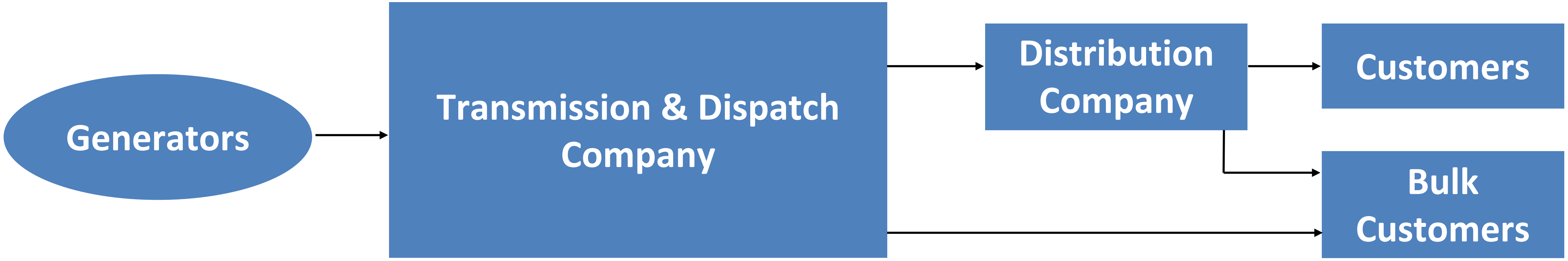
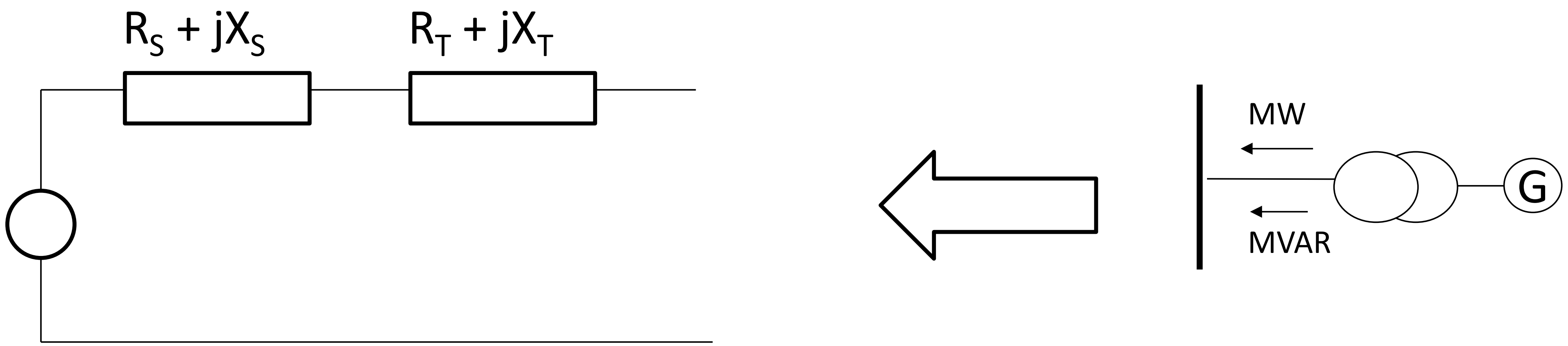
Grid Architecture & Components



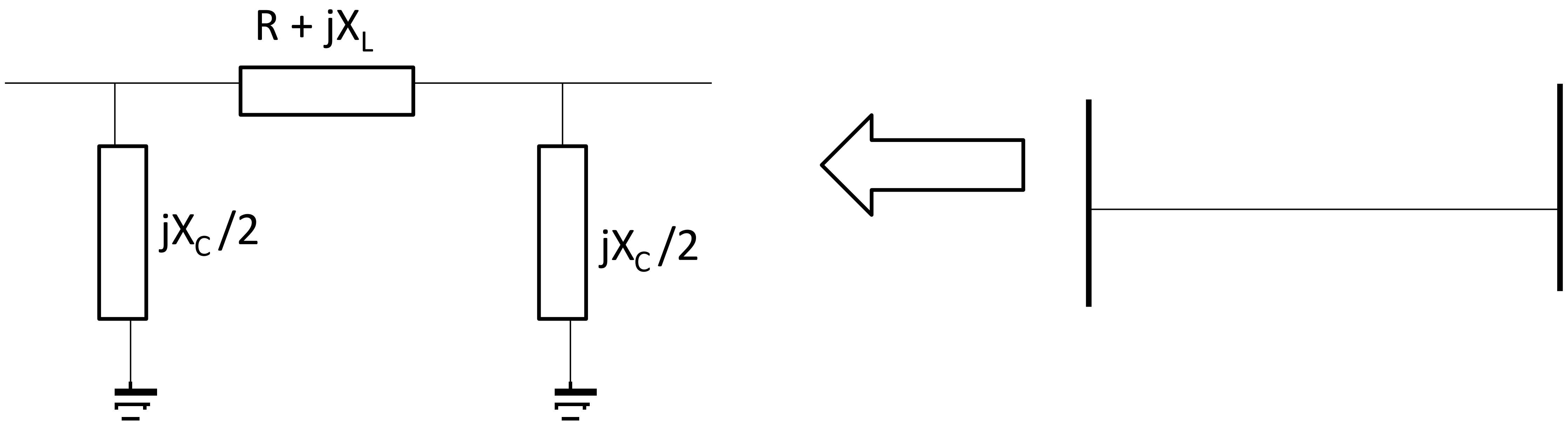
- Generator with Step-Up Transformer
- Transmission Line (OHL or Cable)
- Substations/Step Down Transformers
- Load

Basic Components of a Power System

- **Generator Equivalent Circuit**

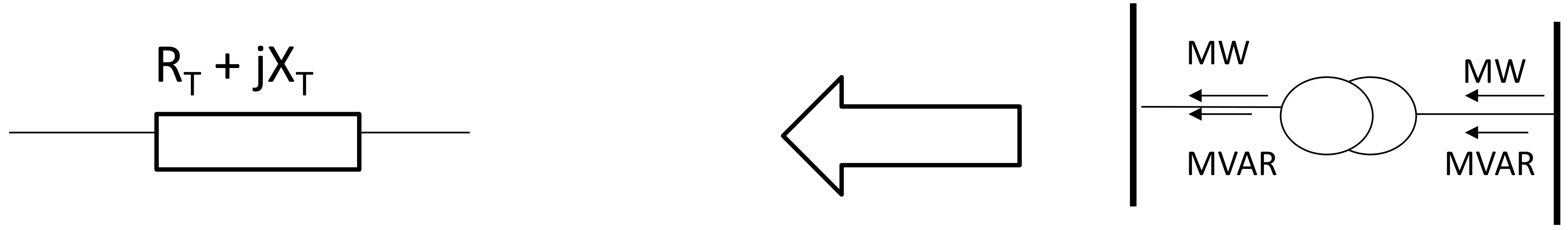


- **Transmission Line Equivalent Circuit**

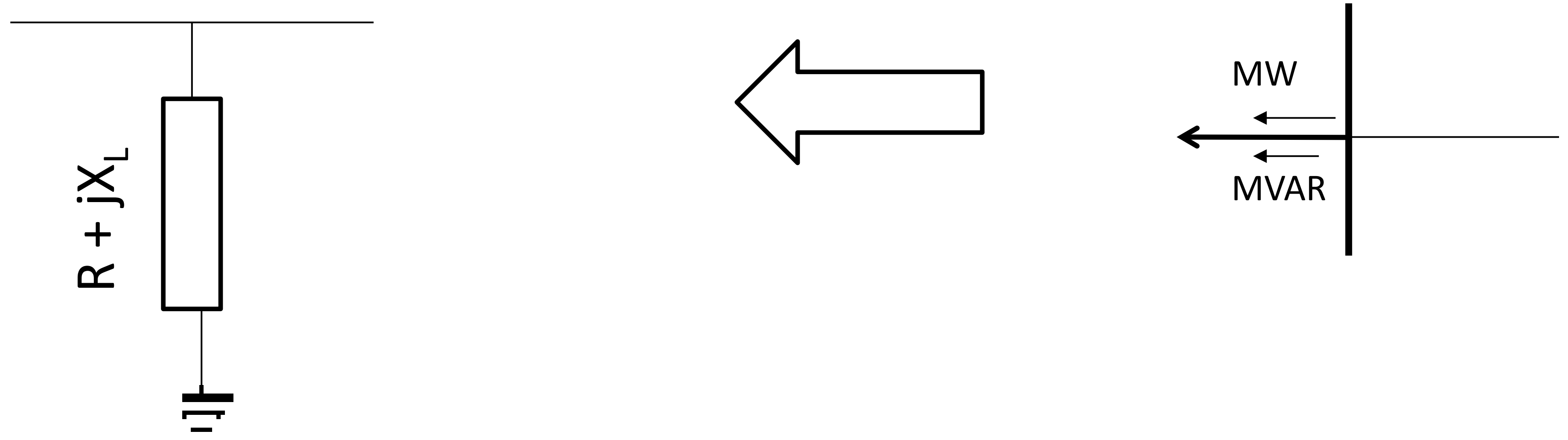


Basic Components of a Power System

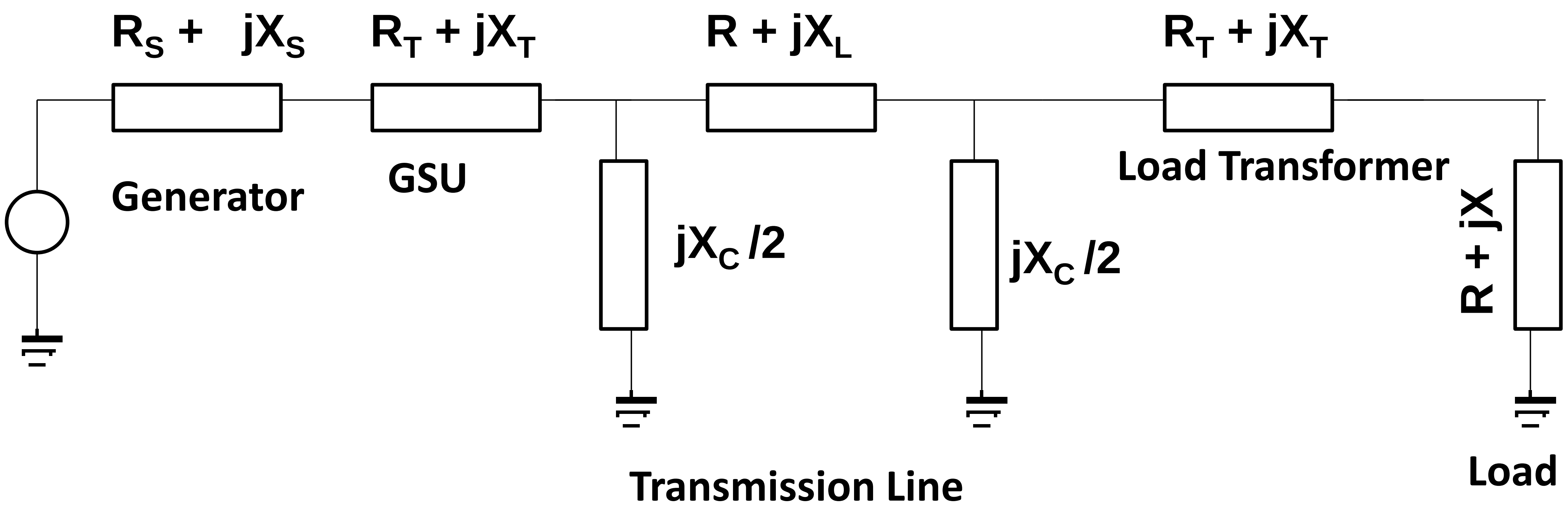
- **Transformer Equivalent Circuit**



- **Load Equivalent Circuit**



Equivalent Model of a Simple Power System



HV , EHV and UHV Levels of Transmission Systems

HVAC

HV:

a. 66 kV,
b. 110 kV, 115 kv, 132 kV, 138 kV

EHV

a. 220, 230 kV
b. 330,380, 400 kV
c. 500 kV
d. 750, 765 kV

UHV

a. 1000 kV, 1100 kV

HVDC

a. ± 400 kV
b. ± 500 kV
c. ± 600 kV
d. ± 800 kV
e. ± 1000 kV

OHL

1. **Sizing (double, triple, etc. bundle)**
    - Double (Twin) bundled for 132 kV and 220 kV
    - Triple or four bundled (Quad bundled) for 220 kV and 400 kV
2. **Height and other Physical Parameters**
    - 132 kV
        - o Tower height 30-33 Meter
        - o Span length 900-1200 Meter
        - o Sag = 0.02 % of the span length
    - 220 kV
        - o Tower height 55-58 Meter
        - o Span Length 800-900 Meters
        - o Sag= 0.02 % of the span length
    - 400 kV
        - o Tower Height 65-68 Meters
        - o Span length quad Bundle 400-500 Meters
        - o Sag= 0.02% of the span Length

OHL

3. Route Considerations

- Enough Right of Way (RoW)
    - 132 kV 50 Meter
    - 220 kV 100 Meter
    - 400 kV 150 Meter

  (1/2 From center of the line)
- Lattice towers if passing through unpopulated areas
- Tubular Poles if passing through populated areas but with enough RoW leaving enough clearing space horizontally and vertically

Cables

1. **Proper sizing and selection considerations**

➢ **As per IEC 60502**

Power cables with extruded insulation and their accessories for rated voltage from 1 kV (Um=1,2 kV) up to 30 kV (Um=36 kV).

➢ **As per IEC 60840**

- Power cables with extruded insulation and their accessories for rated voltage above 30 kV (Um=36 kV) up to 150 kV (Um=170 kV).

➢ **As per IEC 62067**

Power cables with extruded insulation and their accessories for rated voltage above 150 kV (Um=170 kV) up to 500 kV (Um=550 kV)

Cables

2. How to choose the voltage level

- Depends on
  - Amount of power
  - Distance or Line Length to transmit this power

Voltage L-L	Load	Length
11	Less than 10 MVA	Upto 5 Km
33	Upto 20 MVA	10 to 15 Km
66	Upto 40-50 MVA	10 to 30 Km
132	100-150 MVA	20 to 50 km
220	100 to 300 MVA	20 to 50 km
400	500 to 2000 MVA	20 to 50 km

3. Cable connected reactor sizing

Total compensation = 60 % of total cable charging (MVAR)

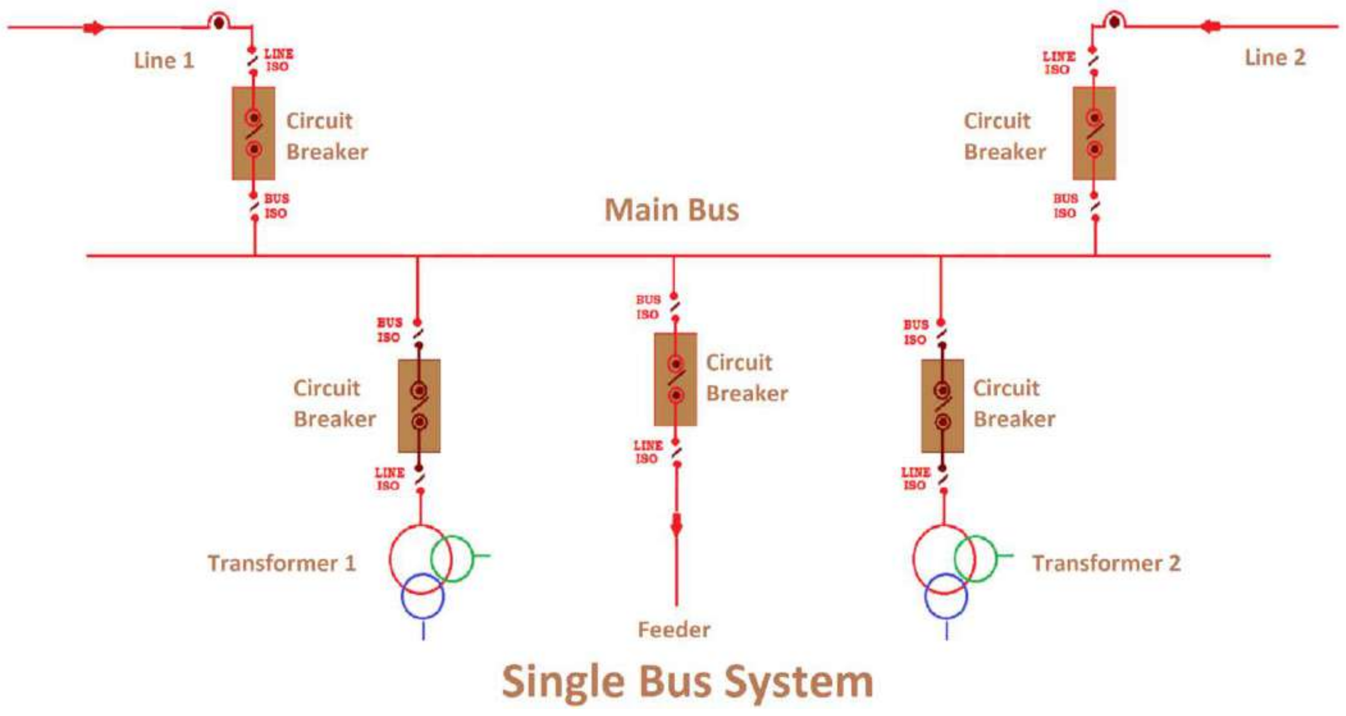
Two reactors each 2x30 % at each end of the cable

Maximum compensation should not be above 80% of total cable charging (avoid resonance)

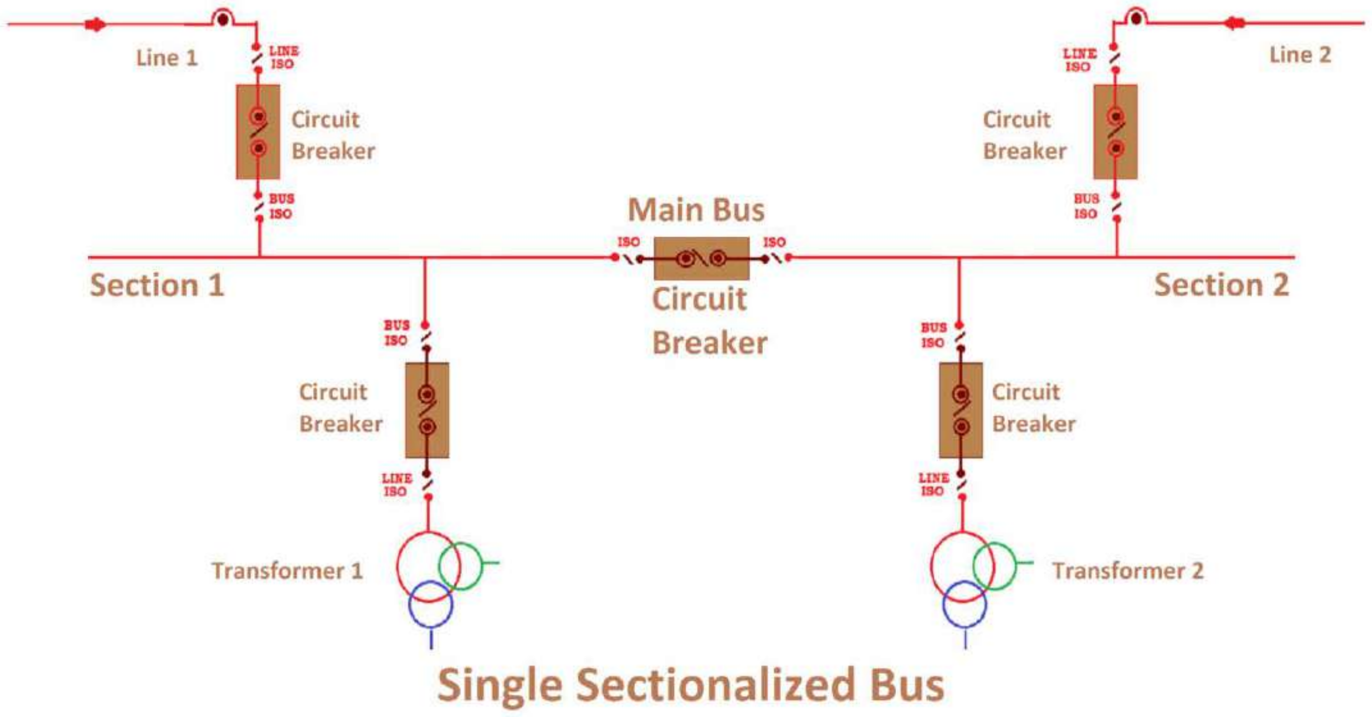
Substation

Busbar configuration (single, double & 1 ½)

1. Single Bus Single Breaker;



Without Sectionalizer



With Sectionalizer

Substation

1. **Single Bus Single Breaker**;
   - A single bus configuration consists of one main bus that is energized at all times and to which all circuits are connected.
   - This arrangement is the simplest, but with least reliability.
   - Bus faults or circuit breakers failure under fault conditions results in complete loss of the substation.
   - Such scheme with a sectionalizer is fine for 11 kV and 33 kV
   - Single bus with sectionalizer between busbar A&B. load cannot be shifted from out-of-service bus to the in-service bus
     - **<u>Single Bus Advantages:</u>**
     - Lowest cost
     - Small land area
     - Easily expandable
     - Simple in concept and operation
     - Relatively simple for the application of protective relaying

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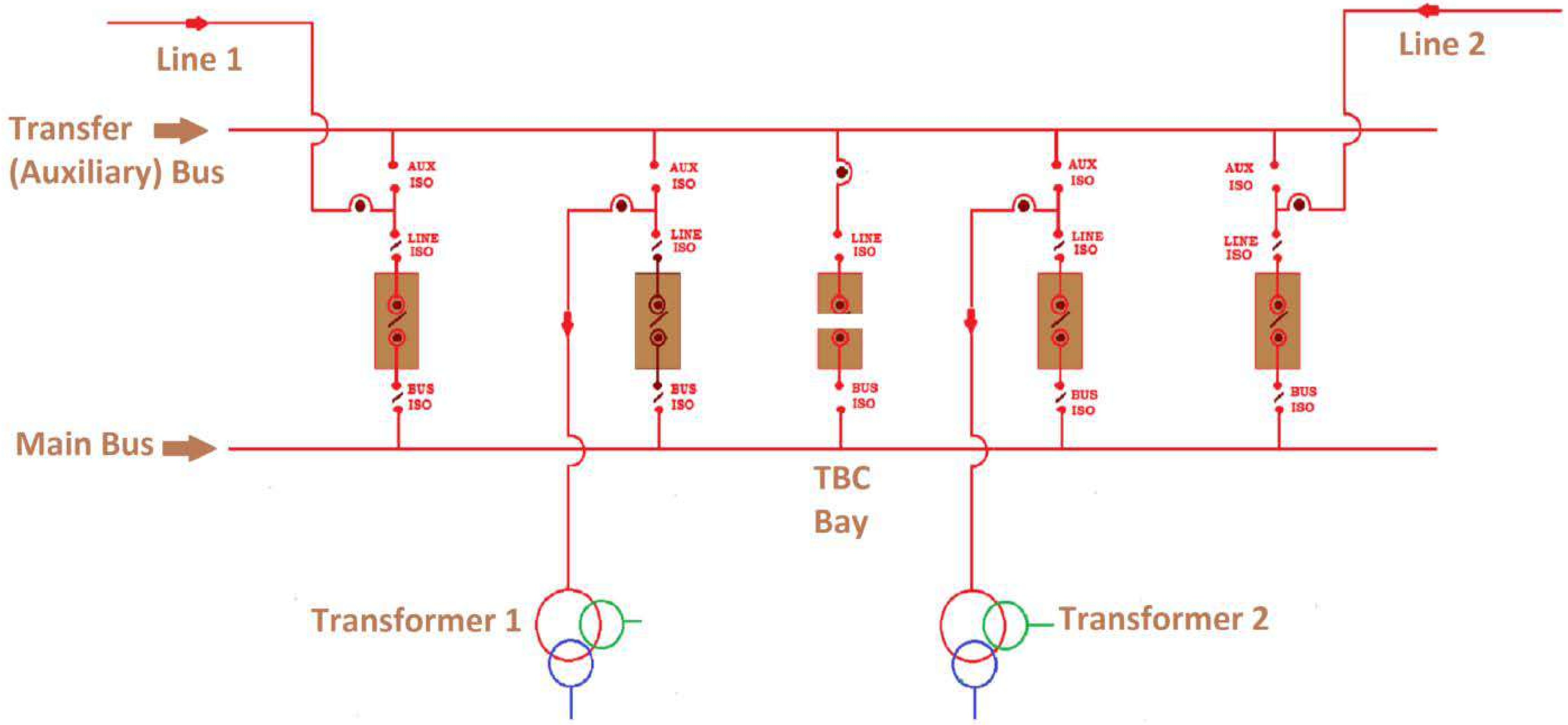
Substation

2. Double Bus Single Breaker



Main & Transfer Bus System

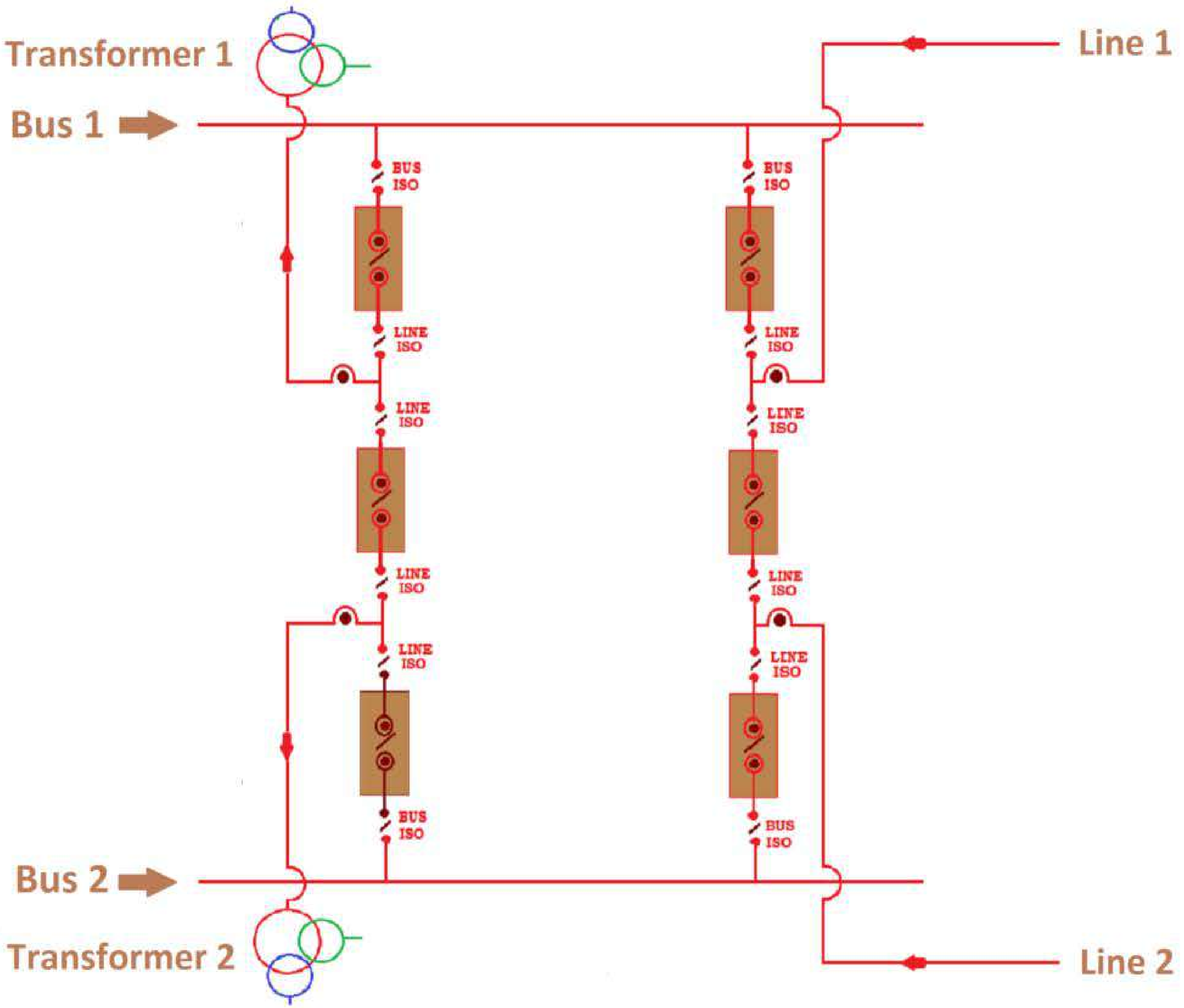
Substation

2. Double Bus Single Breaker

- The double bus–single breaker arrangement connects each circuit to two buses,
- Additional circuit breaker needed for bus tie
- Protection and relaying are complicated
- Bus fault can cause loss of entire substation if all isolators are closed, and circuits are connected to both buses. Usually, circuits are connected to single bus by keeping certain isolators open.
- This arrangement provide acceptable reliability for 66 kV and 132 kV substations
- **<u>Double Bus Advantages:</u>**
  - Maintain service and protection during circuit breaker maintenance
  - Reasonable in cost
  - Fairly small land area
  - Easily expandable
  - More reliable in terms of load shifting if one bus is out of servic

Substation

3. Breaker-and-a-Half Scheme



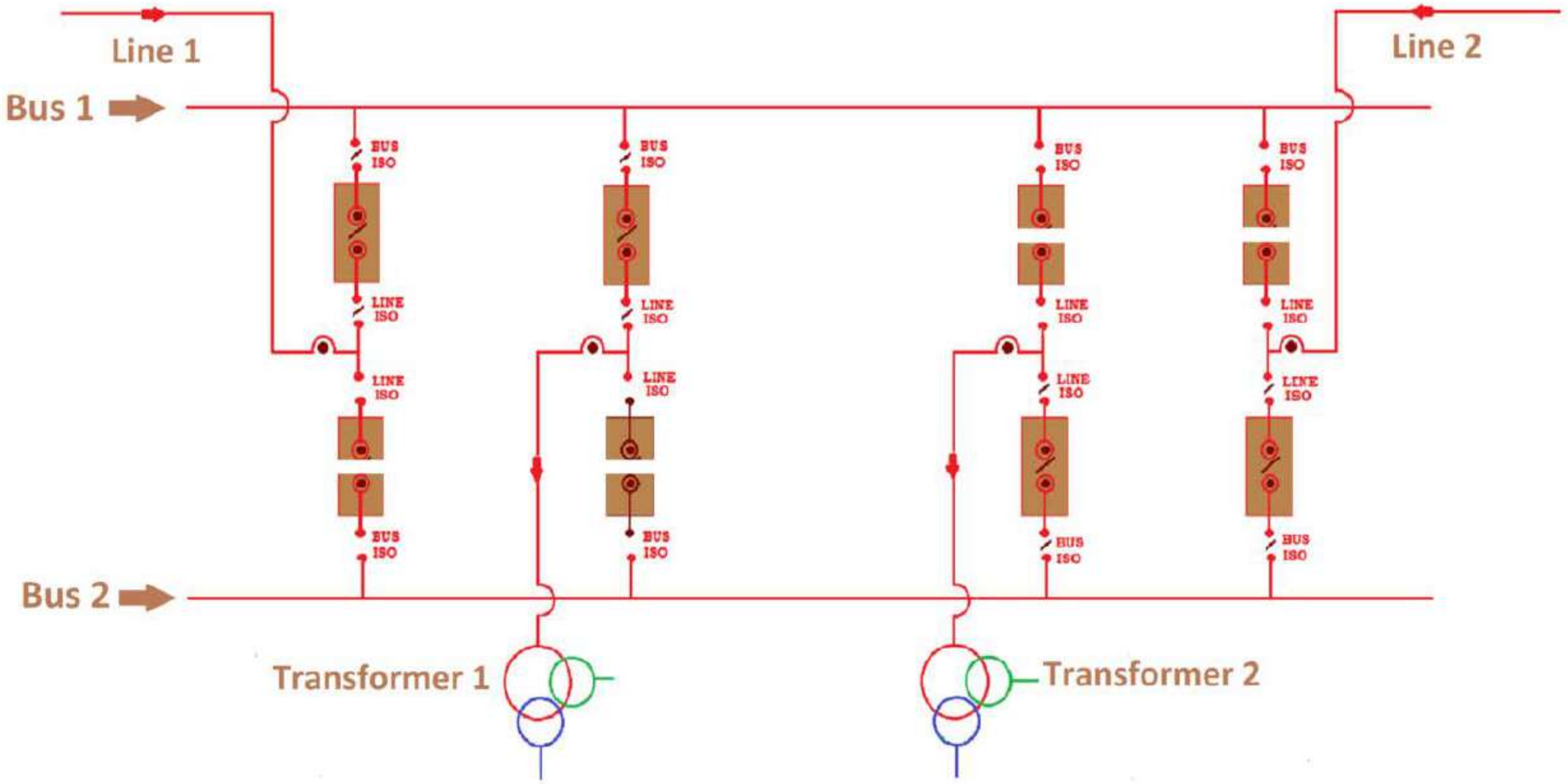
Substation

3. Breaker-and-a-Half Scheme

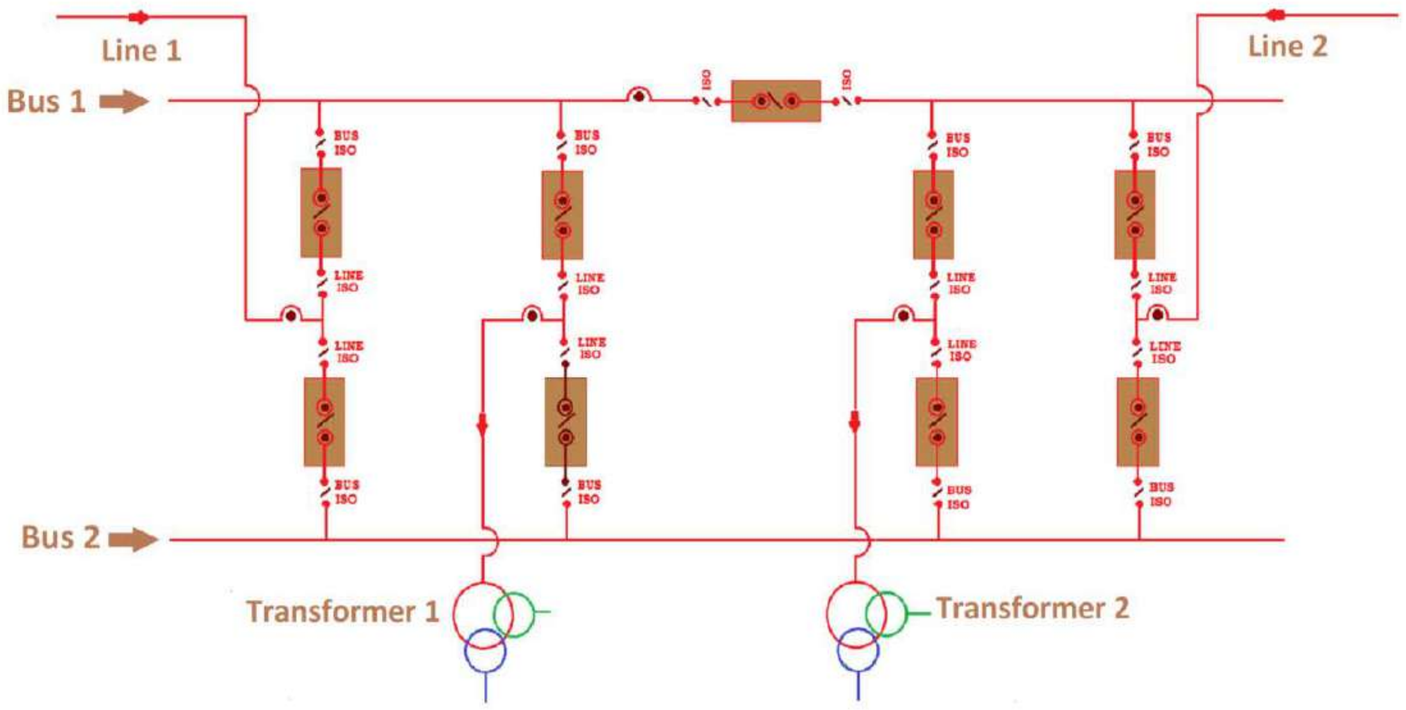
- The breaker-and-a-half scheme is configured with a circuit between two breakers in a three-breaker line-up with two buses; thus, one-and-a-half breakers per circuit.
- This configuration provides for circuit breaker maintenance, since any breaker can be removed from service without interrupting any circuits.
- This scheme provide more reliability for 220 kV, 400 kV and higher kV substations
- **Breaker-and-a-Half Advantages:**
  - Flexible operation and high reliability
  - Isolation of either bus without service disruption
  - Isolation of any breaker for maintenance without service disruption
  - Double feed to each circuit
  - Bus fault does not interrupt service to any circuits
  - All switching is done with circuit breakers

Substation

4. Double Bus Double Breaker



Without Sectionalizer



With Sectionalizer

Substation

4. Double Bus Double Breaker

- Like the breaker-and-a-half, the double breaker-double bus configuration has two main buses that are both normally energized. Here though, each circuit requires two breakers, not one-and-a-half.
- With the addition of the extra breaker per circuit, any of the breakers can fail and only affect one circuit.
- This added reliability comes at the cost of additional breakers, and thus is usually only used at large or sensitive generating stations hence very high cost, 2 breakers per circuit
- **Double Bus Advantages:**
  - Flexible operation and very high reliability
  - Isolation of either bus, or any breaker without disrupting service
  - Double feed to each circuit
  - No interruption of service to any circuit from a bus fault
  - Loss of one circuit per breaker failure
  - All switching with circuit breakers

5. Cost Comparison

Configuration	Relative Cost Comparison
Single Bus	100%
Sectionalized Single Bus	122%
Double Bus Single Breaker	143%
Breaker-and-a-Half	158%
Double Bus Double Breaker	214%

- The comparisons are done with four circuits for each configuration, but do not include costs associated with a power transformer.
- Note that the cost relationships between the configurations may change, depending on the number of circuits used and protective relaying devices that are used.

Substation

6. Transformer sizing to supply at load substations (60 MVA vs 40 MVA)

40 MVA	60 MVA
Load supplied under N-1=36 MVA (90 % loading)	Load supplied under N-1=54 MVA (90 % loading)
Number of consumers	More number of consumers to be fed
Land of substation	Land of substation same as with 40 MVA TFs
Number of substations	Less number of substations to supply same load
Short Circuit Rating of 11 kV Side = 25 kA	Short Circuit Rating of 11 kV Side = 31.5 kA

7. When to choose 2 or 3 Tx

- At planning stage in view of spatial forecast of the zone/area to supply that load in the planning horizon
- Or Leave spare space for 3rd TF at planning stage (usual practice in utilities)

8. Design limits (diversity); how much to go over substation limit

- Depends on % Pre-load condition
- With 50 % Pre-load, TF can overload to 120 % to 150 % for duration specified by manufacturer

Substation

9. Selection of voltage for TX

- 132/11 kV or 66/11 to supply a load of 32 to 64 MVA (2 to 3 TFs of 40 MVA or 54/108 MVA with 60 MVA TFs
- 220/132 kV or 220/66 kV to supply a load of 315, 400 to 630 MVA with 2 or 3 TFS
- 400/220 kV or 400/132 kV to supply a load of 1000-2400MVA with a combination of

  3 or 4 Inter-bus TFs of sizes of 400 MVA, 500 MVA and 800 MVA

10. Sizing and location of shunt reactor

- Shunt reactors for compensation of line charging and mitigate the Ferranti-Effect of 400 kV OHLs/Cables), 220 kV and 132 kV cables are installed at line-ends at terminal substations of these circuits
- Shunt reactors for compensating surplus VARS during light load winter conditions are installed connected to buses as bus-shunt reactors
- Even line-end reactors can behave as bus-shunt reactors by opening of its isolator or if CB controlled

Loads

1. **Industrial:**
   - **Connection criteria**
     - Must comply Power Quality Criteria
     - PF not less than 0.95 at the point of interface with network
     - Must mee its internal reactive power requirements, both static and dynamic internally without overburdening the system to supply excessive VARS from its system
   - **Harmonic share**
     - . Must comply T_{hd} and I_{hd} criteria of IEC and IEEE.
   - **Short Circuit contribution**
     - If it has captive generation, then short circuit current contributions for 3-Ph and SLG must not increase the levels specified for that location such that SC ratings of switchgear of substations should not violate their ratings

Loads

- **Dynamic behavior**
  - No motor stalling under dynamic disturbances (3-Ph, L-L-G) or SLG at network
  - All dynamic reactive power requirements to be met internally by SVC or STATCOM
- **Load Type considerations**
  - Aluminum factory
    - Smelting process causes flicker, harmonics, voltage dip and voltage unbalance
    - Must have an SVC or STATCOM of adequate size to limit all PQ issues to be contained within the plant. No emission of these PQ problems into system.
  - Steel factory
    - Same issues due to smelting to be addressed as above for Aluminum factory

Loads

- Oil & Gas
  - Large and small motors used for pumping and drilling
  - No motor stalling under dynamic disturbances (3-Ph, L-L-G) or SLG at network
  - All dynamic reactive power requirements to be met internally by SVC or STATCOM

2. **Domestic:**
   - Connection Criteria
     - Bulk Customer supplied at Transmission Level Voltages (220 kV, 132 kV or 66 kV
     - Internal distribution network planned and designed complying Transmission Grid Code
     - Load demand in the application to be based on realistic KW/household, MW/Shopping Mall etc. as per Distribution Code.
     - Nature of load to be clearly mentioned in application i.e. how much motor load and maximum size of motor (1-phase and / or 3-phase)

Inverter Based Loads/Data Centers

- They range from
  - hyperscale facilities operated by tech giants, like Meta's planned 2 GW AI training facility in Louisiana,
  - to smaller data centers that serve multiple enterprises.
- Some data center loads are known to have pulsed and non-linear characteristics, giving them extremely quick ramping potential that can introduce power quality and stability issues.
- Cryptocurrency mines are generally not classified as data centers though much of their makeup is similar.
- Cryptocurrency mines may have different types of IT equipment compared to traditional and AI data centers, they may not prioritize uptime as much as a traditional data center
- Four main components in data centers:
  - IT-related equipment: consists of servers, storage, networking gear driven by power electronics
  - Power delivery systems control and distribute power in the facility
  - Cooling systems
  - Miscellaneous

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Thank you

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General Principle and Recent Trends of Power System: Transmission Planning for Power Evacuation from a Plant (Day 1.1 B)

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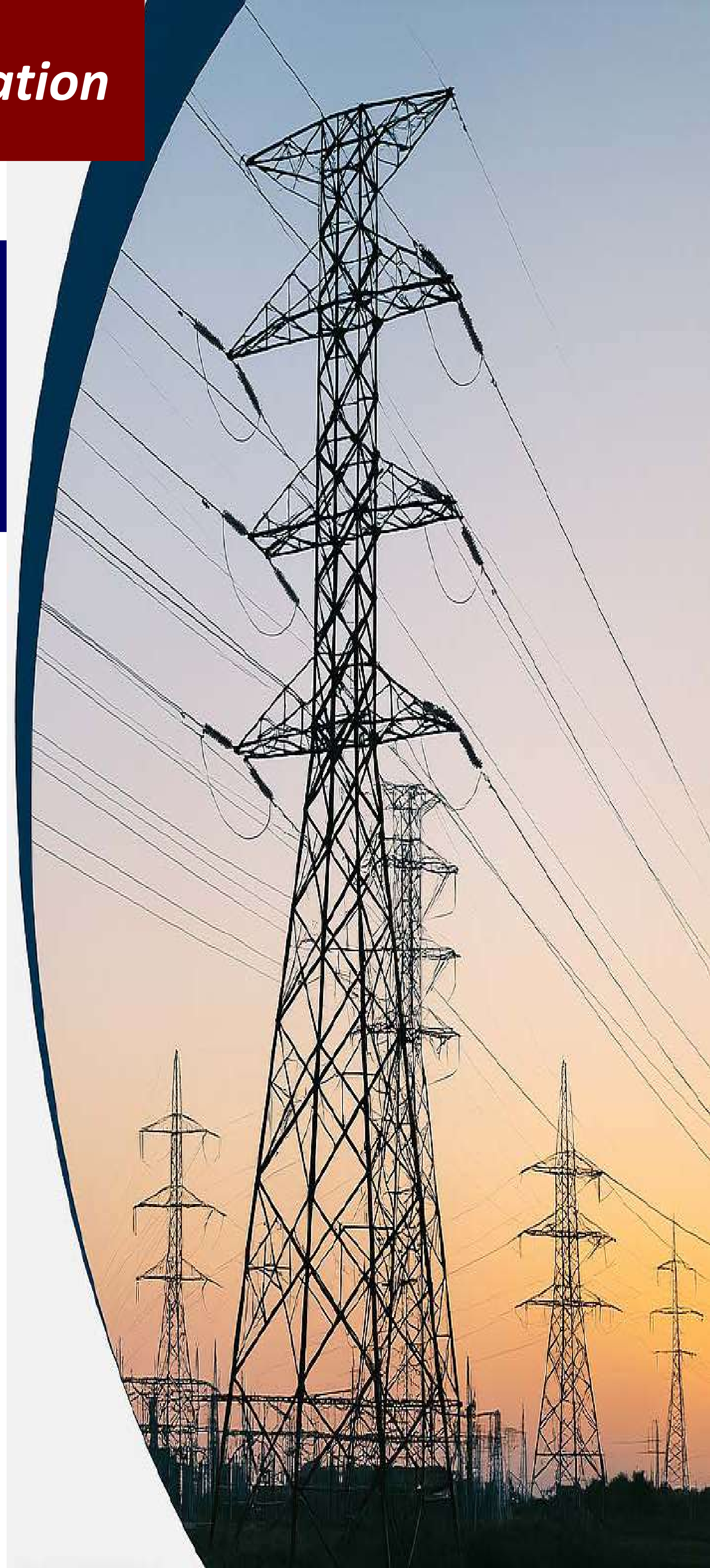

Agenda

1. General Considerations
2. Steady State Considerations
   a. (Power Flow)
   b. Ferranti Effect & Sizing of Reactors
   c. Theoretical Transfer Limit (PV Curve)
3. Impact of Power Plant Interconnection
   a. Short Circuit Analysis
   b. Dynamic Stability
   c. System Wide Stability Considerations

General Considerations

START

Site Visit and Gathering of Data

- Size/Capacity (MW)
- Nature (Conventional or Renewable)
- Location

Selection of Transmission Evacuation Voltage

- Size/Capacity of Power Plant
- Distance from Load Centre
- Availability of nearby voltage network, available capacity & whether conducive to size of plant

Selection of Technology and Type of Transmission

- Overhead Line/Underground Cable
- **HVAC** (medium power and medium distance) or **HVDC** (high power & high distance)
- Technically and Economically most feasible

END

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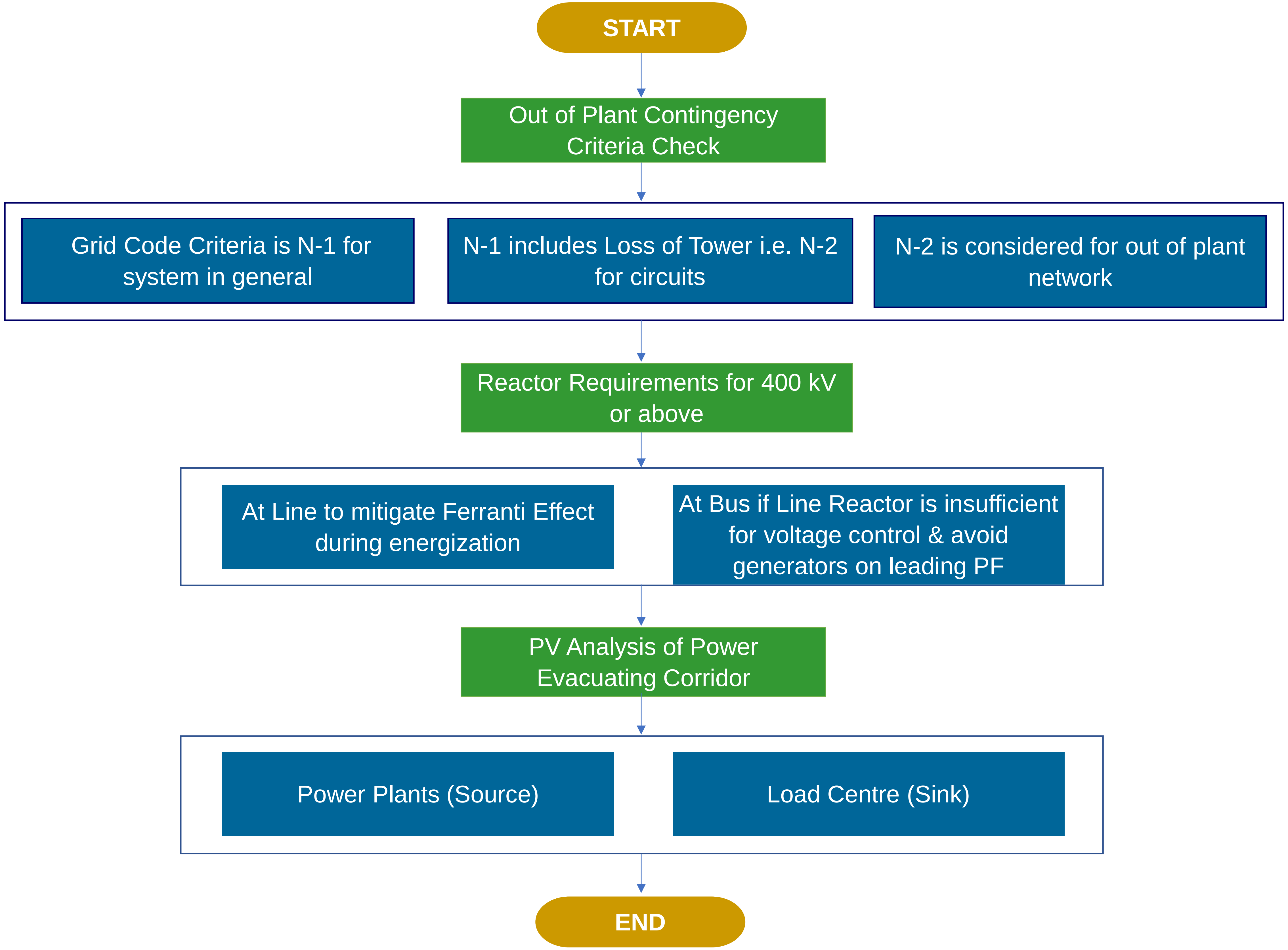
General Considerations

- **Size/Capacity (MW)**
- **Nature:**
  - Conventional (Steam, CC, OC, Hydro etc.)
  - Renewable (Wind or PV/CSP Solar)
- **Location**
- **Selection of Transmission Evacuation Voltage**
  - Depends on
    - Size/Capacity
    - Distance from Load Center
    - Availability of existing nearby voltage network, if conducive to size of plant and available spare capacity in that network

General Considerations

- **Technology and Type of Transmission**
  - **Overhead Line / Underground Cable**
    - Depends on
      - Location and area through which the line will cross through:
        - Near or Away from Load Center
        - Right of Way through plain unpopulated lands or populated areas
  - **HVAC/ HVDC**
    - Depends on
      - Amount of power to be evacuated
      - Distance for power to be transferred
      - HVAC with Series Compensation (Fixed or Dynamic TCSC)
      - HVDC is a good option if power is high (2000 MW and above) and distance to transfer is above 500-600 km.
- **Alternatives of Interconnection**
  - Technically Most Feasible
  - Economically Most Feasible

Steady State Considerations
(Power Flow)



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Steady State Considerations (Power Flow)

- **Out of Plant Contingency Criteria**
  - Qatar Grid Code Criteria is N-1 for system in general
  - N-1 includes Loss of Tower i.e., N-2 for circuits
  - N-2 to be considered for Out Of Plant network
- **Reactor Requirements if Evacuation Voltage is 400 kV or above OHL or EHV/HV Cables**
  - At Line to mitigate Ferranti Effect during energization
  - At Bus, if Line Reactor is insufficient for voltage control and avoid generators to run on leading PF
- **PV Analysis of Power Evacuating Corridor**
  - Power Plant/s (Source)
  - Load Center (Sink)

Steady State Considerations
(Power Flow)

Simplified power transfer equations:

- **Active Power:**

$$P_S = \frac{V_S \times V_R}{X_L} \sin \delta$$

- **Reactive Power:**

$$Q_S = \left[\frac{V_S^2 - V_S V_R \cos \delta}{X_L} \right] - \frac{V_S^2}{X_C}$$

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Steady State Considerations
(Power Flow)

- **Path impedance**
  - As the "X_L" of a path is increased, the reactive power usage of the path increase (greater I^2X_L) and the reactive power transfer across the path decreases
- **Power angle (δ)**
  - When the power angles are this small the cosine of δ is close to one.
  - The result is that while MW flow is strongly impacted by power angles, MVAR flow is typically weakly impacted
- **System equipment**
  - When voltage control equipment such as capacitors, reactors, or tap changing transformers are used to adjust voltage this equipment is actually controlling the flow of reactive power

Steady State Considerations
(Power Flow)

- **Reactive sources and loads**
  - Reactive power is closely related to system voltage levels
  - When voltage level needs to be increased, reactive supply also increased.
  - Generators may produce more reactive power or shunt capacitor may be placed in-service
- **Voltage magnitude**
  - Reactive power flow is strongly tied to voltage magnitude
  - When a generator is asked to increase its terminal voltage, it does so by increasing its DC excitation current
  - This increase the generator internal excitation voltage
  - The higher internal voltage of the generator leads more MVAR flowing out of unit
- **Transmission line charging**
  - Transmission line provide reactive power to the system during light loading
  - Transmission line absorb reactive power from the system during heavy loading
  - The amount of reactive power a transmission line provides to the system is related to the line voltage. The greater the voltage, the more MVAR the line will supply

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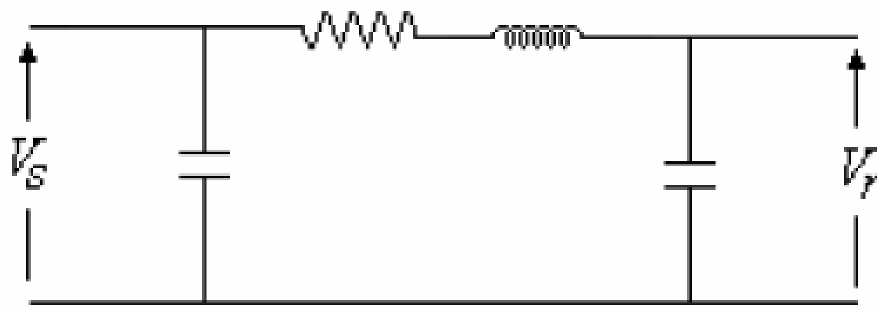
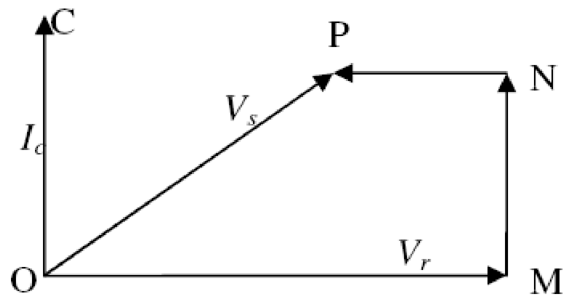
Steady State Considerations
Ferranti Effect & Sizing of Reactors

- **Ferranti Effect & Sizing of Reactors**
  - Rise in voltage at the receiving end of an open circuit is due to the flow of charging current through line inductance.
  - This is known as Ferranti Effect and is due to the voltage drop across the line inductance (due to charging current) being in phase with the sending end voltages. Therefore both capacitance and inductance is responsible to produce this phenomenon.
  - Capacitance (and charging current) is low in short line but significant in medium line and appreciable in long line. Therefore, this phenomenon occurs in medium and long lines.
  - Line capacitance is assumed to be concentrated at the receiving open end.
  - *Ferranti Effect for same value of charging as of a long line, but for cable the same charging will not cause that level of Ferranti Effect as for line.*
  - *Total Reactor Sizes at both ends should not be more than 80 % of Total Line Charging*
  - *Additional compensation for voltage control to be placed as Bus-Reactor*

Steady State Considerations
Ferranti Effect & Sizing of Reactors (Contd.)

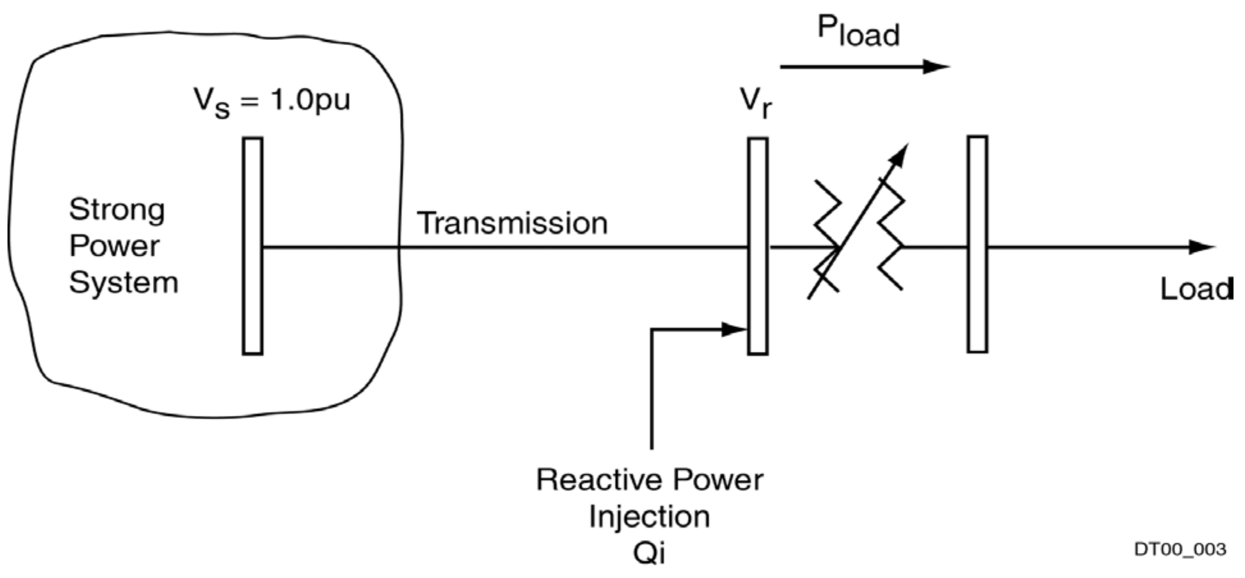


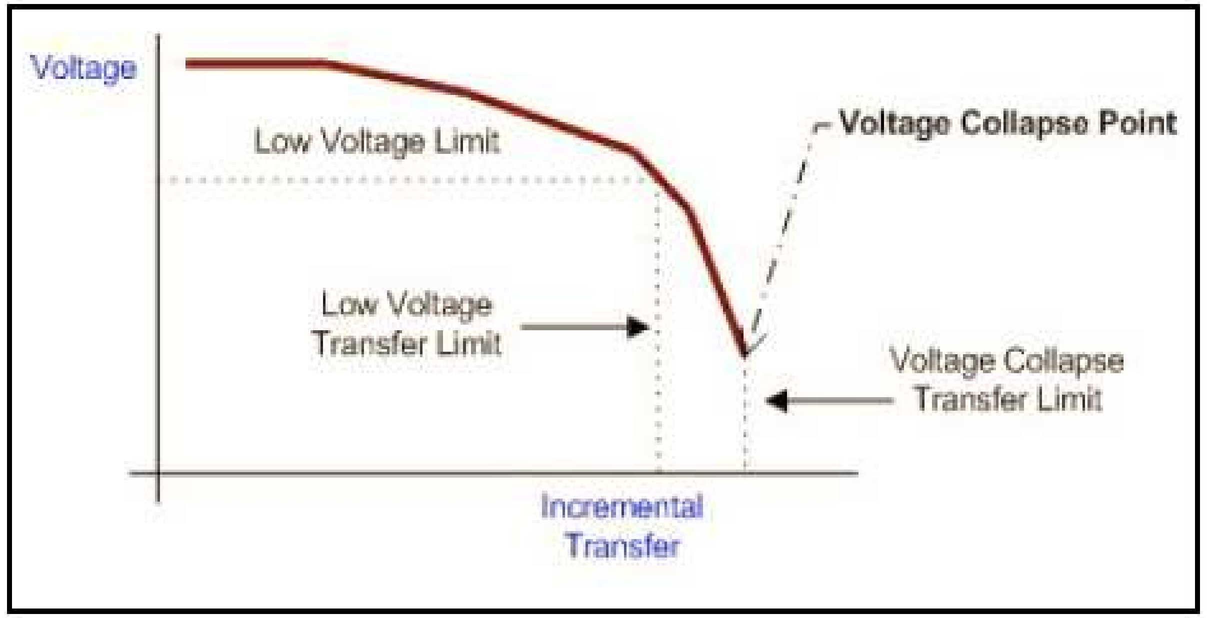


- OM = receiving end voltage Vr
- OC = Current drawn by capacitance = Ic
- MN = Resistance drop
- NP = Inductive reactance drop (Rise in voltage)
- OP = Sending end voltage at no load and is less than receiving end voltage (Vr)
- Since, resistance is small compared to reactance; resistance can be neglected For cables Inductance is also small compared to capacitance, Inductive drop (rise) also negligible
- In Pre-Energization case, sending-end source side (power plant) and receiving end may be two islands with no common swing bus.
- Converted Case of power flow with TYSL solution techniques to be used for switching study
- EMT Studies to validate sizes of Reactors fulfilling switching criteria.

Steady State Considerations
Theoretical Transfer Limit (PV Curve)

- Theoretical Transfer Limit is evaluated by PV Analysis (Available in PSS/E Solutions
- Define sending end side as a "Source" subsystem and receiving side as "sink"
- Voltage instability occurs at the knee point of the PV curve where the voltage drops rapidly with an increase in the transfer power flow
- The power flow solution will not converge beyond this limit, indicating voltage instability
- Operation at or near the stability limit is impractical and a satisfactory operating condition must be ensured to prevent voltage collapse





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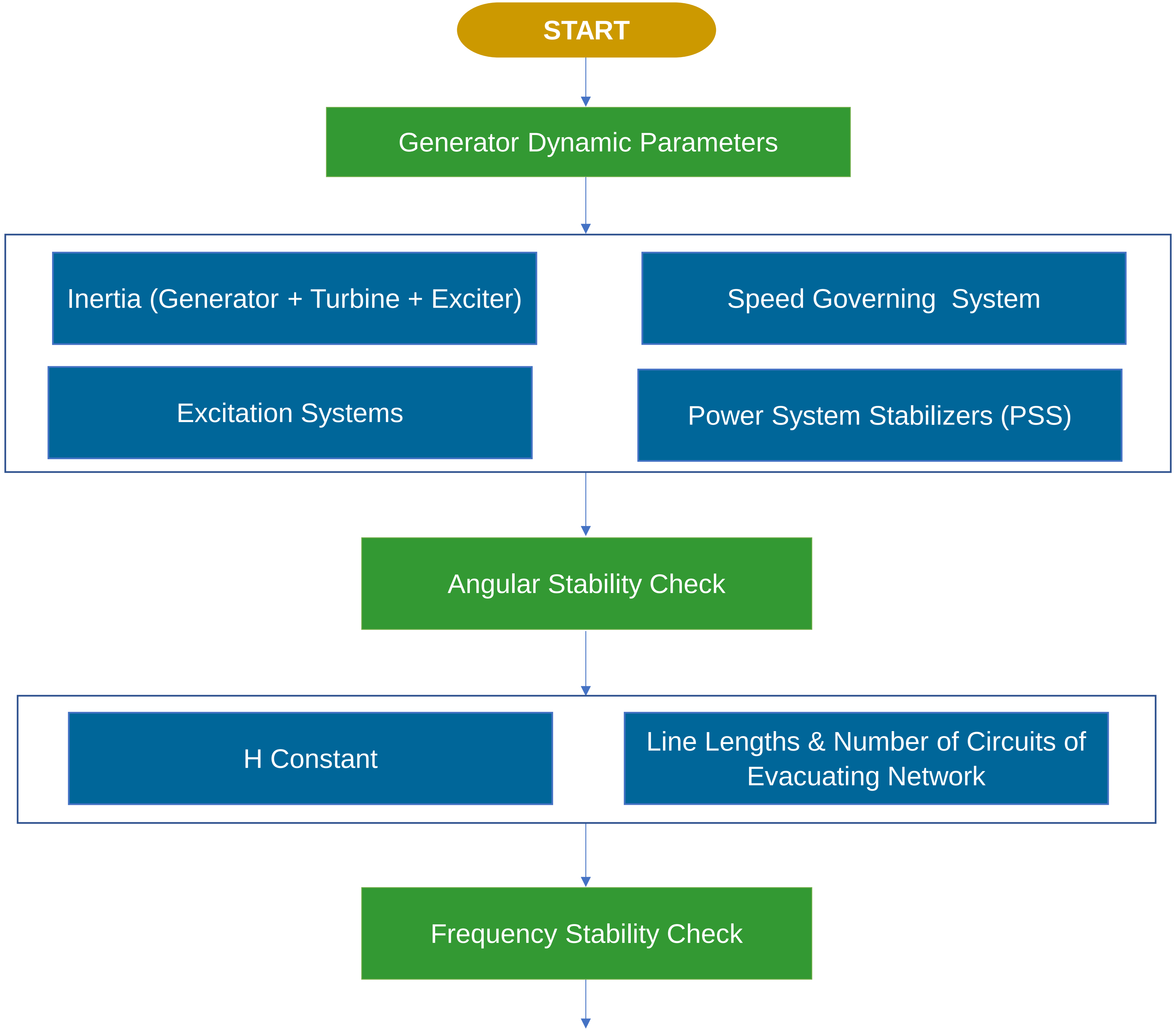
Impact of Power Plant Interconnection
Fault Levels

- Determination of Fault Current contributions from the power plant to the system (SLG and 3-Phase)
- Determination of Total Fault Levels (SLG and 3-Phase) Symmetrical and Asymmetrical (combined from the plant and the system)
- Specifications of Circuit Breakers duty and other equipment of power plant substation t based on these fault levels
- A specific margin is also considered over and above the calculated Fault Levels for specifying the switchgear rating of the power plant substation.
- Typical ratings of switchgear of high-power plants is 40 kA, 50 kA and 63 kA. (At places of high accumulation of power generation, it is reaching to 80 kA now)

Power Plant Interconnection
Dynamic Stability



Power Plant Interconnection
Dynamic Stability

RoCoF depends on H Constant & Primary Reserve/Governor Action and Size of LUR

Settling Frequency depends on Primary/Secondary Reserve

If instability, then UFLS to operate in stages

↓

Synchronizing Torque Check

↓

H Constant

If inadequate, it leads to first swing instability

↓

Damping Torque Check

↓

Controllers of Generators, i.e. Exciter, Governor, PSS

Line Loading and Line Length out of Power Plant

If inadequate, it leads to oscillatory instability and poor damping

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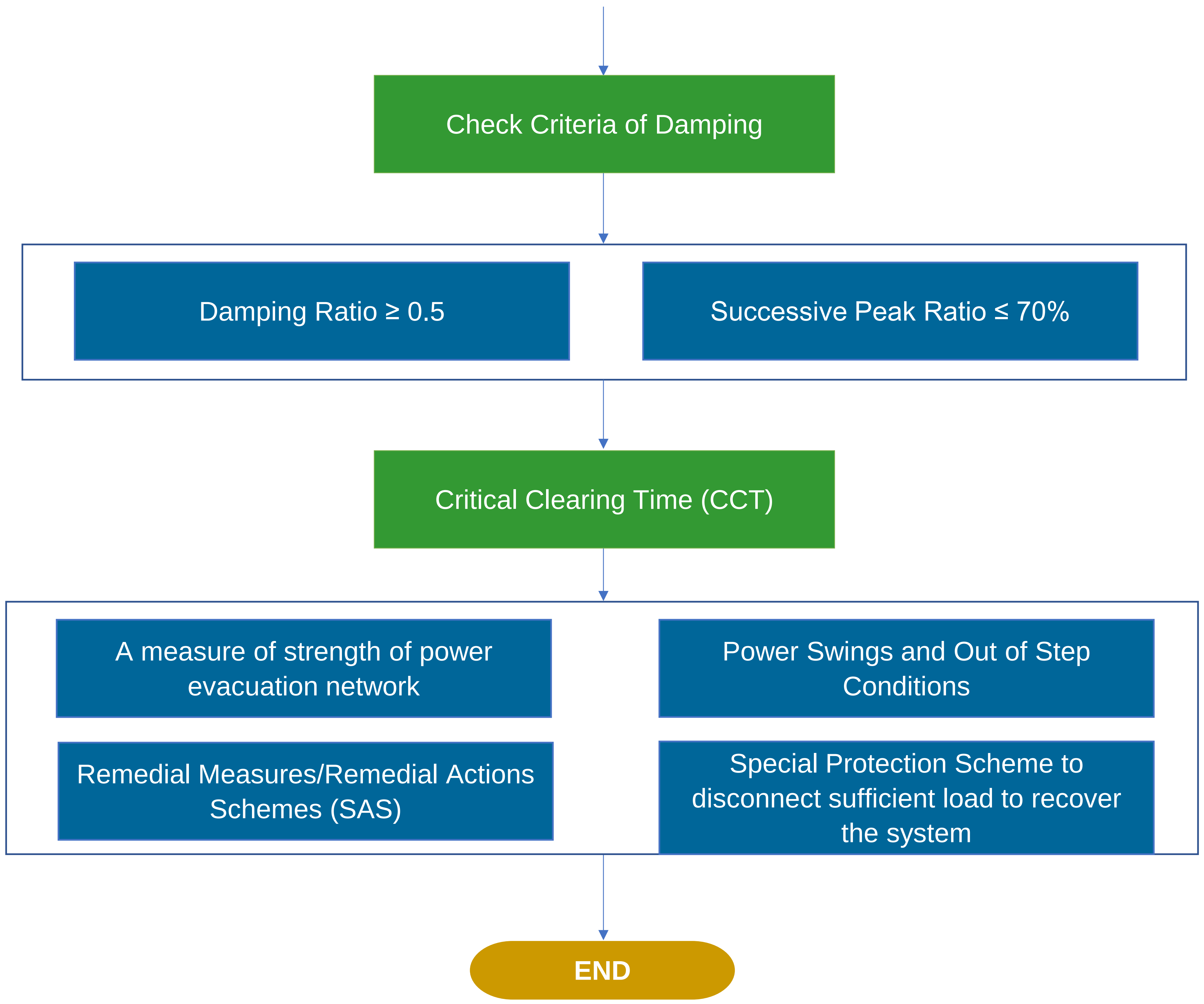
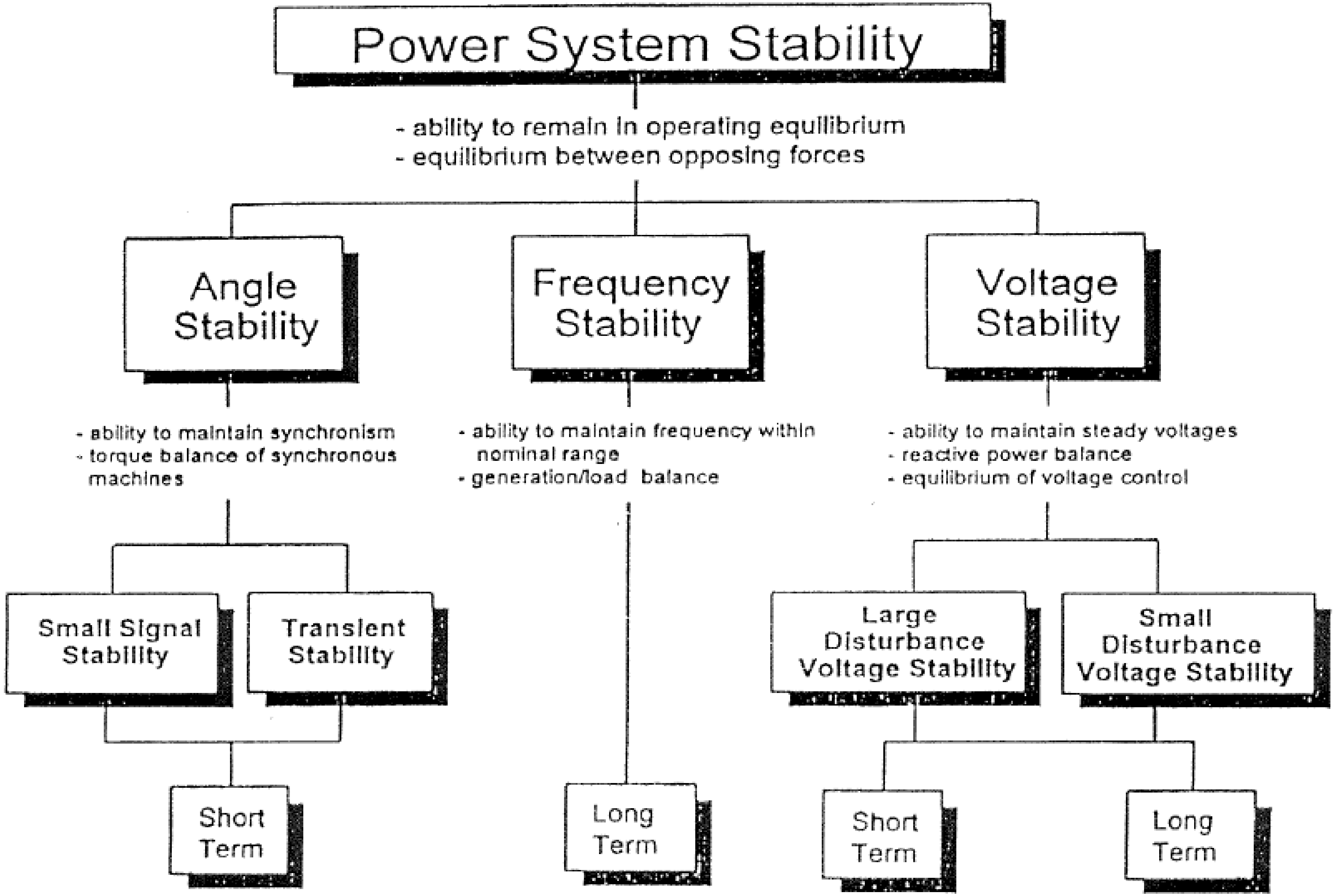
Power Plant Interconnection
Dynamic Stability



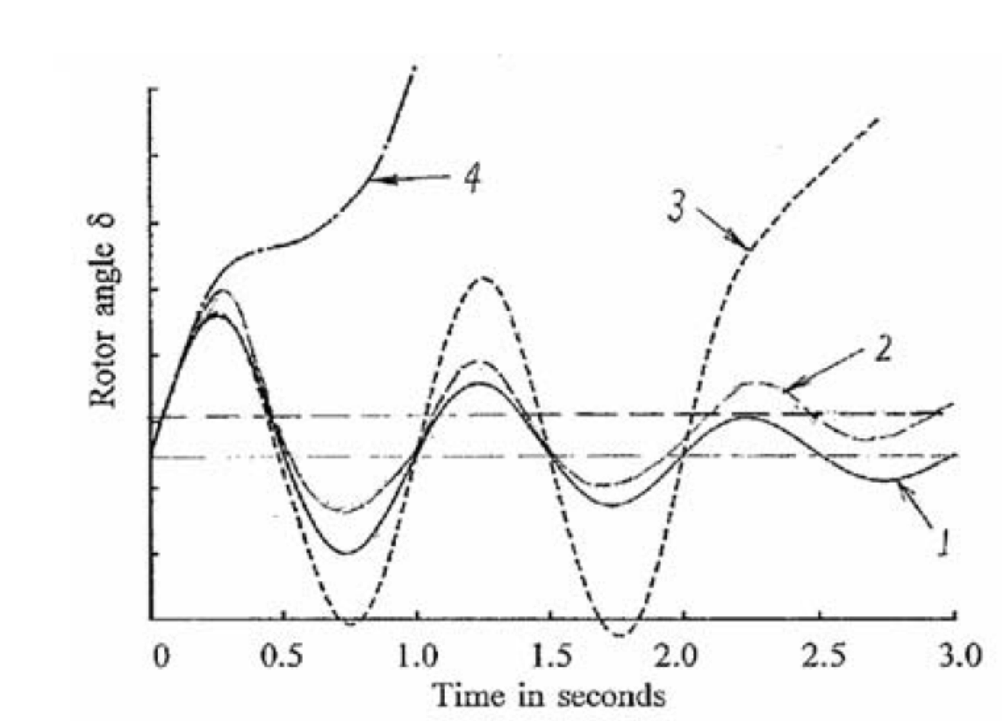
Power Plant Interconnection
Dynamic Stability



Power Plant Interconnection
Dynamic Stability

- **Transient Stability**
  - **Angular Stability (Rotor Angle Stability)**
- **Depends on**
  - H Constant
  - Line Lengths &

  Number of Circuits of Evacuating Network
  - Case 1 – Steady state stable
  - Case 2 – Transient stable
  - Case 3 – Small signal unstable
  - Case 4 – First swing unstable



- Instability that may result can be of two forms:
  - Aperiodic increase in rotor angle due to lack of sufficient **synchronizing torque**
  - Periodic rotor oscillations of increasing amplitude due to lack of sufficient **damping torque**
- Generally occurs when two large areas or networks have “weak”/high impedance interconnections

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Power Plant Interconnection
Dynamic Stability

- **Adequate Synchronizing Torque**
  - Depends on H constant
  - If inadequate → Lead to First Swing Instability
- **Adequate Damping Torque**
  - Depends on
    - Controllers of Generators i.e. Exciter, Governor, PSS
    - Line Loading and Line length out of power plant
  - If inadequate → Lead to Oscillatory instability → Poor Damping
- **Criteria of Damping**
  - Damping Ratio ≥ 0.5
  - Successive Peak Ratio (SPR) ≤ 70 %
- **Critical Clearing Time (CCT)**
  - Maximum clearing time after which system gets unstable
  - A Measure of Strength of Power Evacuating Network
    - Number of lines emanating from power plant
    - H constant

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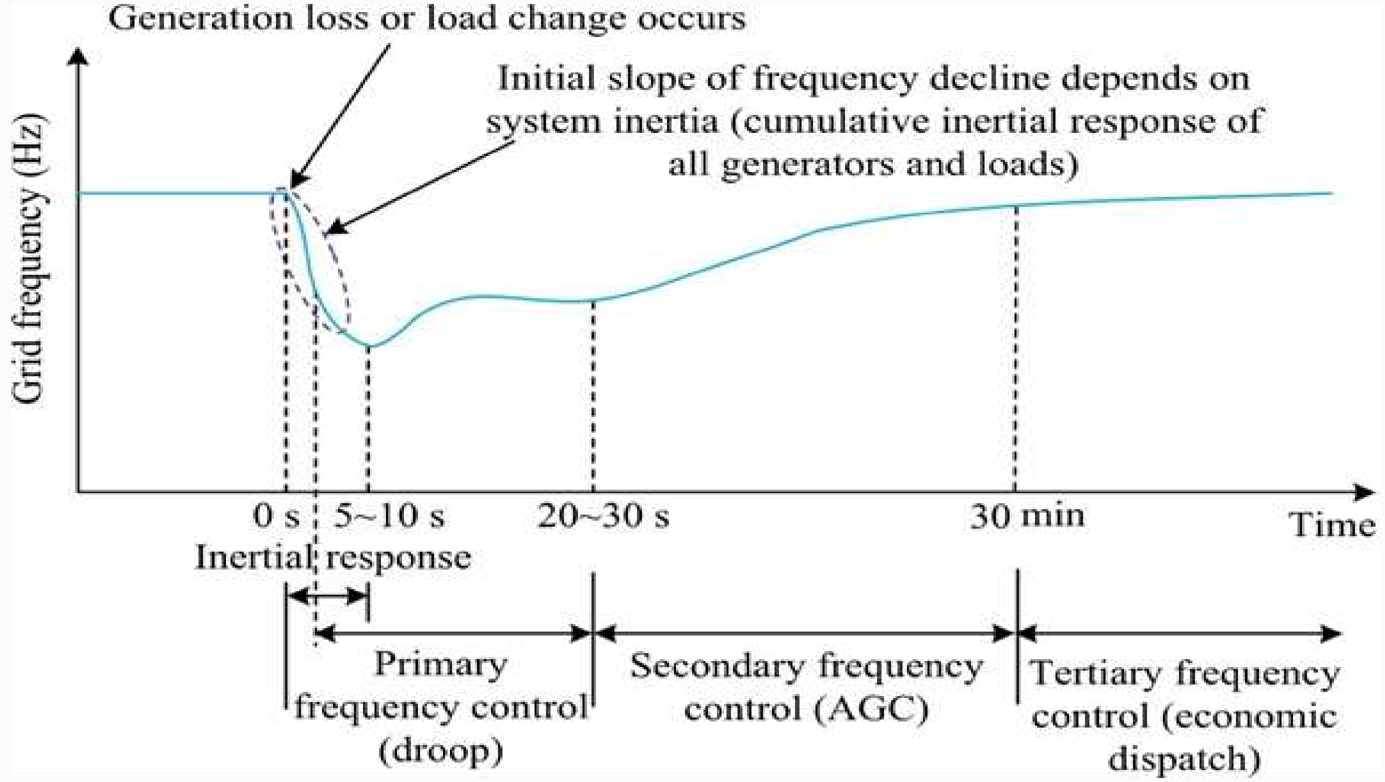
Power Plant Interconnection
Dynamic Stability

- **Frequency Stability**

$$RoCoF = \frac{\Delta P_{imbalance}}{Pload} \cdot \frac{fo}{2\,Hsys}$$



- **RoCoF depends on System Equivalent Inertia**
  - The international benchmarking shows 0.5 Hz/s or more except for UK where it is 0.125-1 Hz/s.
- **Settling Frequency depends on Primary/Secondary Reserve**
- **If instability then UFLS to operate in stages**

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System Wide Stability Considerations

- **Power Swings and Out of Step Conditions**
  - Excessive Power Flow in a Dynamic Contingency (N-1) or (N-2) may result in Power Swings
  - Out of Step Relays to be planned to installed at such power corridors
- **Remedial Measures / Remedial Action Schemes (RAS)**
  - Special Protection Scheme to disconnect sufficient load or generation to recover the system from an eventuality leading to blackout
  - Cross Trip Schemes
- **Interarea Oscillations**

- Interarea oscillatory modes may e present in a longitudinal system
- Range 0.2HZ to 0.7 Hz
- Power System Stabilizers (PSS) to be installed at generators having Large Participtaion Factors detected in Model Analysis (Small Signal Stability Analysis)

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Thank you

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Capacity Building on Advance & Innovative Transmission System Design and Optimization

General Principle and Recent Trends of Power System: Transmission Planning for Supply to Load Centers (Day 1.1 C)

By

Hassan Jafar Zaidi

CEO, Power Planners International, Pakistan

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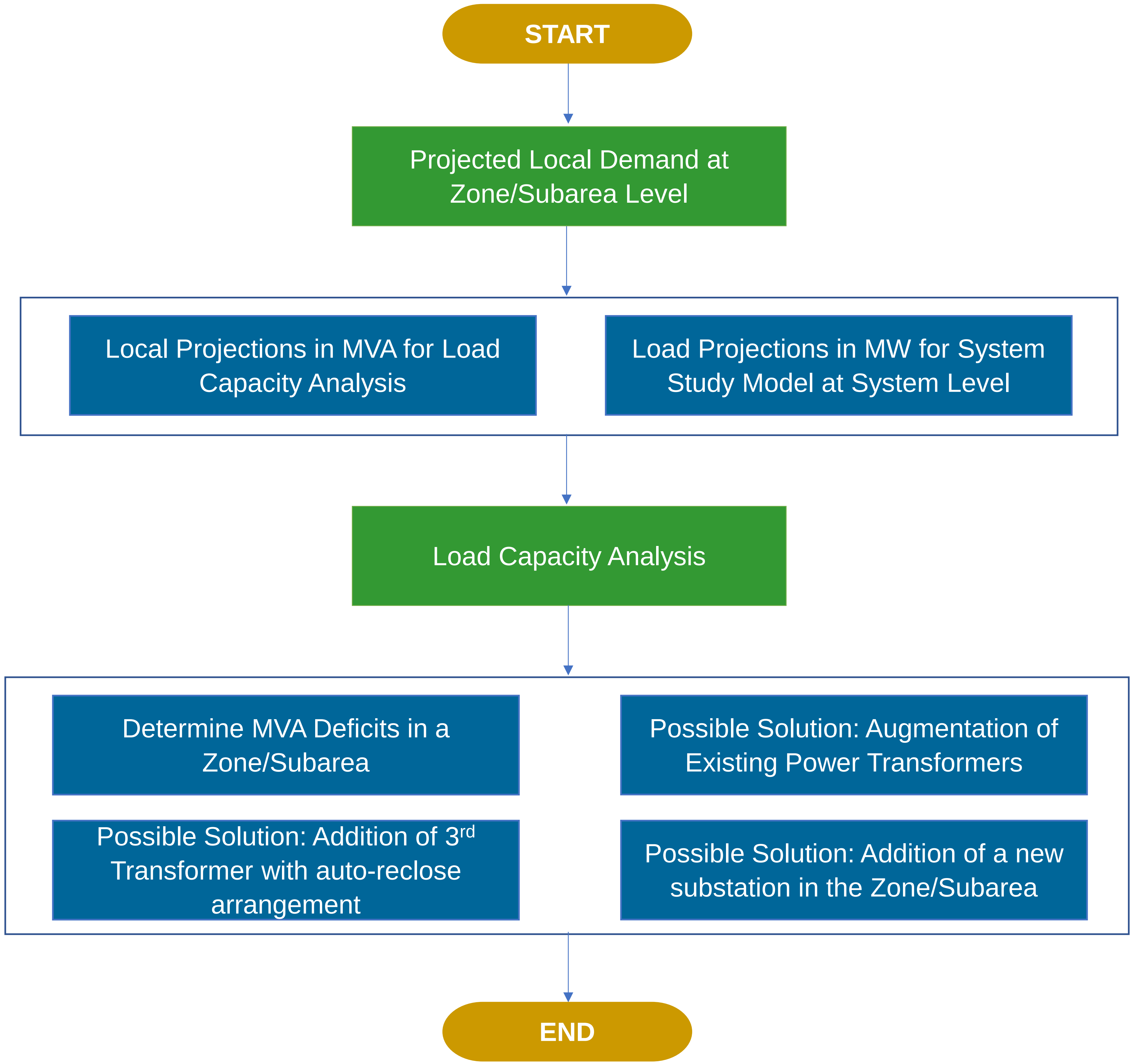
Under SAARC Energy Center
14th-16th October 2025 Thimphu, Bhutan

Agenda

1. Load Demand: Spatial Demand Forecast
2. Steady State Analysis
3. Steady State Requirements of Reactive Power Compensation
4. Fault Levels of Load Substations
5. Dynamic Stability Analysis: Voltage Stability Issues
6. Steady State & Dynamic Needs of Industrial Loads

Load Demand: Spatial Demand Forecast



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Load Demand: Spatial Demand Forecast

- **Determine the projected local demand at Zones/Subarea Level**
  - Local Projections in MVA for Load Capacity Analysis
  - Load Projections in MW for System Study Model at System Level
- **Load Capacity Analysis**
  - Determine MVA Deficits in a Zone/Subarea
  - Plan adding additional MVA capacity in that Zone by
    - Augmenting Existing Power Transformers capacity, say from 40 MVA to 67 MVA or so
    - By adding a 3rd Transformer with auto-reclose arrangement with parallel transformers
    - Adding a new substation in that Zone/Subarea

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Steady State Analysis

START

Develop the Network Model for Ultimate Year of Planning Period

Update the PSS/E Model by representing diversified loads at load buses

Develop alternative schemes of interconnection for newly proposed substations at 66 kV and 132 kV

Update the PSS/E model for each alternative scheme

Update generation dispatch with additional plants to meet the load for ultimate year of study

Run Power Flow simulations for each alternative for normal and contingency conditions

Identify reinforcements at 66 kV, 132 kV, 220 kV and 400 kV due to additional supply from EHV network

END

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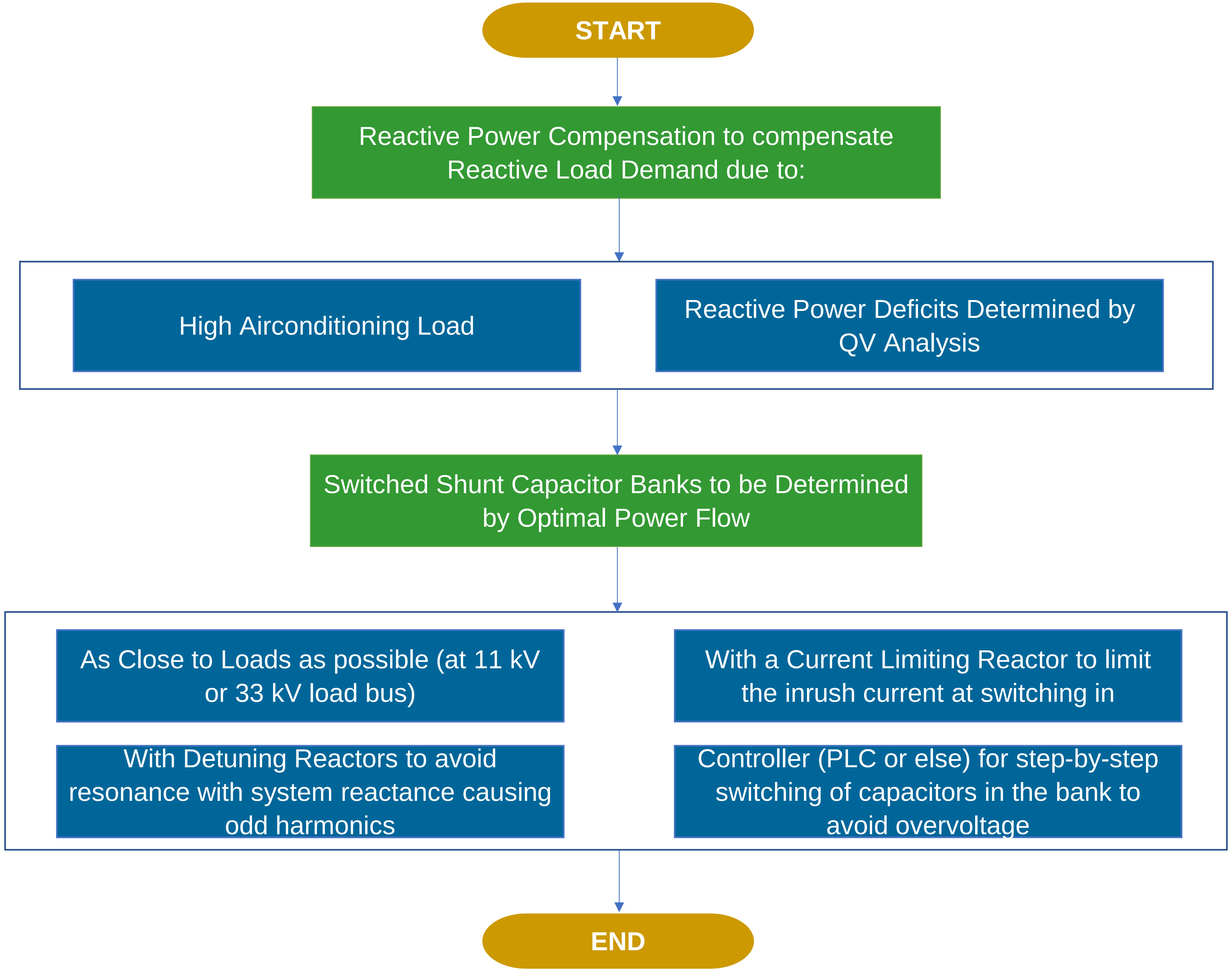
Steady State Analysis

- **Develop the Network Model for Ultimate Year of Planning Period (say 2030)**
  - Update the PSS/E Model by representing the diversified loads at load buses
  - Develop alternative schemes of interconnection for newly proposed substations at subtransmission level of 66 kV and 132 kV.
  - Update PSS/E Model for each alternative scheme
  - Update generation dispatch with additional plants (if any) with their interconnection scheme to meet the load (+loss) for the ultimate year of study
  - Run Power Flow simulations for each alternative for normal and contingency conditions.
  - Identify reinforcements not only at 66, 132 kV but also at 220 and 400 kV due to additional supply from EHV network**.**
  - **Develop the Network Model for Intermediate Years of Planning Period (say 2027) by reverting back from the ultimate year and perform same steady state analysis**
- **Perform Automatic AC Contingency Calculations (ACCC)**
  - For N-1
  - For N-2 for special cases (No Islanding Cases)
  - **Propose Reinforcements for N-1**
  - **Propose Reinforcement for N-2 for EHV network (400 kV) if required**
  - **Propose Operational Measures for N-2 for 220/132/66 kV network if required**

Reactive Power Compensation
Steady State Requirements



Reactive Power Compensation
Steady State Requirements

- **RPC to compensate Reactive Load Demand**
  - High Reactive Load Demand due to
    - High A/C Load (Domestic and Commercial)
    - Motor Load (Industrial)
- **QV Analysis**
  - Identify local deficits of reactive power (Zone or Subarea level)
- **Switched Shunt Capacitor Banks to be installed**
  - Optimal Power Flow (OPF) for optimal sizes and locations
  - As Close to Loads as possible (at 11 kV or 33 kV load bus)
  - With a Current Limiting Reactor to limit the Inrush current at switching IN.
  - With Detuning Reactors to avoid Parallel/Series Resonance with system reactance causing Odd Harmonics.
  - Controller (PLC or else) for step by step switching of capacitors in the Bank to avoid overvoltage due to Back-to-Back switching in a row.

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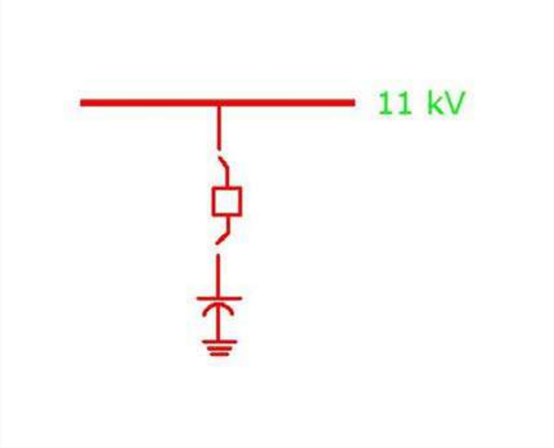
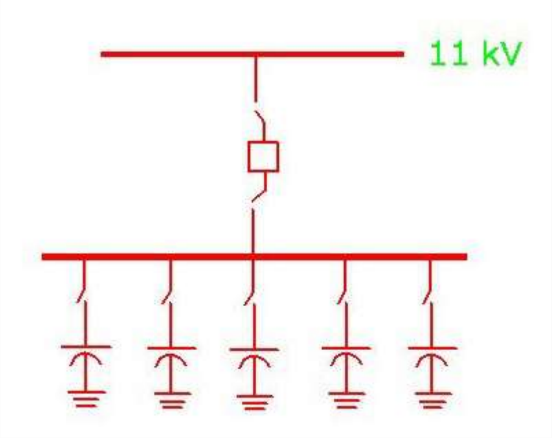
Reactive Power Compensation
Steady State Requirements

- **Switched Shunt Capacitor Banks**
  - Issues of Fixed Capacitor resolved by Switched Shunts

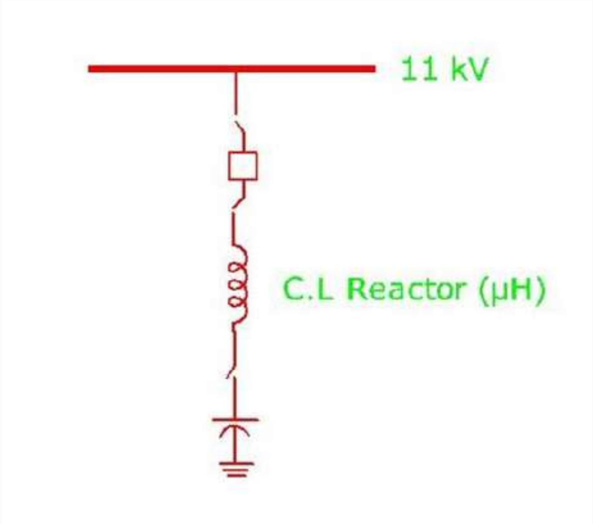


Fixed Capacitor

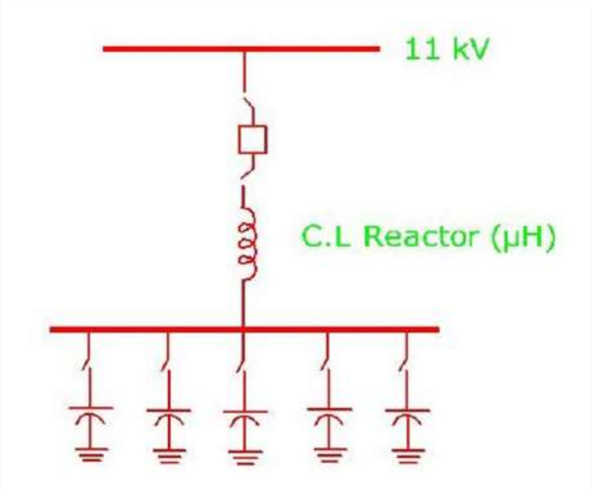


Switched Shunt Capacitor Bank

  - Issues of Inrush Current and Resonance



Capacitor Bank With CLR



Switched Shunt Capacitor Bank with Detuning Reactor

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Fault Levels of Load Substations

START

Evaluate Fault Levels (Symmetrical and Asymmetrical)

- R/X ratio is high due to highly meshed network of Doha
- DC component is high and its decay is low due to highly meshed cable network of Doha
- Asymmetrical value is high due to highly meshed network of Doha
- SLG fault levels are high due to concentrated generation in Doha

Remedial Measures to be studied

- CLR for 3-Phase Faults
- NGR for SLG Faults

END

Short Circuit Analysis

- **Fault Levels decides switchgear ratings of bus equipment**
  - Primary side
  - Secondary Side
  - Load side (11 kV)
- **Remedial Measures**
  - Impedance of 132/11 kV or 66/11 k **Primary side** transformers
  - Parallel operation of transformers or individual with a sectionalizer, Normally Open (manual or auto-reclose)
  - NGR at secondary side or MV (11 kV) side if SLG levels are high.

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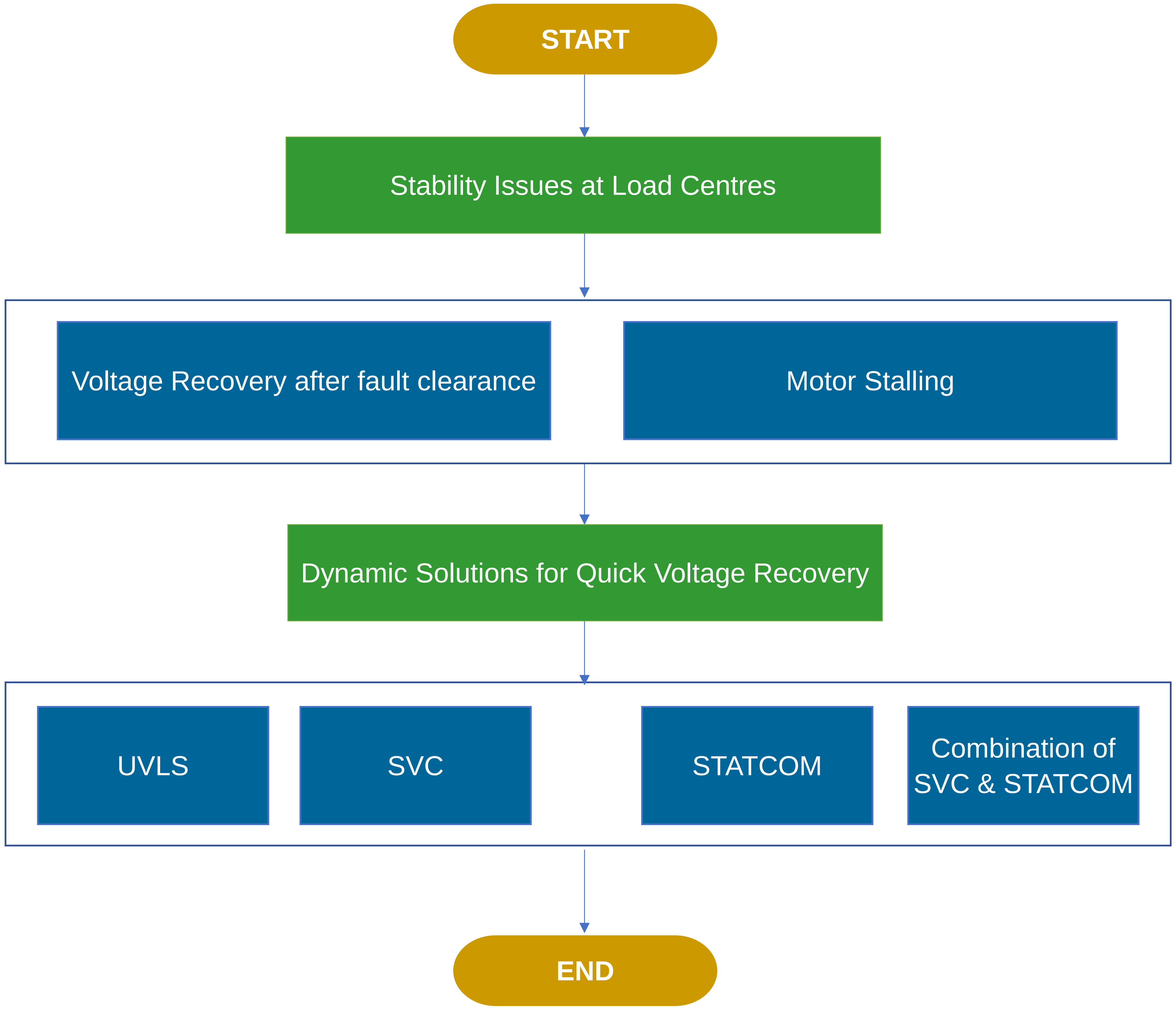
Dynamic Stability Analysis
(Voltage Stability Issues)



Dynamic Stability Analysis
(Voltage Stability Issues)

- **Issues At Load Centers**
  - Voltage Recovery after fault clearance
  - Motor stalling
- **Can Shunt Capacitors help**
  - No. Because VAR Output is reduced under voltage sag/dip

$$MVAR = \frac{kV^2}{Xc}$$

  - When the voltage dips to say 70 % (0.7 PU), the output of capacitor bank will reduce to nearly 49 % (i.e. $0.7^2 = 0.49$)
  - **Reacceleration Torque of Motors:**
  - When an induction motor is first started (or has stalled and is rebuilding speed) it may draw 5 to 8 times its normal MVAR to build magnetic field.
  - The in-rush of MVAR to return the motors to rated speed may be enough to trigger a transient voltage collapse.

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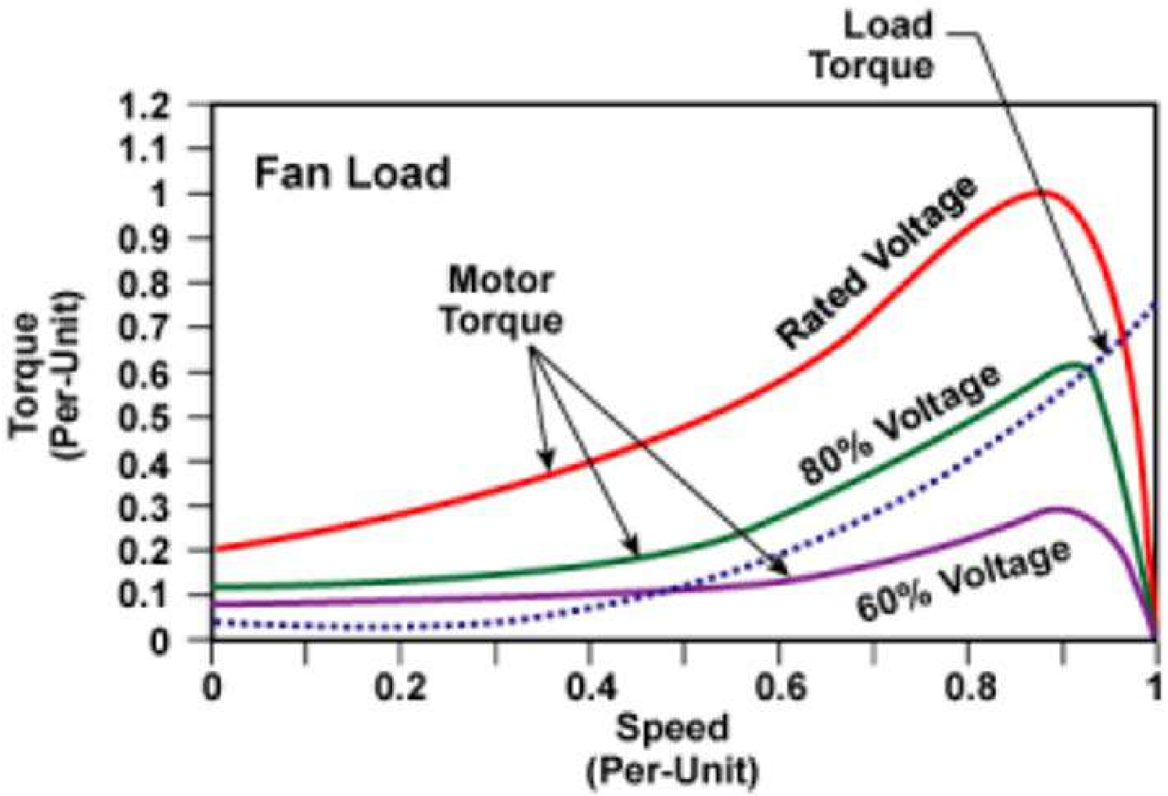
Dynamic Stability Analysis
(Voltage Stability Issues)

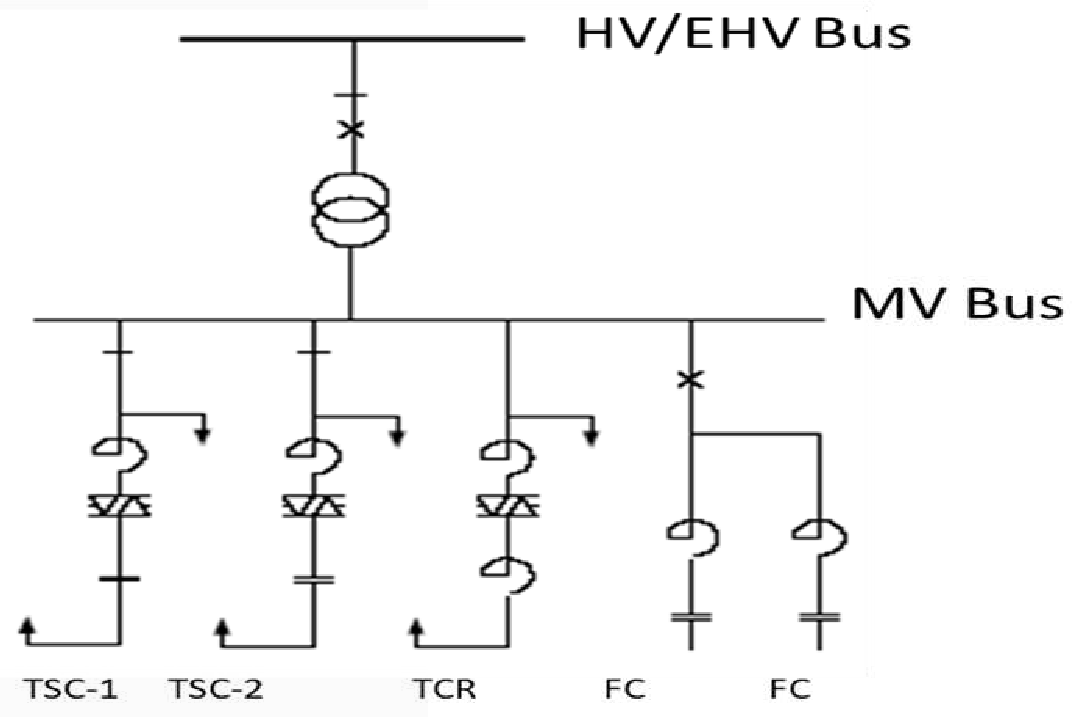
- This in-rush of reactive power typically lasts only a few seconds but can severely depress system voltages.
- If a severe voltage disturbance strikes a system with a heavy concentration of induction motors, during voltage drop induction motors will slow down.
- Once the system voltage start to recover the motor load will automatically try to pick up speed, but if the recovery of voltage is very slow then the motors would start stalling as the reacceleration torques of induction motor is proportional to square of the voltage.



Dynamic Stability Analysis
(Voltage Stability Issues)

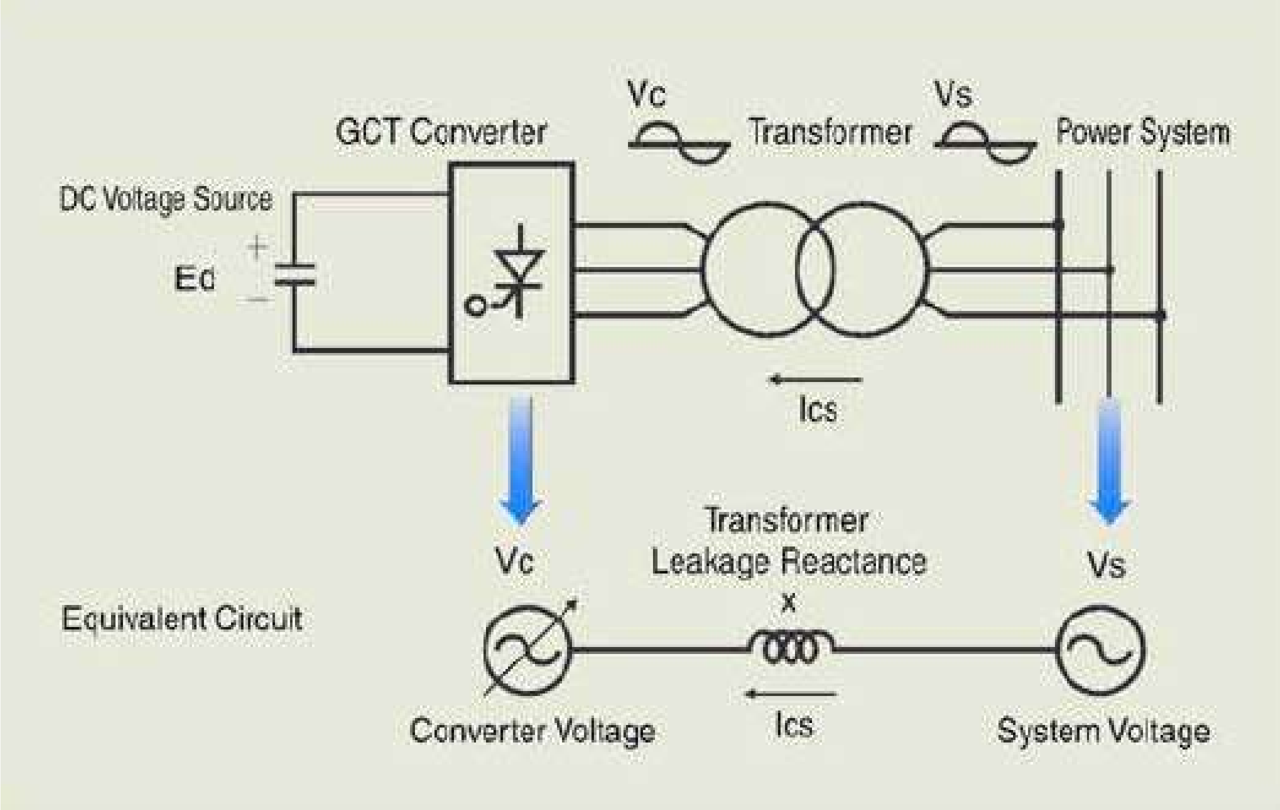
- **Dynamic Solutions for Quick Voltage Recovery:**
  - UVLS
  - SVC
  - STATCOM
  - Combination of SVC & STATCOM
- UVLS is not a likeable solution: May be a temporary solution
- SVC is a good option due to quick response time

- **Essential Components of SVC**
  - Thyristor Switched Capacitor (TSC)
  - Thyristor Controlled Reactor (TCR)
  - Fixed Capacitor/Filter Banks (FC)
  - Step-up Transformer from MV to HV/EHV
  - Controller



Dynamic Stability Analysis
(Voltage Stability Issues)

- **Dynamic Solutions for Quick Voltage Recovery:**
  - **STATCOM** is a constant current source once it reaches its limit while the SVC is a constant impedance device when it reaches its limit.
  - The reactive power at the terminals of the STATCOM depends on the amplitude of the voltage source. For example, if the terminal voltage of the VSC is higher than the AC voltage at the point of connection, the STATCOM generates reactive current; on the other hand, when the amplitude of the voltage source is lower than the AC voltage, it absorbs reactive power



Steady State & Dynamic Needs of Industrial Loads

- **Nature of Industrial Loads**
  - High Component of Large Motors (High Percent)
    - Big Industry
    - Pumping Station
  - Smelting Load / Arc-Furnace (Aluminum, Steel etc.)
  - Traction Load (Railway)
- **Reactive Power Requirement**
  - Steady State
  - Dynamic
    - Motor Staring
      - SVCs
      - STATCOM/
      - Combinations of SVC/STATCOM

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Steady State & Dynamic Needs of Industrial Loads

- **System Strength**
  - **Shot Circuit Ratio:**

$$SCR = \frac{MVAsc}{MW}$$

MVA_{sc} is Minimum Short circuit MVA (Weak System with Min. Generation

MW is the Load (or inverter based generator/HVDC) to be connected

  - **Effective Short Circuit Ratio ESCR**

$$ESCR = \frac{MVAsc - Qc}{MW}$$

Qc is Reactive Power Compensation

  - **Criteria:**

Strong systems with high ESCR:	ESCR > 3.0
Systems of low ESCR:	3.0 > ESCR > 2.0
Weak systems with very low ESCR:	ESCR < 2.0

  - **Important for**
    - Smelting Load / Arc-Furnace (Aluminum, Steel etc.)
    - Traction Load (Railway)

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Steady State & Dynamic Needs of Industrial Loads

- **Issues of Weak System**
  - Flicker
  - Harmonics
  - Voltage Unbalance
  - Voltage Dip
- **Forced Oscillation Mode**
  - Source of forced oscillation on 12th January,2022 was Dubai Aluminum Plant which is connected to an Aluminum Smelting Plant in its vicinity.
  - Arc-furnace in this smelting plant seems to be a likely source of this forced oscillation
  - Battery Energy Storage Systems (BESS) is a good device to absorb extra energy from FO, to reduce its energy level
  - BESS should be considered to be installed at suitable locations, especially at the smelter plants with a control strategy to modulate the active power of BESS
- It should be mandatory for all smelting plants to install such devices (BESS, SVC, STATCOMs) inside their bounds to prohibit the spread of oscillatory pollution to the system

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Questions
Answers

Thank you

Capacity Building on Advance & Innovative Transmission System Design and Optimization

General Principle and Recent Trends of Power System: Modern Grid Technologies (Day 1.1 D)

By

Hassan Jafar Zaidi

CEO, Power Planners International, Pakistan

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Under SAARC Energy Center

14th-16th October 2025 Thimphu, Bhutan

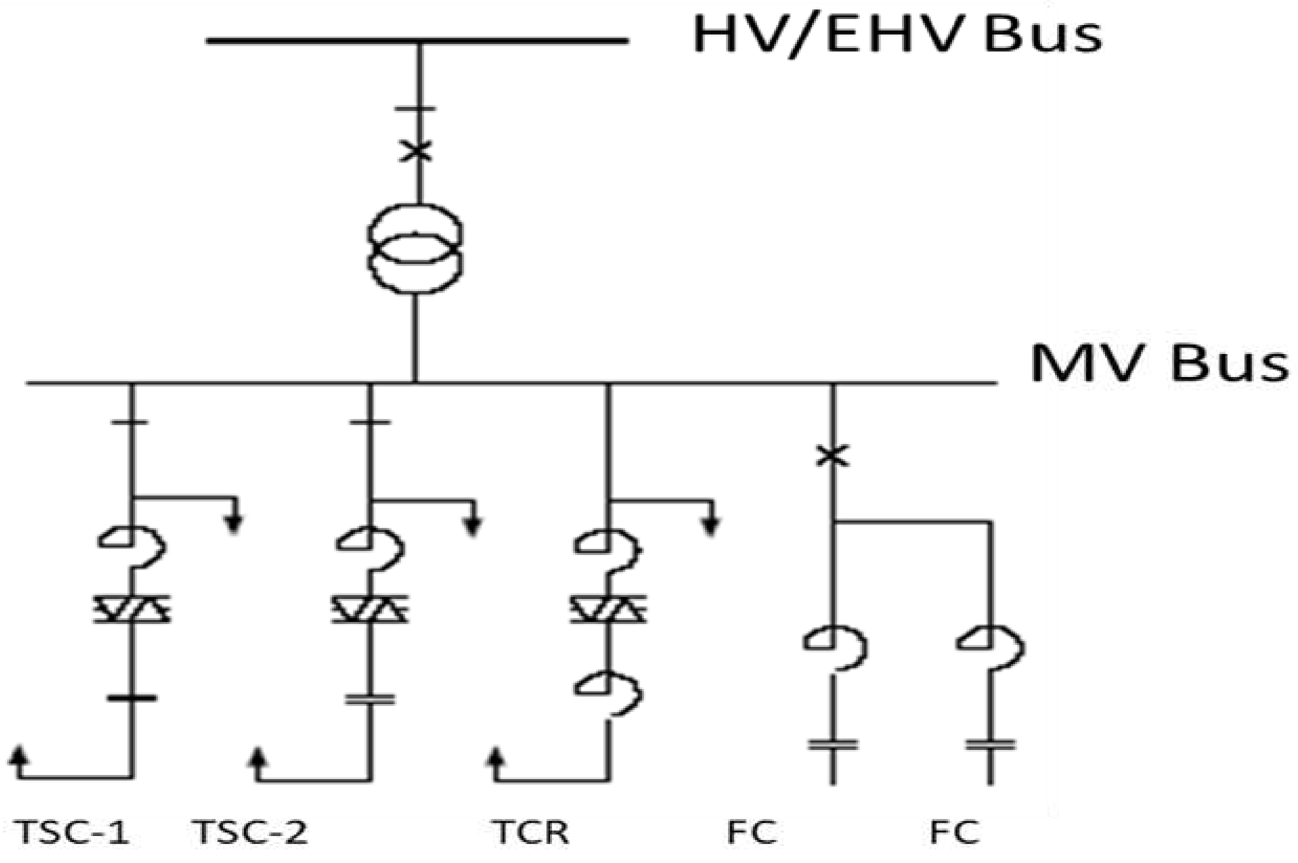
Agenda

1. Overview of FACTS
   a. Static VAR compensator (SVC)
   b. Static Condenser (STATCON)
   c. Static Compensator (STATCOM) (ABB's brand name)
   d. SSSC: Static Synchronous Series Compensator
   e. TCSC: Thyristor Controlled Series Compensator
2. HVDC Technology,
   a. Applications and Advantages with special reference to hydropower export to India.
   a. HVDC Link Components

Static VAR compensator (SVC)

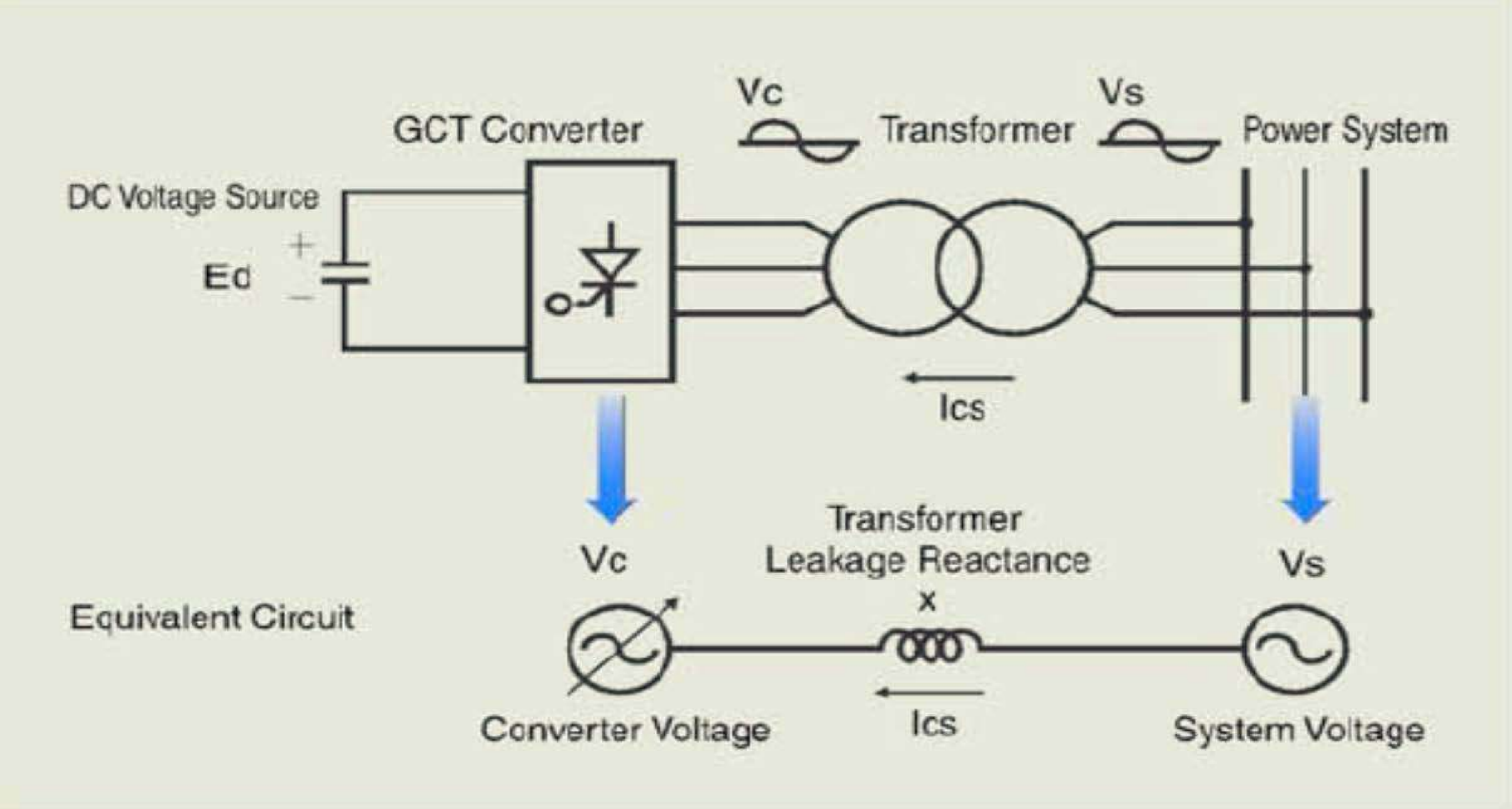
Essential Components of SVC

- Thyristor Switched Capacitor (TSC)
- Thyristor Controlled Reactor (TCR)
- Fixed Capacitor/Filter Banks (FC)
- Step-up Transformer from MV to HV/EHV



STATCOM

- Static synchronous compensator (STATCOM), also known as a "static synchronous condenser" ("STATCON"), is a regulating device used on AC electricity transmission networks.
- A power electronics voltage-source converter and can act as either a source or sink of reactive AC Power to an electricity network.
- Voltage source is created from a DC Capacitor and therefore a STATCOM has very little active power capability.



STATCOM

- Given a sufficient number of thyristor-bridges it is possible for a converter to synthesize a controlled ac voltage with acceptable harmonic content behind the converter transformer reactance
- For pure reactive control, ac voltage is kept in phase with terminal voltage
- No net exchange of active power with network, dc capacitor remains charged at desired level
- Converters have losses that tend to discharge capacitor. To replenish the capacitor charging, synthesized voltage is controlled to slightly lag terminal voltage and maintain small flow of active power between network and condenser.
- By this same mechanism capacitor voltage is controlled, which determines magnitude of internal voltage and determines reactive exchange with network

Comparison of SVC and STATCOM

- STATCOM is a constant current source once it reaches its limit while the SVC is a constant impedance device when it reaches its limit.
- Reactive power output of STATCOM is proportional to voltage when it reaches limit
- Reactive power at terminals of e STATCOM depends on amplitude of voltage source.
  - If terminal voltage of VSC is higher than AC voltage at point of connection, STATCOM generates reactive current;
  - If amplitude of voltage source is lower than AC voltage, it absorbs reactive power
- Response time of a STATCOM is shorter than an SVC, mainly due to fast-switching times provided by IGBTs of voltage source converter
- STATCOM also provides better reactive power support at low AC voltages than an SVC
- Since reactive power from a STATCOM decreases linearly with AC voltage (as current can be maintained at rated value even down to low AC voltage)

Series Compensation

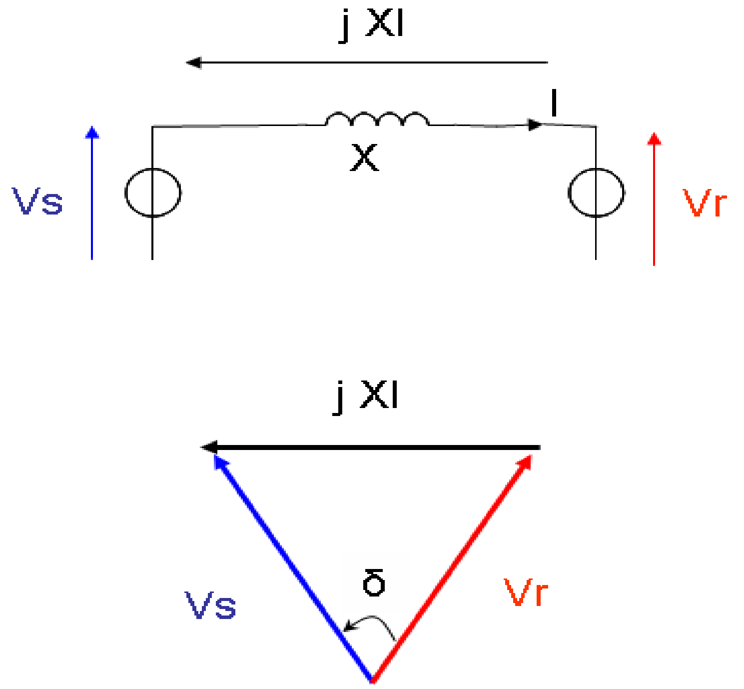
- In series compensation, FACTS is connected in series with power system.
- It works as a controllable voltage source.
- Series inductance exists in all AC transmission lines. On long lines, when a large current flows, this causes a large voltage drop. To compensate, series capacitors are connected, decreasing the effect of the inductance
- Power transfer capability is thereby increased depending upon power equation
- FACTS for series compensation modify line impedance: X is decreased so as to increase the transmittable active power. However, more reactive power must be provided

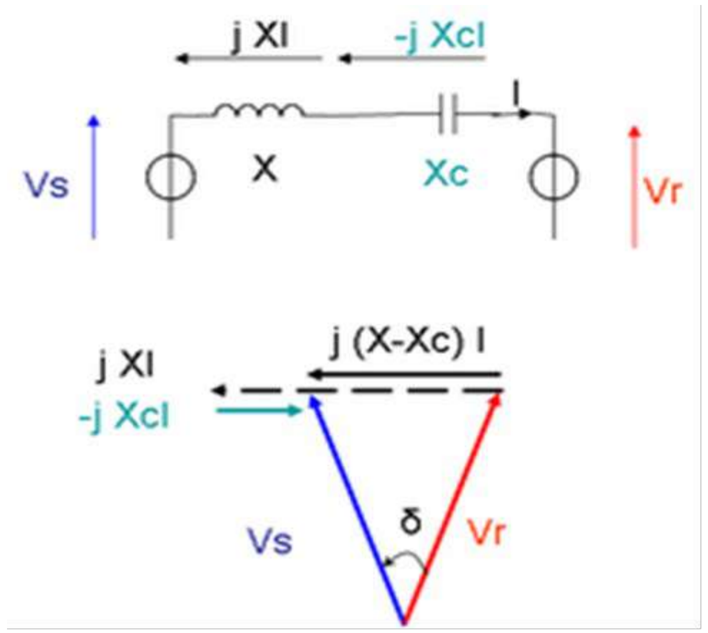
$$P = \left(\frac{EV}{X}\right)\sin(\delta)$$

δ = Power Angle

$$P = \frac{V^2}{X - Xc}\sin(\delta)$$

$$Q = \frac{V^2}{X - Xc}(1 - \cos\delta)$$





Series Compensated Line

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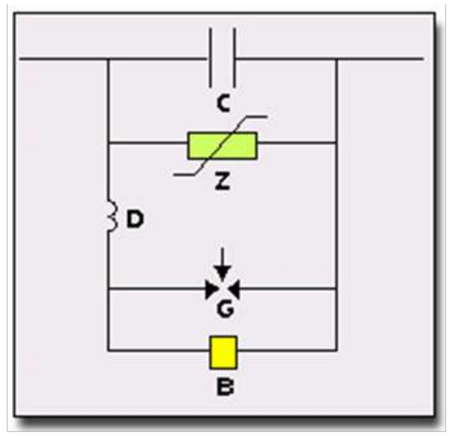
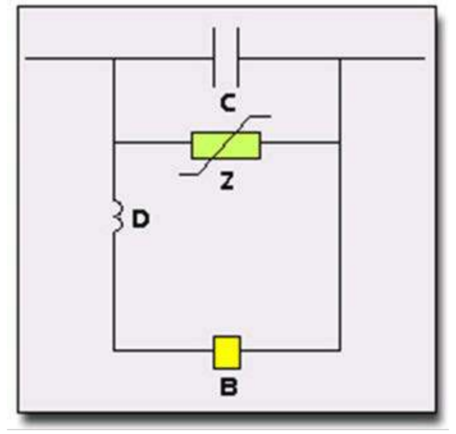
Series Compensation

- A non-linear resistor of zinc-oxide (ZnO) type limits voltage across series capacitor during a fault sequence and reinserts bank immediately on termination of fault current
- Energy is normally absorbed by ZnO varistor without necessitating firing of spark gap or closing of by-pass breaker
- Series capacitor and ZnO varistor are in circuit during fault period and reinsertion takes place automatically and without delay when line fault is cleared.
- For fault currents higher than MOV design value spark gap will trigger and remove stress on MOV
- Series capacitor will be bypassed: post fault reinsertion will be delayed
- Triggering of spark gap only takes place when fault occurs on same line segment as series capacitor is installed, then stability of transmission is not affected by bypass action



Scheme with Spark Gap



Gapless Scheme

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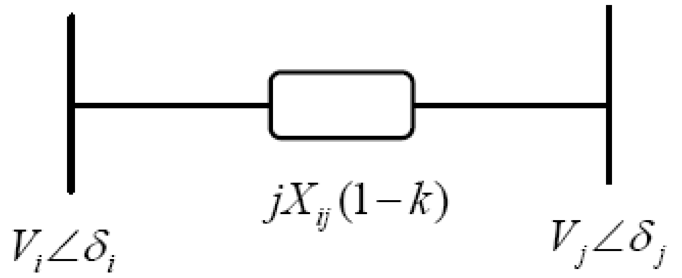
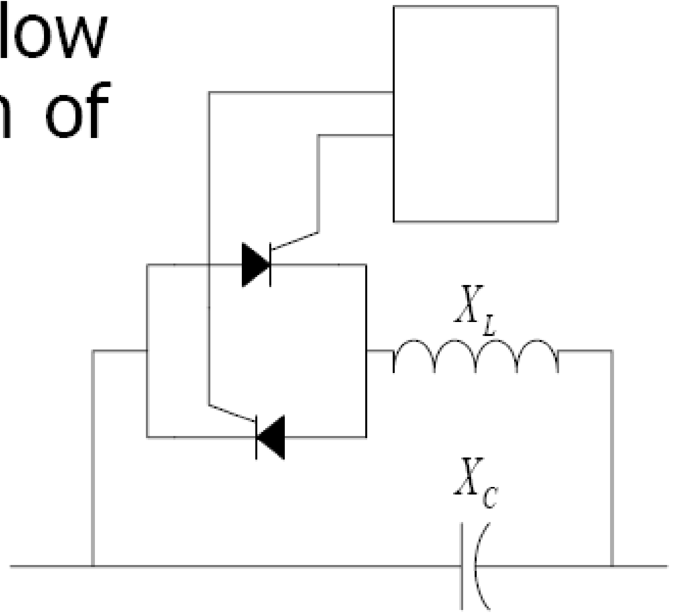
Thyristor Controlled/Switched Series Compensation

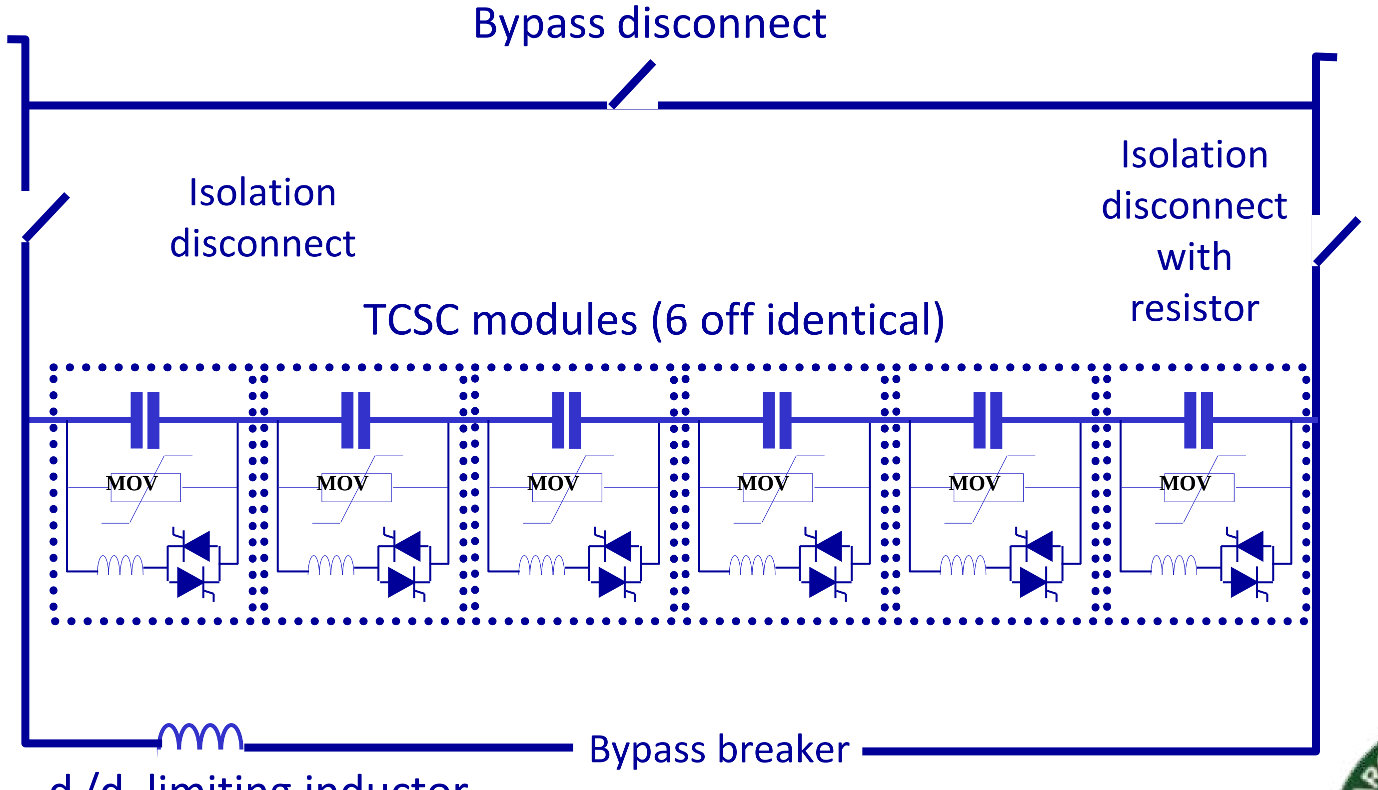
- Static Synchronous Series Compensator (SSSC)
- Thyristor-Controlled Series Capacitor (TCSC): a series capacitor bank is shunted by a thyristor-controlled reactor
- Thyristor-Controlled Series Reactor (TCSR): a series reactor bank is shunted by a thyristor-controlled reactor
- Thyristor-Switched Series Capacitor (TSSC): a series capacitor bank is shunted by a thyristor-switched reactor
- Thyristor-Switched Series Reactor (TSSR): a series reactor bank is shunted by a thyristor-switched reactor

TCSC controls line flow through the modulation of the line reactance.





$$P = \frac{V_i V_j}{X_{ij}(1-k)} \sin(\delta_{ij})$$



HVDC Technology

- **Applications**
  - Long-distance, bulk-power: best for long distance export of power from Bhutan to India
  - Sea and land cable transmission
  - Asynchronous interconnections
  - Power flow control
  - Congestion relief
- **Ratings**
  - Power range up to 4000 MW at ± 500 kV
  - Power range up to 5000 MW at ± 600 kV
  - Voltage range increasing to ± 800 kV and ±1000 kV
  - Power range up to 6000-8000 MW MW at ± 800 KV and ±1000 kV
- **Advantages**
  - Generator Outlet Transmission
  - More power on fewer lines
  - Cross Border Interconnection: asynchronous transfer of power between two countries

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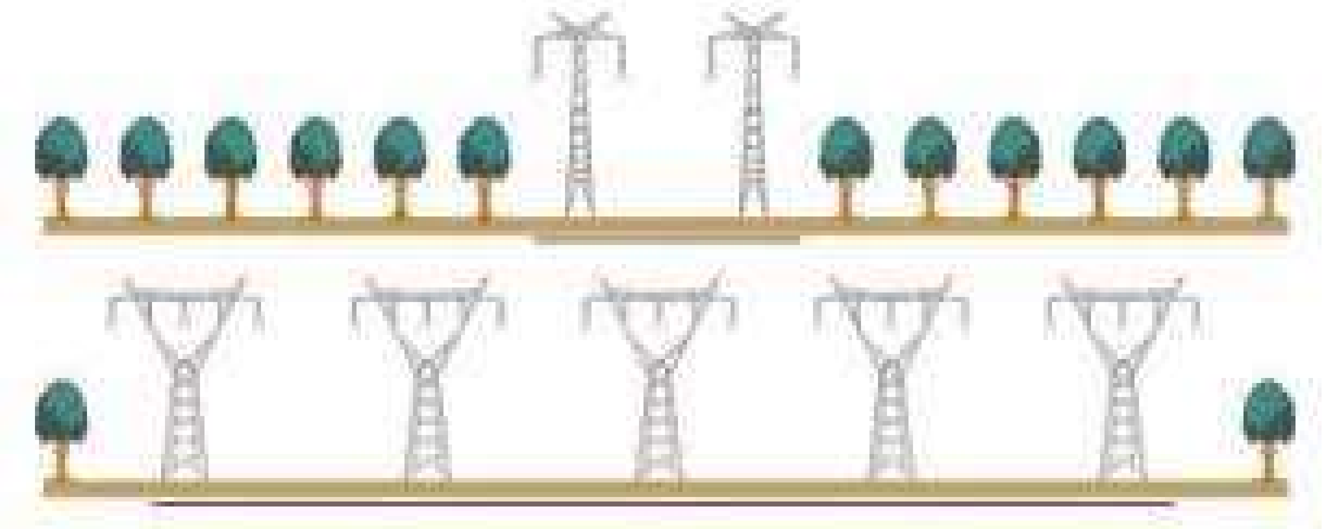
HVDC Technology

- Improved stability
- Lower installed cost
- Reduced losses
- Reduced ROW:
  - Figure compares two 3,000 MW HVDC lines for the 1,000 km Three Gorges - Shanghai transmission, China, to five 500 kV AC lines that would have been used if AC transmission had been selected



- Interconnections between different regions of a big country (e.g. India, Pakistan)
- Firm capacity
- Bypass congestion
- Avoid loop flow
- Interconnect diverse regions

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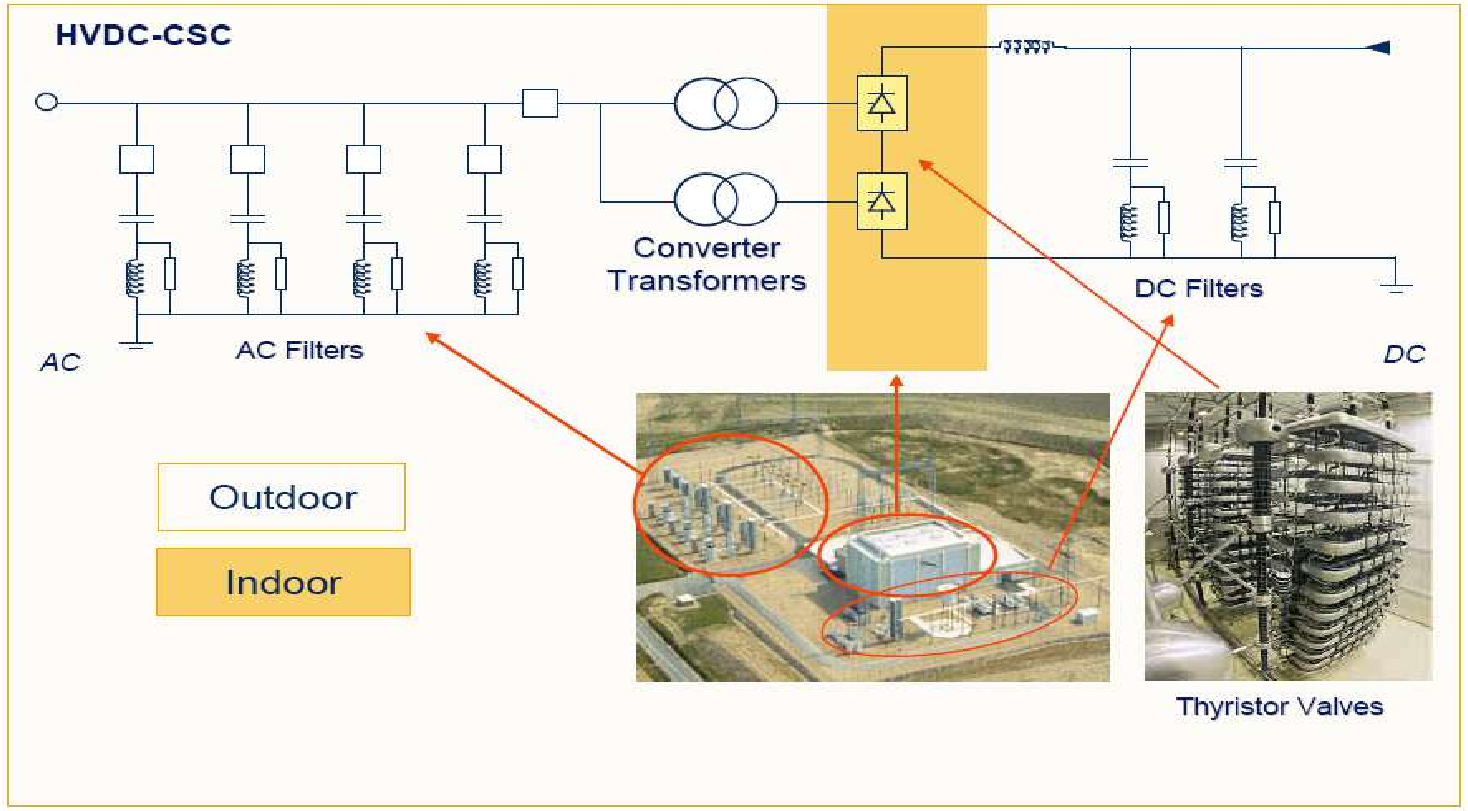
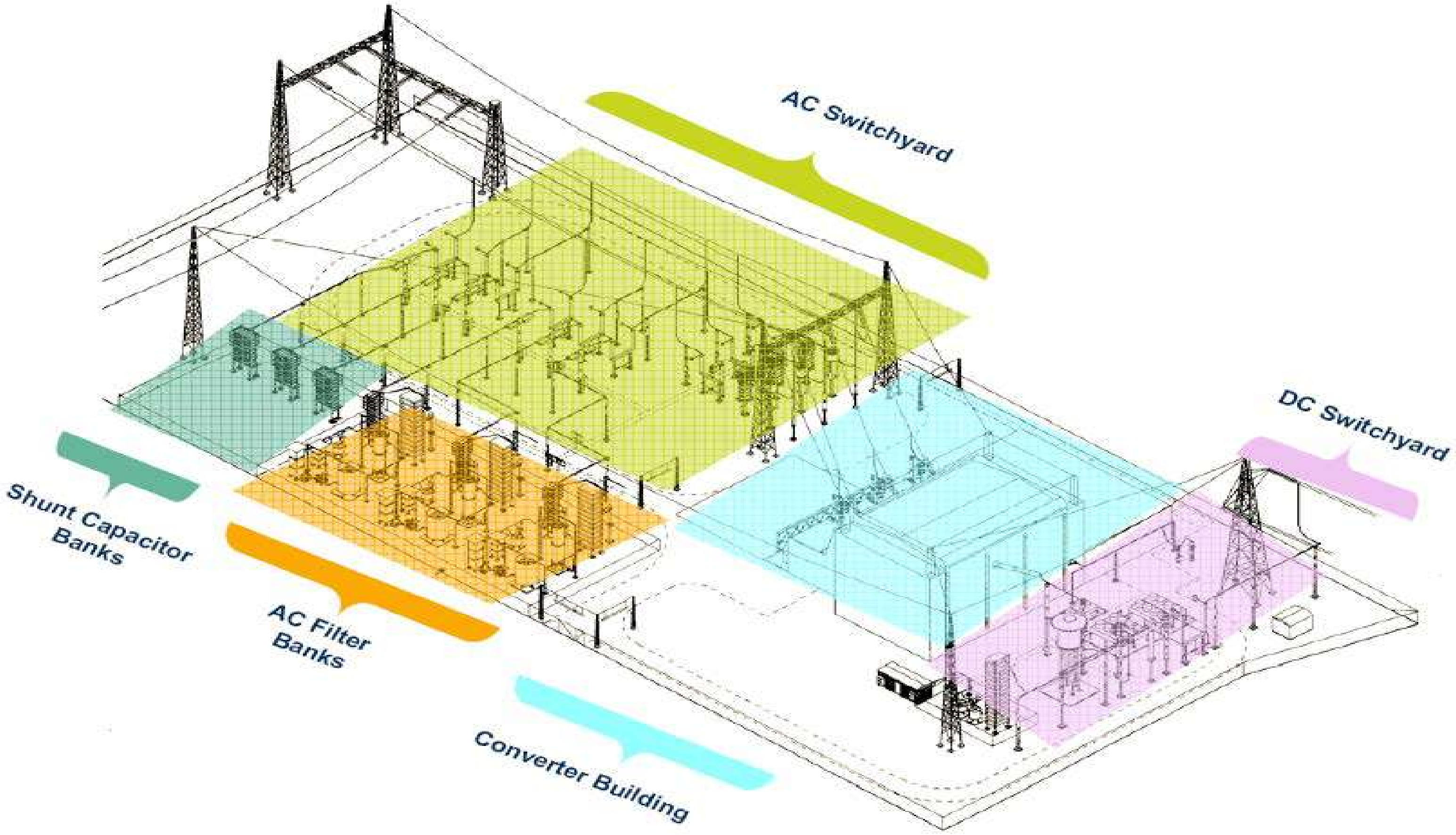
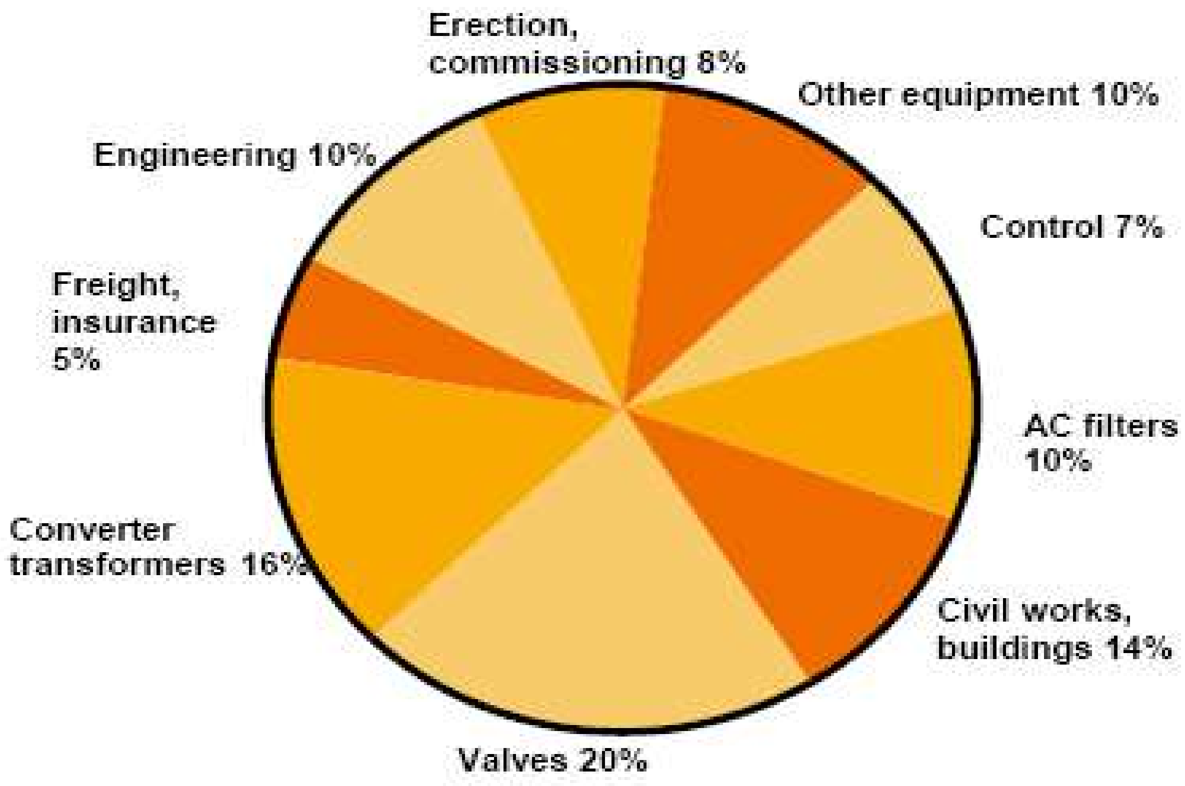
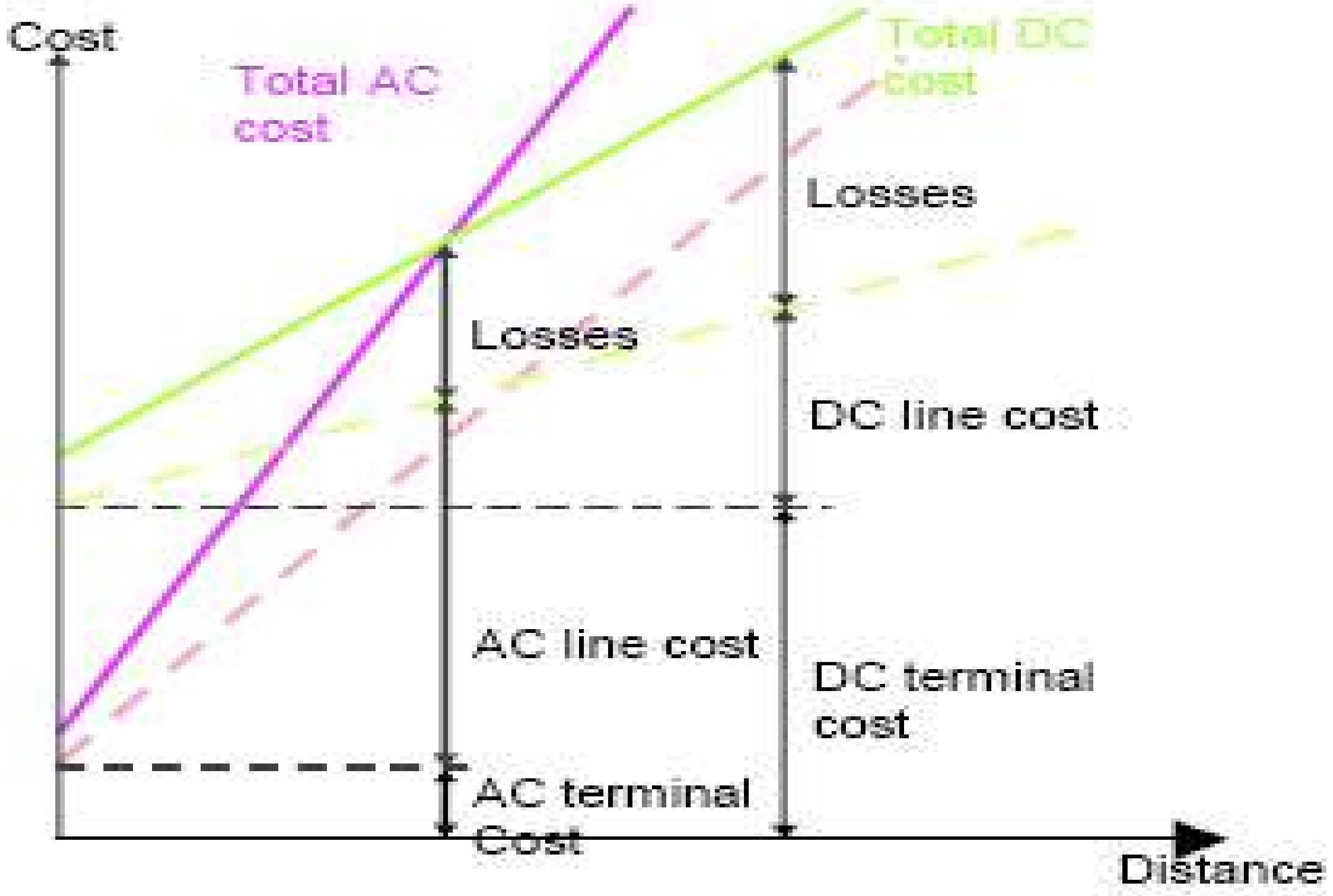
HVDC Technology

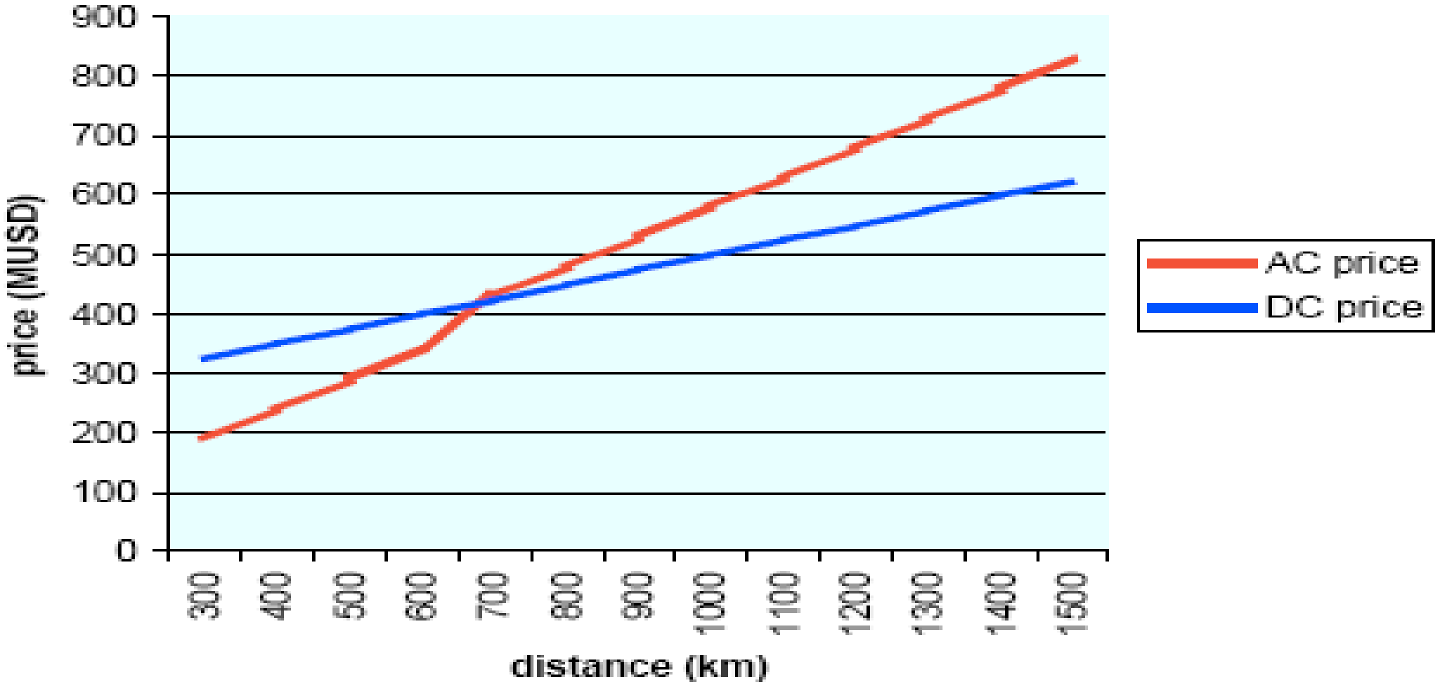




HVDC Technology

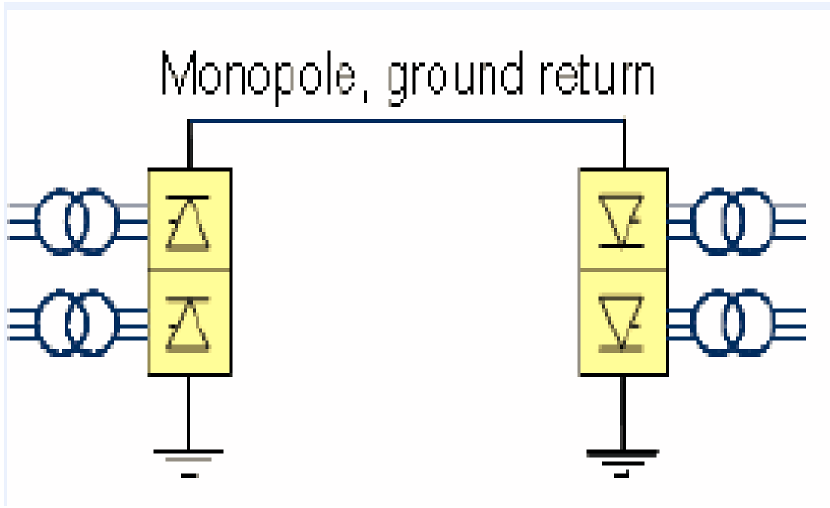




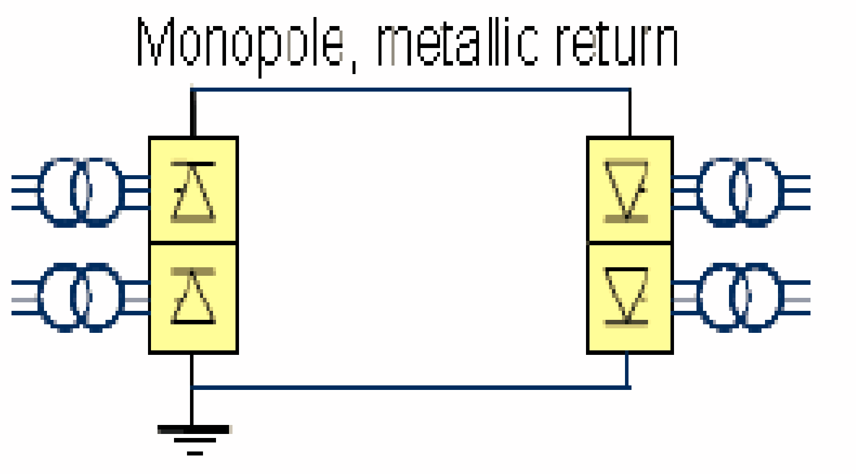


HVDC Technology

Monopolar Links

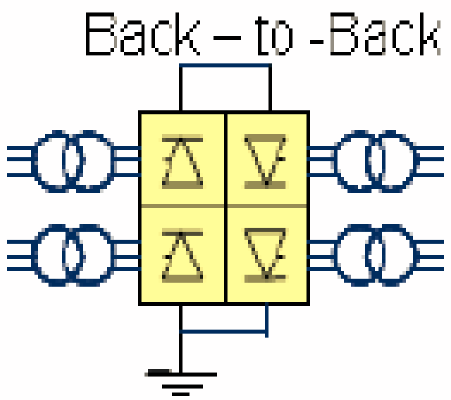


- It uses one conductor, usually the negative polarity
- Usually used in cable transmission
- Instead of ground return, a metallic return may be used where the earth resistivity is very high or possible interference with underground/underwater metallic structures is objectionable
- The conductor forming the metallic return is at low voltage
- Ground current can have side effects on underground gas or oil pipelines that line within a few miles of the system electrode stations
- Pipelines act as conductors for the ground currents which can cause corrosion of the metal



Back-to-Back HVDC System

- (For Asynchronous Cross Border Intertie)
  - Presently between India and Bangladesh (GCC with KSA)
  - Can be god or export of power from Bhutan to India



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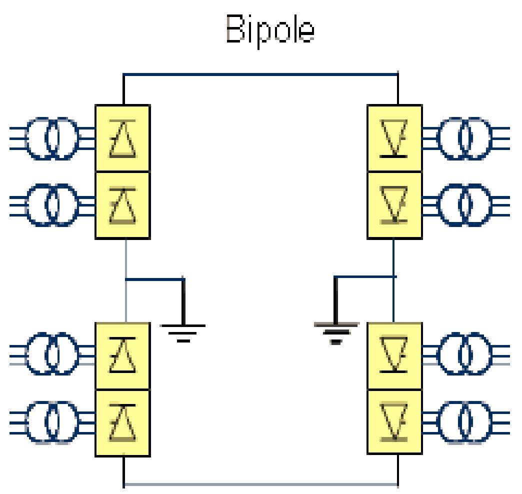
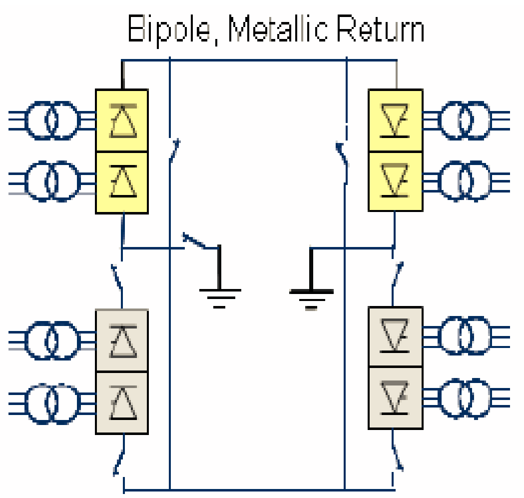
HVDC Technology

Bipolar Links:

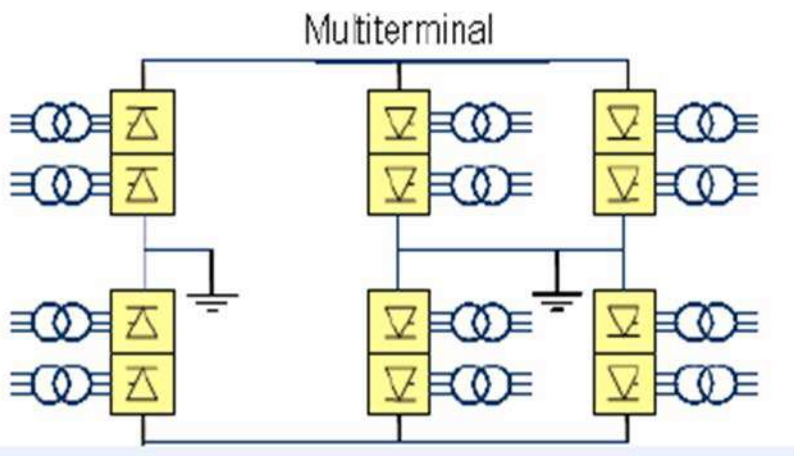
- It has two conductors, one positive and other negative.
- Each terminal has two converters of equal rated voltage, connected in series on the dc side
- Junction between the converters is grounded
- Normally current in two conductors is equal
- Two poles can operate independently. If one pole is isolated due to fault on the conductor, other pole can operate with ground and carry half of rated load or more by using overload capacity of its converters and line
- If ground currents are not tolerable or when ground electrode is not feasible for reasons such as high resistivity. A 3rd conductor is used as a metallic neutral
- It serves as the return path when one pole is out of service or there is unbalance during bipolar operation
- Neutral return conductor requires low insulation and may also serve as shield wire for overhead lines. If it is fully insulated it can serve as a spare





Multi-Terminal HVDC

- It is formed when the dc system is to be connected to more than two nodes on the ac network (Can be from Bhutan to two different locations in India)



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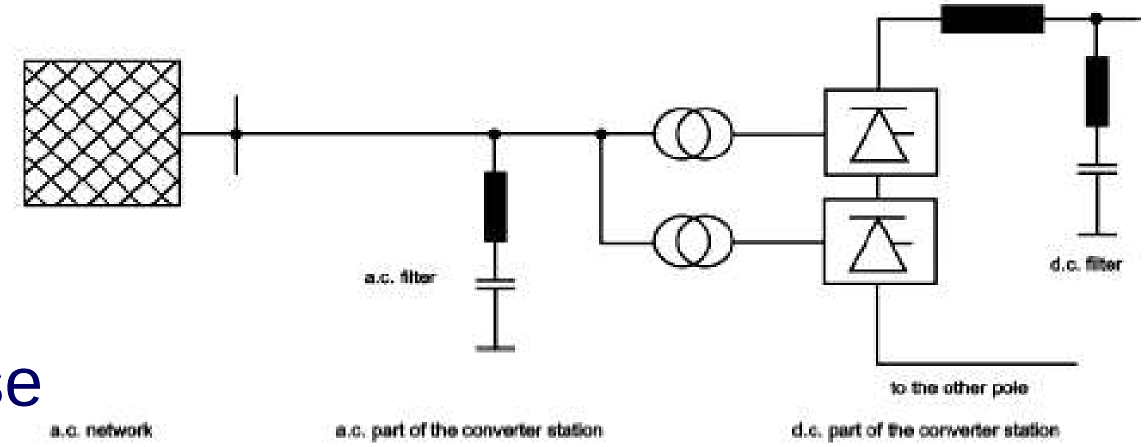
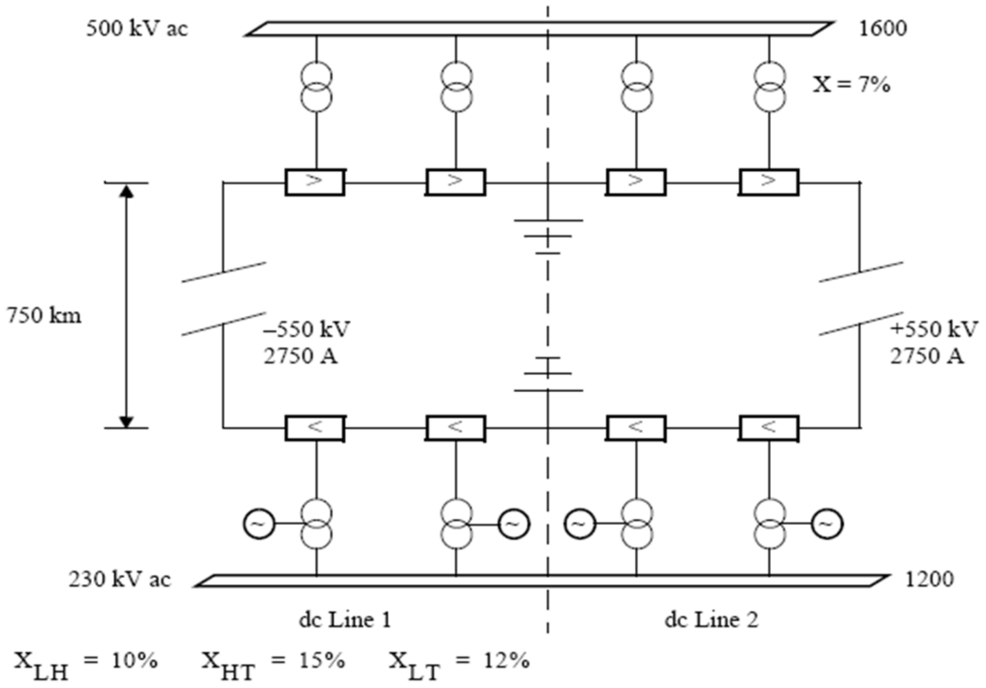
HVDC Links Components

Converters:

- They perform ac/dc and dc/ac conversion
- Consists of valve bridges and transformers with tap changers
- The bridges can be connected in 6-pulse or 12-pulse arrangement
- Converter transformers provide ungrounded 3-phase voltage source of appropriate level to the valve bridges
- With the valve side of the transformer ungrounded, the dc system will be able to establish its own reference to ground usually by grounding the +ve or –ve end of the valve converter
- Two main converter technologies
- Line Commutated Converters LCC, based on thyristors and widely used for bulk power transfer, overhead line projects
- Voltage Source Converters VSC, based on IGBTs, which offer superior flexibility, controllability, and black start capability, for cable-based, offshore, and flexible HVDC.





HVDC Links Components

Smoothing Reactors:

- There are large reactors having inductance as high as 1.0 H connected in series with each pole of each converter station. They have the following purposes:
- Decrease harmonic voltages and currents in the dc line
- Prevent commutation failure in inverters
- Prevent current from being discontinuous at light load
- Limit the crest in dc rectifier during shirt circuit on the dc line

Harmonic Filters:

- Converters generate harmonic voltages and currents on both ac and dc sides. These harmonics may cause overheating of capacitors and nearby generators and interfere with telecommunication systems. Filters are used on both ac and dc sides

HVDC Links Components

Reactive Power Supplies:

- DC converters inherently absorb reactive power
- Under steady state conditions, the reactive power consumed is about 50 % of active power transferred
- Reactive power sources are provided near the converters
- Under transient conditions, the consumption of reactive power may be much higher
- For strong ac systems, these are usually switched shunt capacitors
- Depending on the demand placed on the dc link and on the ac system part of the reactive power may be supplied from SVC, SVS or STATCOMs
- Capacitors in the Banks also provide some component of the required VARs

Electrodes:

- Most dc links are designed to use earth as a neutral conductor
- The connection to earth requires a large surface area conductor to minimize current densities and surface voltage gradients
- This conductor is referred to as electrode

HVDC Links Components

DC Lines:

- They may be overhead lines or underground/underwater cables
- Except for the number of conductors and spacing required dc lines are very similar to ac lines

AC Circuit breakers:

- For clearing the faults in transformers and for taking the dc link out of service, circuit breakers are used on the ac side
- They are not used for clearing of DC faults
- DC faults are cleared more rapidly by converter control (by blocking or bypassing the valves)
- All two-terminal dc lines consist of the line commutated converters
- The converter stations may include a commutation capacitor. The existence of the commutation capacitor affects the extent of the dc line model and its impact on solution performance as explained below

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Thank you

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Capacity Building on Advance & Innovative Transmission System Design and Optimization

Principle of Power Flow Study
Load Flow Analysis
(Day 1.2 A)

By

Hassan Jafar Zaidi

CEO, Power Planners International, Pakistan

Under SAARC Energy Center

14th-16th October 2025 Thimphu, Bhutan

Agenda

1. Purpose of Power Flow Analysis
2. Practical interpretation of results
    a. voltage profiles
    b. power flows
    c. losses
3. Introduction to the Iterative methods
    a. Gauss Siedel Method
    b. Newton-Raphson method

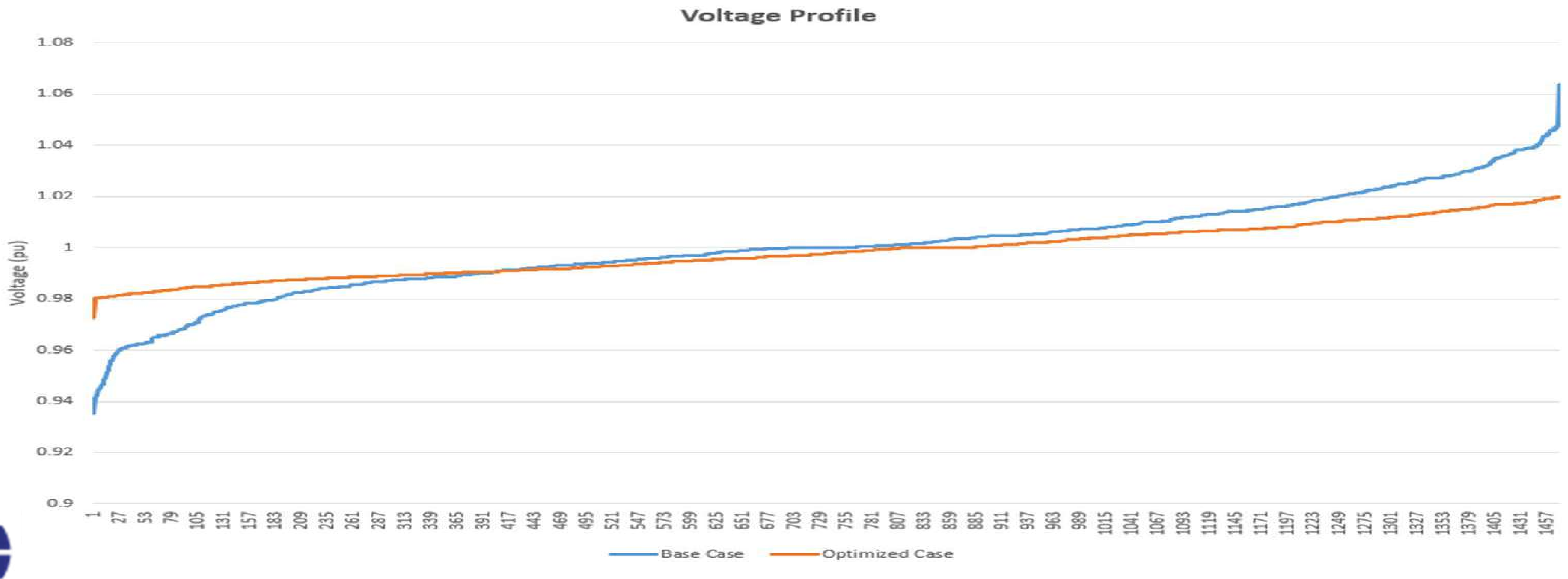
Purpose of Power Flow

1. The object is to determine the nodal voltages and hence the branch power flow in a transmission network for a given set of steady-state operating conditions.
2. Power flow analysis provide the basic means by which the power system is engineered to serve its load, while incurring capital and operating costs in the optimum ratio to one another
3. Given the load power consumption at all buses of the electric power system and the generator power production at each power plant, we find the power flow in each line and transformer of the interconnecting network.
4. The power system must operate
   - without overloading transmission lines or transformers,
   - stay within acceptable voltage limits at all buses, and
   - maintain generator reactive power outputs between acceptable limits.

Practical Interpretation of Results

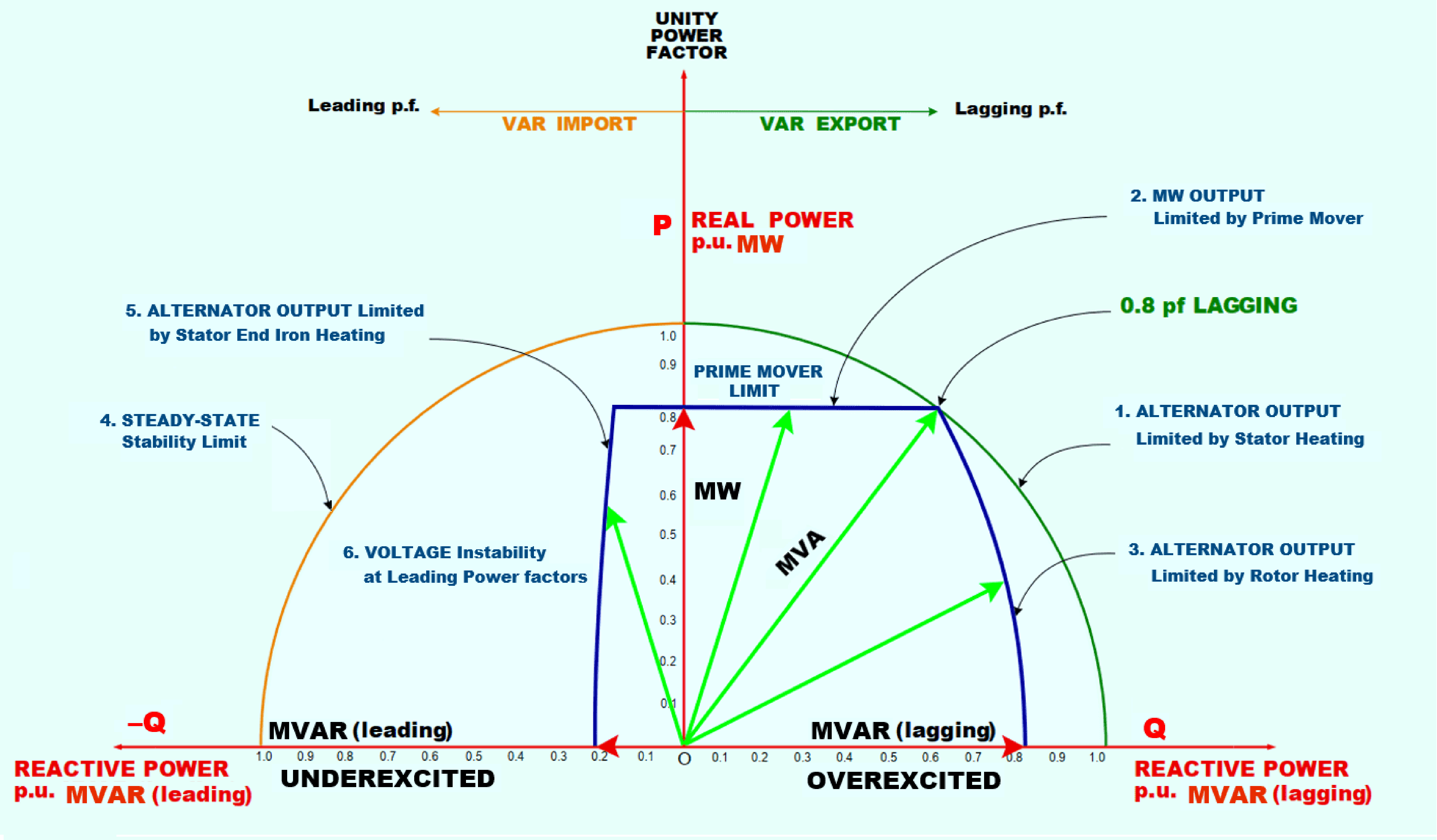
- **Normal and Contingency Limits**
  - **Normal = ± 5 % (0.95-1.05 PU or 95 % to 105 %)**
  - **Contingency = ± 10 % (0.90-1.10 PU or 90 % to 110 %)**

Voltage Profile Not to be at Extremes of Permissible Normal Limits to allow Margins for Contingency Conditions



Practical Interpretation of Results

VAR Generation/Absorption Not to be at Maximum Capability to allow Margin for Contingency Condition



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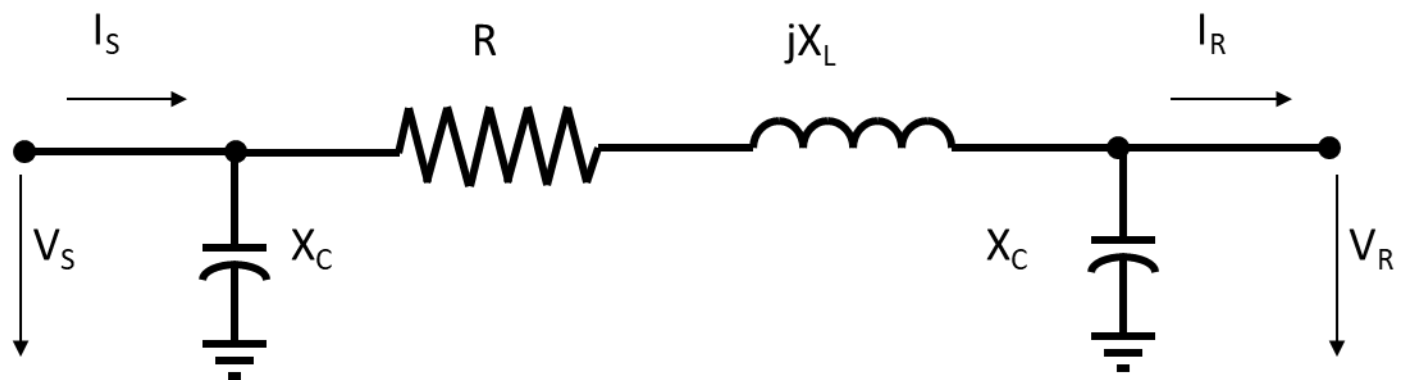
Development of Power Transfer Equations

To calculate the power transfer, the following electrical data are required:

- Sending and the receiving bus voltages that include the magnitude and angle (|V| and θ)
- Series impedance of the transmission path connecting to the buses ($R + jX_L$)
- Natural capacitance (charging) of the transmission path connecting to the two buses (jB)
- The PI model of the transmission line can be represented in the below figure:



- IS and IR are current flows in sending and receiving part of the busbar
- VS and VR are Voltage in sending and receiving part of the busbar
- The impedance of the line is expressed as Z = R + jXL
- The line charging of the line is represented as XC

Development of Power Transfer Equations

- The complex power (the MVA or S) is always equal to the voltage times the current

$$S_S = P_S + jQ_S = V_S \times \hat{I}_S = \frac{V_S^2}{\hat{Z}} + \frac{V_S^2}{\hat{X}_C} - \frac{V_R V_S \angle\delta}{\hat{Z}}$$

$$S_R = P_R + jQ_R = V_R \times \hat{I}_R = -\frac{V_R^2}{\hat{Z}} - \frac{V_R^2}{\hat{X}_C} + \frac{V_R V_S \angle\delta}{\hat{Z}}$$

- The "j" symbol signifies that the reactive power terms are 90^0 out-of-phase with the active power terms
- The angle term "δ" is the voltage angle between the sending (V_S) and receiving (V_R) buses
- The hat symbol (^) is a math concept (called a conjugate) used to ensure the proper sign conventions are used for reactive power

To simplify the power transfer equations, the equation on the sending end can be expressed as follows

Active Power:

$$P_S = \frac{V_S \times V_R}{X_L} \sin\delta$$

Reactive Power:

$$Q_S = \left[\frac{V_S^2 - V_S V_R \cos\delta}{X_L}\right] - \frac{V_S^2}{X_C}$$

Factors that Effect Active Power Flow

- **System generation & load**
  - ➢ Active power always flows from generation to load
- **Voltage magnitude**
  - ➢ Higher voltages allow transfer of more active power
- **Path impedance**
  - ➢ X_L increased either active power flow decreases, or power angle will decrease
- **Power angle (δ)**
  - ➢ Active power flow along a path is normally changed by changing the path power angle
- **System equipment**
  - ➢ System equipment has natural impedance and so impacts the flow of active power

Factors that Effect Reactive Power Flow

- **Reactive sources and loads**
  - ➢ Reactive power is closely related to system voltage levels
  - ➢ When voltage level needs to be increased, reactive supply also increased.
  - ➢ Generators may produce more reactive power or shunt capacitor may be placed in-service
- **Voltage magnitude**
  - ➢ Reactive power flow is strongly tied to voltage magnitude
  - ➢ When a generator is asked to increase its terminal voltage it does so by increasing its DC excitation current
  - ➢ This increase the generator internal excitation voltage
  - ➢ The higher internal voltage of the generator leads more MVAR flowing out of unit

Path impedance

➢As the "X_L" of a path is increased, the reactive power usage of the path increase (greater I^2X_L) and the reactive power transfer across the path decreases

Factors that Effect Reactive Power Flow

Power angle (δ)

- When the power angles are this small the cosine of δ is close to one.
- The result is that while MW flow is strongly impacted by power angles, MVAR flow is typically weakly impacted

System equipment

- When voltage control equipment such as capacitors, reactors, or tap changing transformers are used to adjust voltage this equipment is actually controlling the flow of reactive power

Transmission line charging

- Transmission line absorb reactive power from the system during heavy loading
- Transmission line provide reactive power to the system during light loading
- The amount of reactive power a transmission line provides to the system is related to the line voltage. The greater the voltage, the more MVAR the line will supply

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Losses

Active Power Losses:

- I^2 R depends on current and Resistance.
- Current includes both active and reactive component flowing through the line
- Transformer Losses:
  - Provided by manufacturer in the name plate data
    - Full Load Losses (Copper Loses) = I^2 R, where I is full load current
    - No Load Losses (Iron Losses or Core Losses) , fixed losses

Reactive Power Losses:

- I^2 X depends on current and Reactance.
- Current includes both active and reactive component flowing through the transformer

Loss Reduction:

- Shunt capacitors reduce the reactive current flow: total I is reduced, thus I^2 R and I^2 X reduced

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Capacity Building on Advance & Innovative Transmission System Design and Optimization

Principle of Power Flow Study
Steady State Stability : P-V and Q-V study
(Day 1.2 B)

By

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CEO, Power Planners International. Pakistan

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Under SAARC Energy Center
14th-16th October 2025 Thimphu, Bhutan

SAARC ENERGY CENTRE ISLAMABAD

Agenda

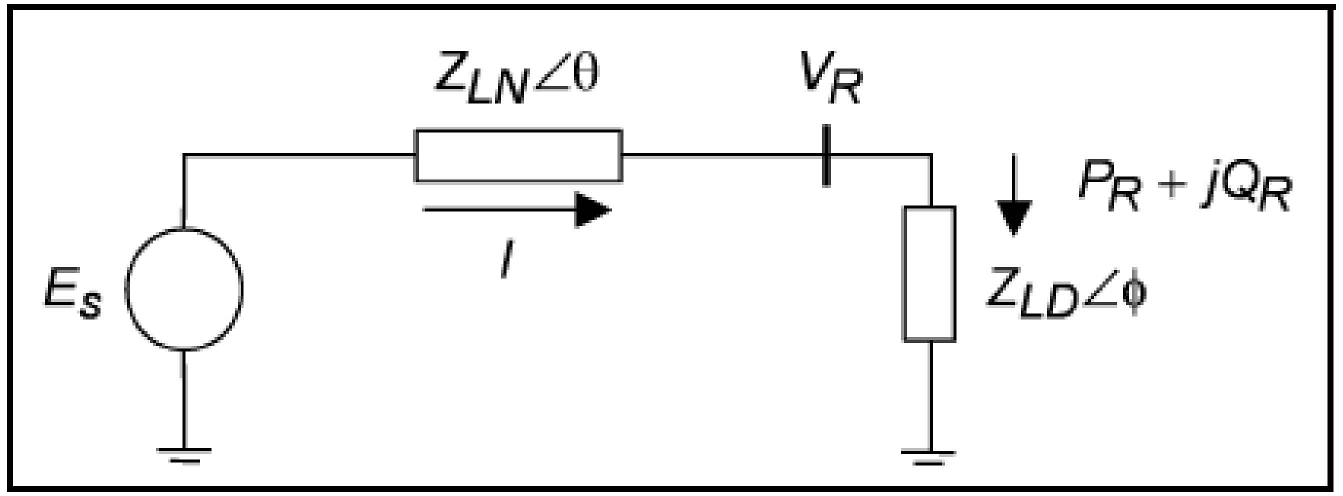
1. PV Analysis
    a. Purpose
    b. Technique
2. QV Analysis
    a. Purpose
    b. Technique

PV/QV Analysis

1. PV/QV analyses are designed for studies of slow voltage stability, which could be analyzed as a steady-state problem
2. They are power flow based analyses used to assess voltage variations with active and reactive power change
3. Two methods are used to determine the loading limits imposed by voltage stability under the steady-state conditions
4. The PV/QV analyses do not provide solutions to specific problem but function as tools that can be directed by the user to perform analyses in the solution of problems associated with the steady-state voltage stability of power systems

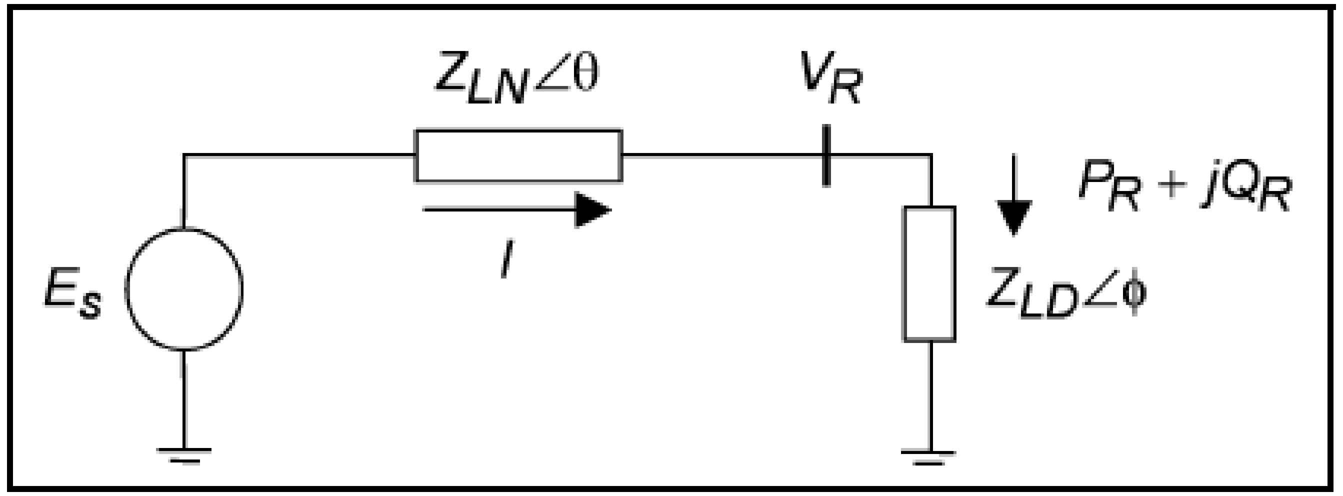
PV Analysis: PV Curve

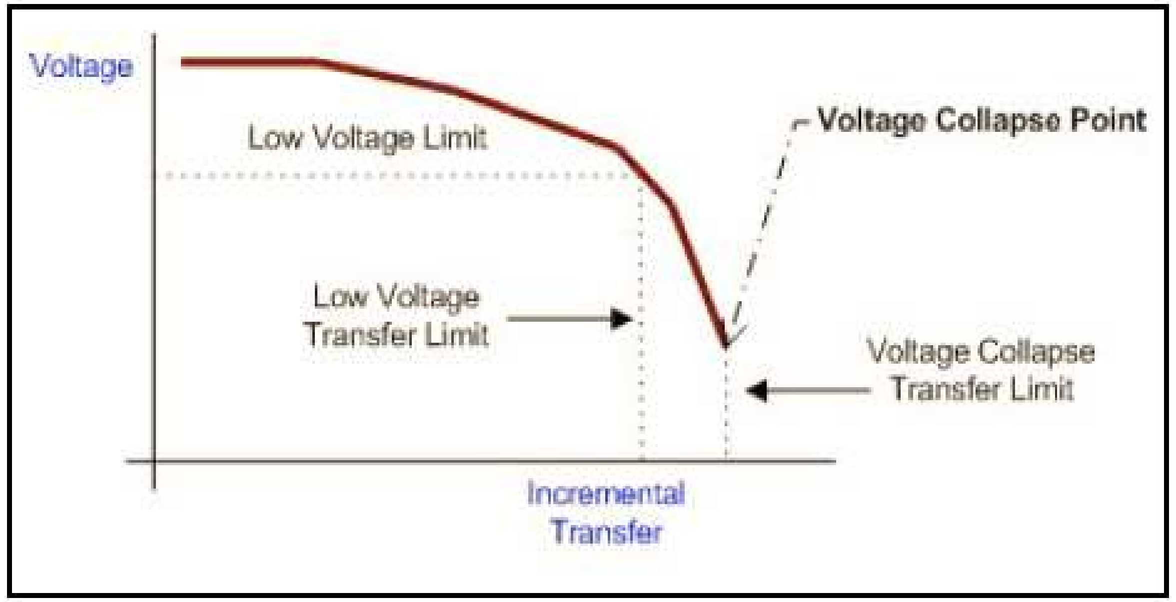
1. PV curves are parametric study involving a series of ac power flows that monitor the changes in one set of power flow variables with respect to another in a systematic fashion
2. This approach is a powerful method for determining transfer limits that account for voltage and reactive flow effects
3. As power transfer is increased, voltage decreases at some buses on or near the transfer path
4. The transfer capacity where voltage reaches the low voltage criterion is the low voltage transfer limit
5. Transfer can continue to increase until the solution identifies a condition of voltage collapse; this is the voltage collapse transfer limit
6. This can be demonstrated using a simple two terminals network as in Figure above.



PV Analysis: PV Curve

1. The loading of the network can be increased by decreasing the value of ZLD
2. This is done with Es, load power factor and line parameters fixed
3. As ZLD is decreased gradually the load power, PR, increases, hence the power transmitted will increase.
4. As the value of ZLD approaches ZLN the value of PR starts to decrease gradually due to F
5. However, from above Equation it is seen that as ZLD decreases the receiving voltage VR decreases gradually
6. PV curves are typically used for the knee curve analysis. It is as named because of its distinctive shape at the point of voltage collapse as the power transfer increases
7. Depending on the transfer path, different buses have different knee point. The buses closer to the transfer path will normally exhibit a more discernible knee point





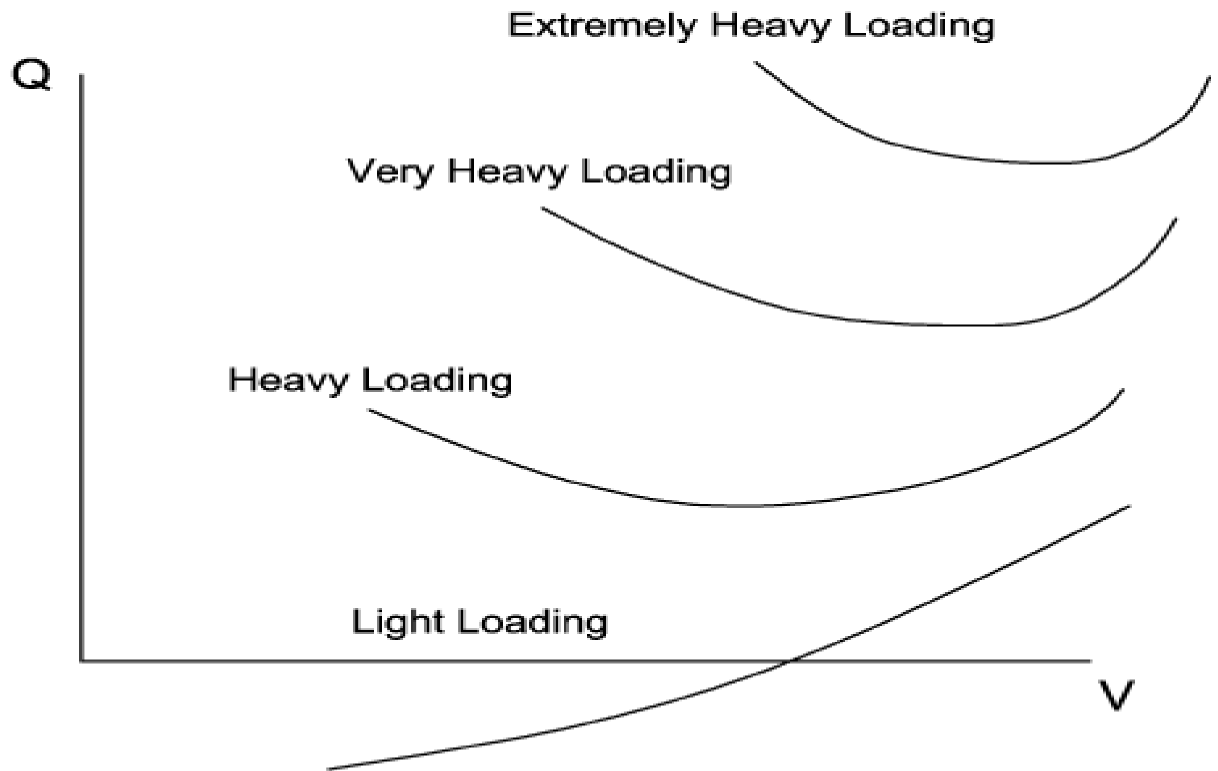
PV Analysis: PV Curve

1. Voltage instability occurs at the knee point of the PV curve where the voltage drops rapidly with an increase in the transfer power flow
2. The power flow solution will not converge beyond this limit, indicating voltage instability
3. Operation at or near the stability limit is impractical and a satisfactory operating condition must be ensured to prevent voltage collapse
4. In PSS®E, the PV curves are generated by selecting two subsystems where the power transfer between the subsystems is incremented in a defined step size for a series of ac power flow calculations while the bus voltages, generator outputs and the branch flows of the system are monitored
5. When the bus voltages are plotted as a function of the incremental power transfer the PV curves are obtained
6. One of the subsystems in the study must be defined as the study (source) system and another as the opposing (sink) system
7. The power flows from the study subsystem to the opposing subsystem

QV Analysis

1. QV curves are used to determine the reactive power injection required at a bus in order to vary the bus voltage to the required value
2. The curve is obtained through a series of ac power flow calculations
3. Starting with the existing reactive loading at a bus, the voltage at the bus can be computed for a series of power flows as the reactive load is increased in steps, until the power flow demonstrates convergence difficulties as the system approaches the voltage collapse point
4. Figure-1 is a typical of the QV curves that will be generated for a system that is stable at moderate loading and unstable at higher loadings

Figure-1



QV Analysis

1. The bottom of the QV curve, where the change of reactive power, Q, with respect to voltage, V (or derivative dQ/dV) is equal to zero, represents the voltage stability limit
2. Because all reactive power compensator devices are designed to operate satisfactorily when an increase in Q is accompanied by an increase in V, the operation on the right side of the QV curve is stable, whereas the operation on the left side is unstable
3. Also, voltage on the left side may be so low that the protective devices may be activated
4. The bottom of the QV curves, in addition to identifying the stability limit, defines the minimum reactive power requirement for the stable operation
5. QV curve can be used to examine the type and size of compensation needed to provide voltage stability
6. This can be performed by super-imposing the QV characteristic curves of the compensator devices on that of the system. Capacitor characteristic can be drawn over the system's QV curves as shown in Figure -2

Figure-2

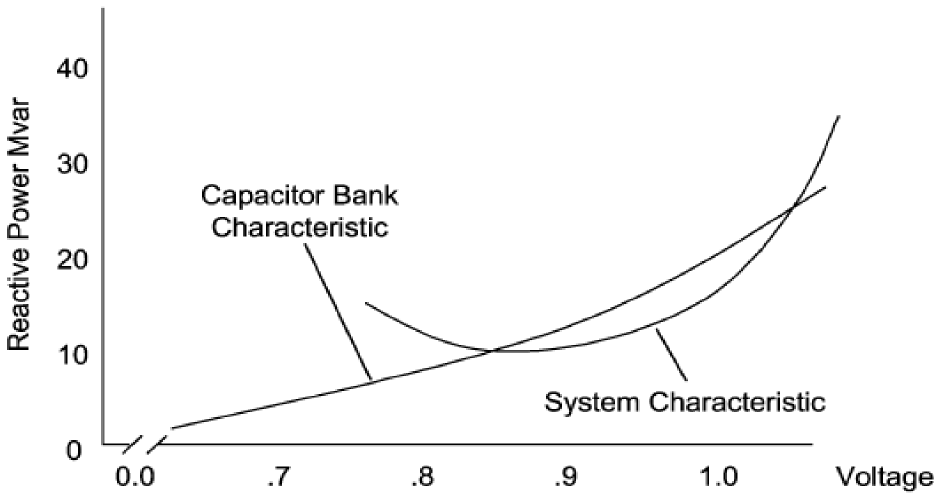
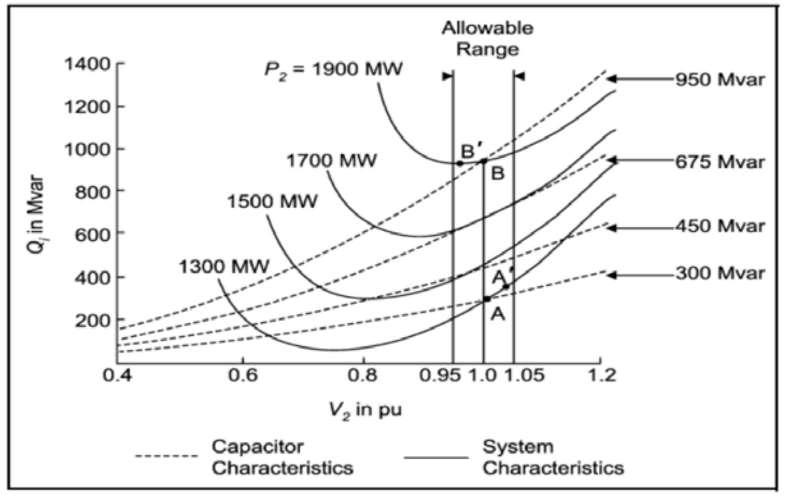


Figure-3



QV Analysis

1. Figure 3 shows the QV curves for a range of capacitor banks with different rating super-imposed on the system's QV curves under different loading conditions
2. From the plot we can determine that capacitor rating of 300 MVAR is required to maintain 1 pu voltage at loading of 1300 MW, 450 MVAR at 1500 MW and so on
3. For the case of very high loading at 1900 MW, even though the capacitor bank rating of 950 MVAR can maintain a voltage of 1 pu, point B is not a stable operating point
4. If there is a drop in voltage from point B to B', the ability of the capacitor to supply reactive power is decreased more than the drop in requirement of the system. This will result in continuous drop in voltage
5. Alternatively, if the voltage is increased above point B, the capacitor will supply more reactive power than the increase in requirement of the system. This will result in continuous rise in voltage.
6. Hence, the criterion for stable operating point when using a reactive power compensator is as follow:

$$\text{System } d_Q/d_V \leq \text{Compensator } d_{Qcomp}/d_V$$

where:

d_Q/d_V is the change of the system's reactive power, Q, with respect to voltage, V

d_{Qcomp}/d_V is the change of the compensator's reactive power output, Qcomp, with respect to voltage, V

QV Analysis

1. For case of light loading at 1300 MW with capacitor rating of 300 MVAR, point A is a stable operating point. If voltage is increased from point A to A', capacitor will supply less reactive power than the increase in system's demand, hence reducing the voltage to 1 pu
2. Alternatively, if voltage is decreased from point A towards the bottom of the QV curve, capacitor will supply more reactive power than the system's demand, hence returning the voltage to 1 pu
3. In PSS®E, QV curves are generated by artificially introducing a synchronous condenser, with high reactive power limits, at a bus to make this a PV bus
4. As the scheduled voltage set point (bus voltage) of the QV bus is varied in steps for a series of ac power flow calculations, the reactive power output from the condenser is monitored
5. QV curves are commonly used to identify voltage stability issues and reactive power margin for specific locations in the power system under various loading and contingency conditions. QV curves are also used as a method to size shunt reactive compensation at any particular bus to maintain the required scheduled voltage
6. From the curves we can determine the reactive power required to hold the desired scheduled voltage in base case and under various contingencies

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Thank you

Capacity Building on Advance & Innovative Transmission System Design and Optimization

Principle of Power Flow Study Short-Circuit Analysis: (Day 1.2 C)

By

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Under SAARC Energy Center

14th-16th October 2025 Thimphu, Bhutan

SAARC ENERGY CENTRE ISLAMABAD

Agenda

1. Objectives of SC Analysis
2. Types of faults (LG, LL, LLG, LLLG),
3. Calculation methods (per-unit, MVA),
4. Application
    a. in protection relay setting
    b. equipment rating

Objectives of SC Analysis

1. Evaluate the maximum fault levels to determine the ratings for specifications of switchgear of a new proposed substation:
   a. Power Plants switching station
   b. Load substation
2. Evaluate the maximum fault levels to see if the levels are within the rated limits of existing equipment of substations
3. In case of violations, propose the mitigation measures and test their adequacy
4. Evaluate minimum fault levels to assess the strength of the system for
   a. Installing the shunt compensation devices
   b. Connecting the special devices, FACTS, RE Plants, Inverter based Loads etc.
   c. Relay settings and Protection Coordination

Symmetrical System Balanced System

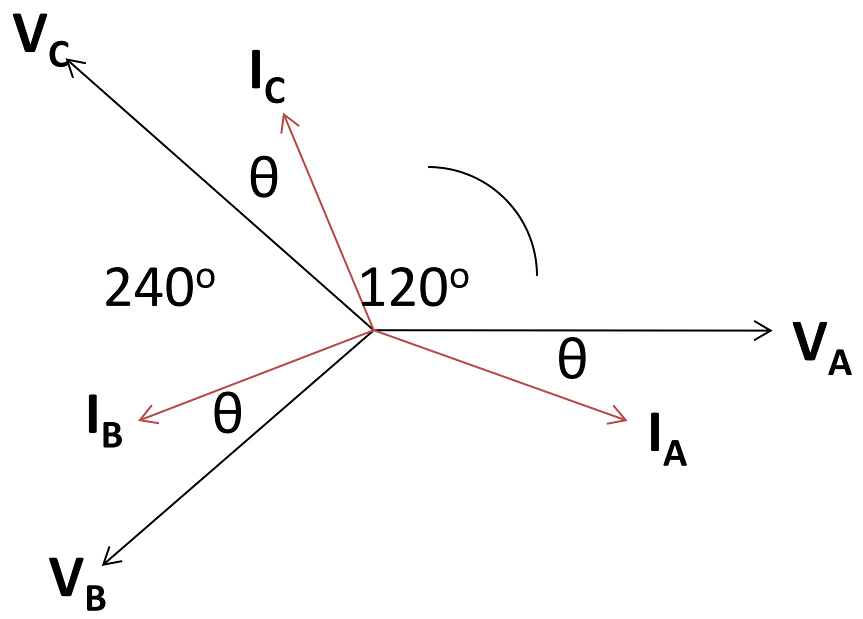
- **Symmetrical means**
  - Voltages are equal in magnitude and 120º apart
  - Phase impedances are same
  - Line Currents are equal in magnitude and 120º apart
- Balanced 3-Phase Symmetrical System

$$|V_A| = |V_B| = |V_C|$$

$$|I_A| = |I_B| = |I_C|$$

$$|Z_A| = |Z_B| = |Z_C|$$

- Phases a, b and c are displaced by 120º
- All currents lagging the voltages by angle θ
- It is very rare; majority of faults are unsymmetrical
- It is most severe and imposes more heavy duty on circuit breake



$$V_{Phase} = \frac{V_{L\text{-}L}}{\sqrt{3}}$$

$$MVA = \sqrt{3}\, V_{L\text{-}L} \times I$$

Symmetrical Components Theory Background

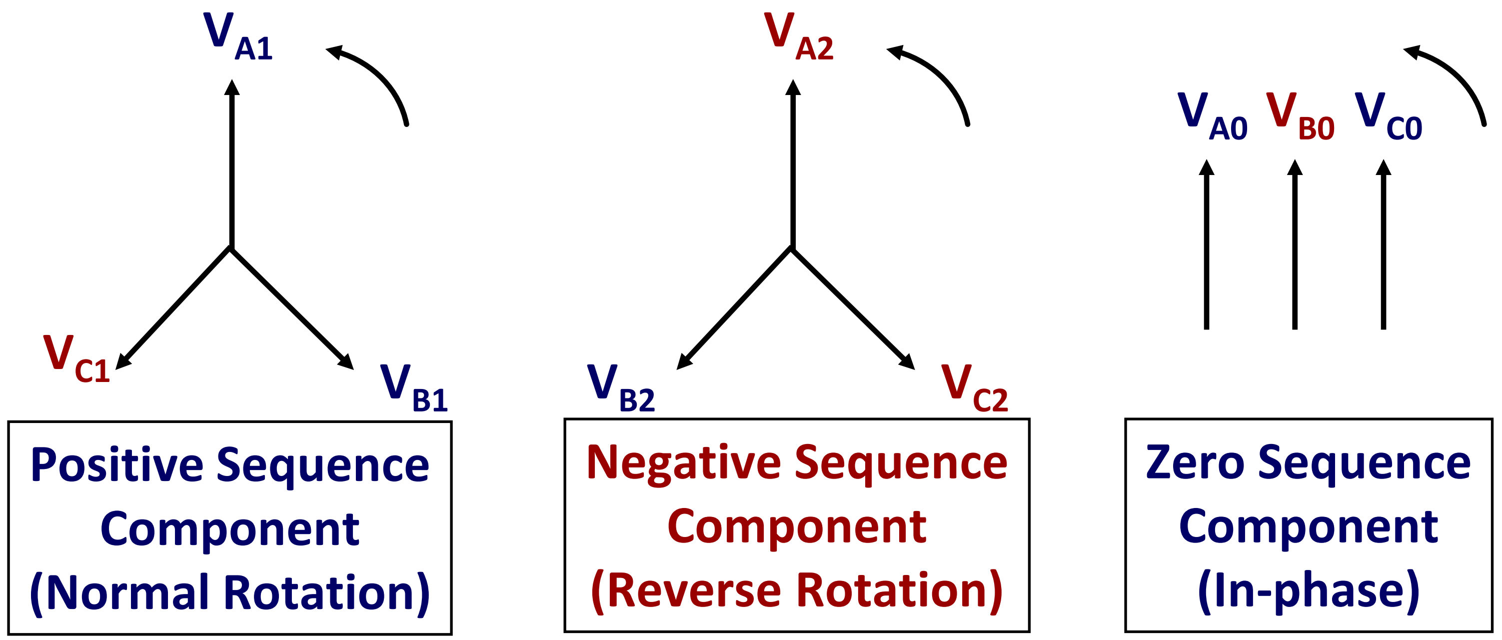
- C.L. Fortesque, an American mathematician, consultant to Westinghouse, wrote a paper in 1918 and developed a mathematical model transforming unbalanced 3-phase vectors into a system of balanced symmetrical components
- An unbalanced 3-phase system was resolved into three systems of balanced symmetrical components
  - Positive sequence
  - Negative sequence
  - Zero sequence
- Each system can be treated separately just as balanced 3-phase problems were solved in the past by reducing the constants and voltages to per-phase values and solving on 1-phase basis
- It applies equally to voltages and currents
- All components rotate counterclockwise like usual phase quantities

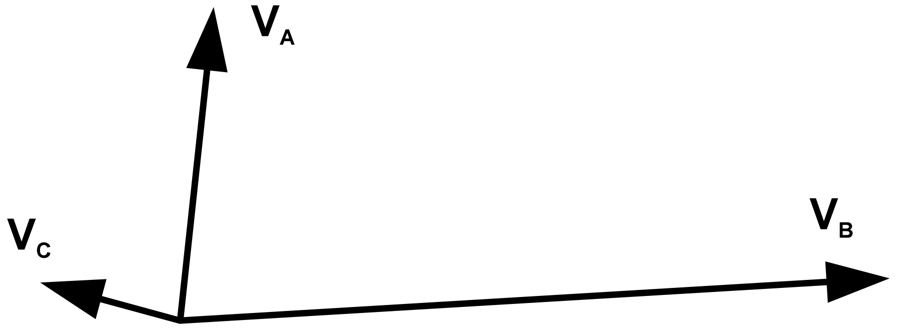
Symmetrical Components Theory
Positive, Negative and Zero Sequences

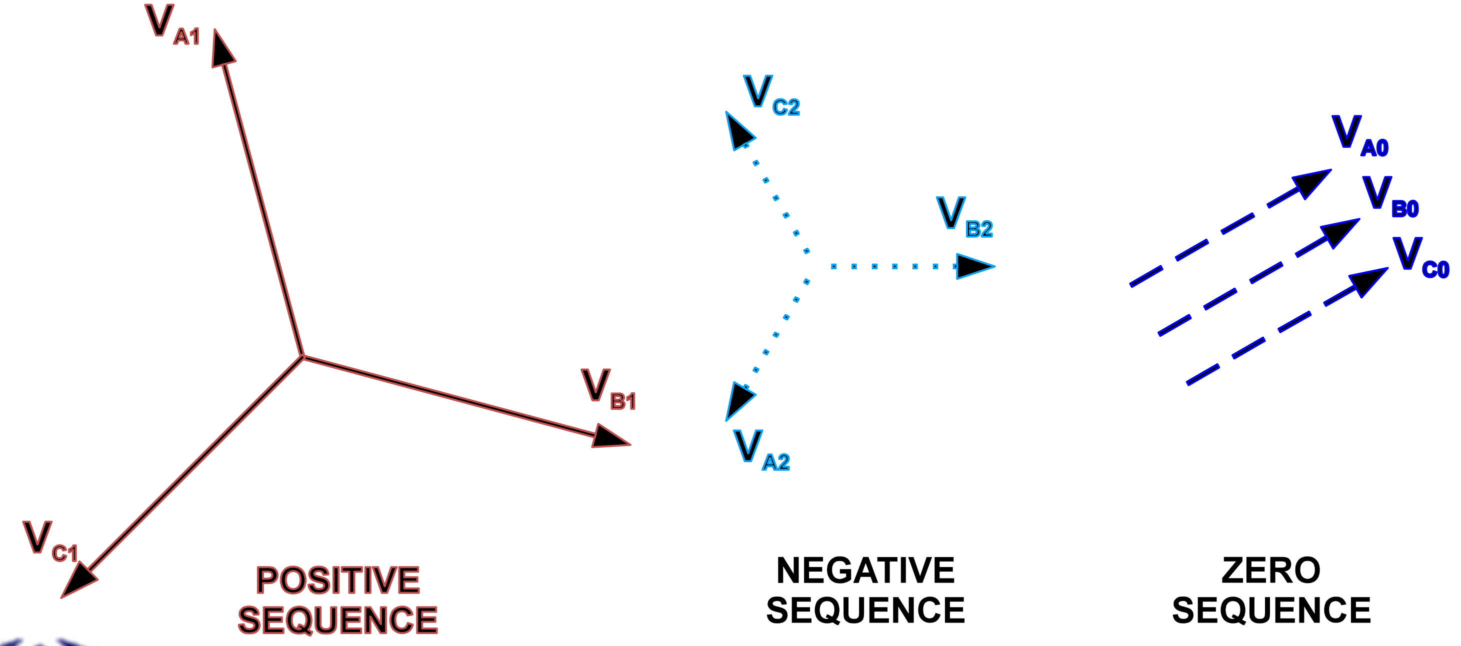
$V_A = V_{A1} + V_{A2} + V_{A0}$

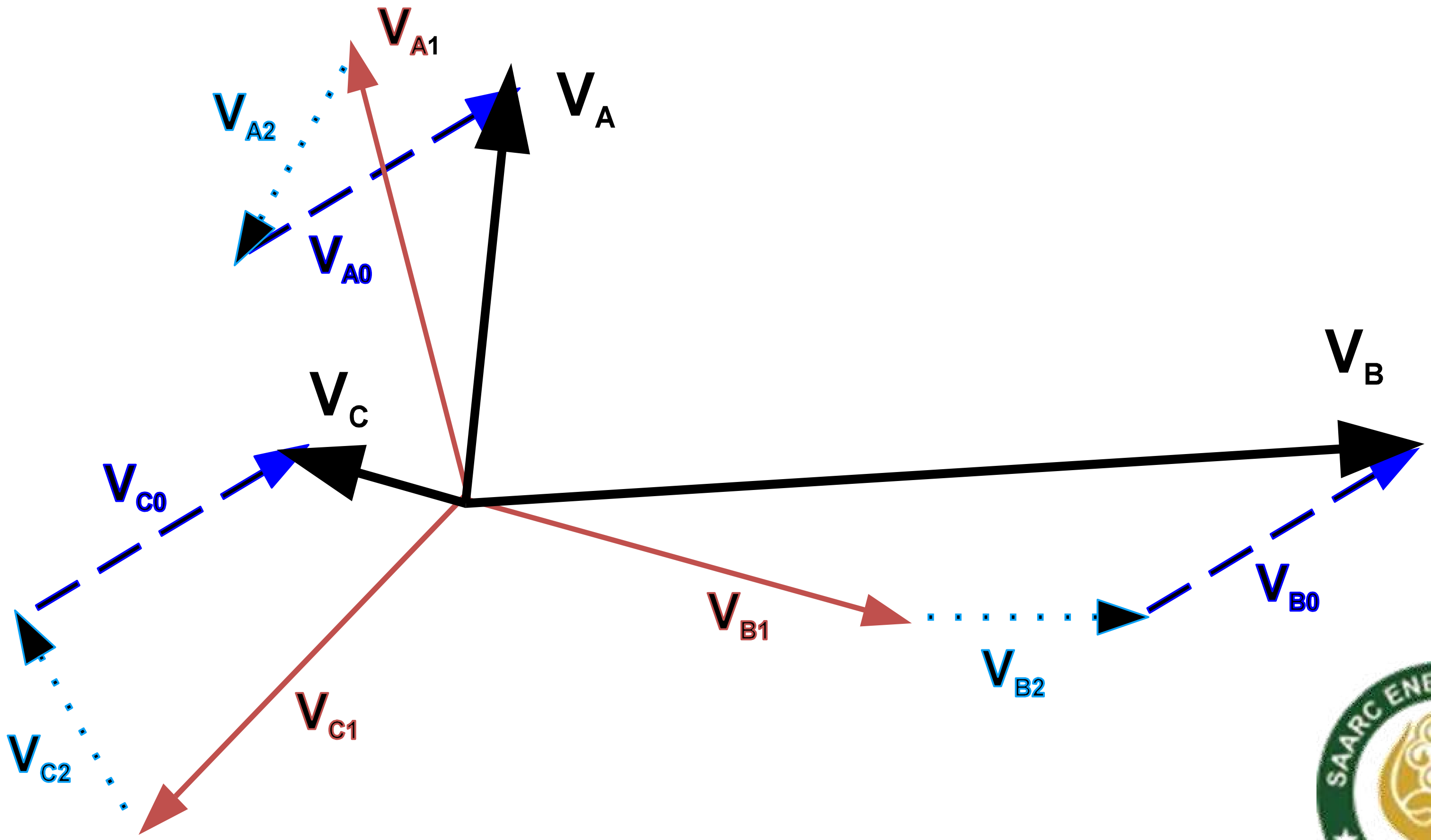
$V_B = V_{B1} + V_{B2} + V_{B0}$

$V_C = V_{C1} + V_{C2} + V_{C0}$





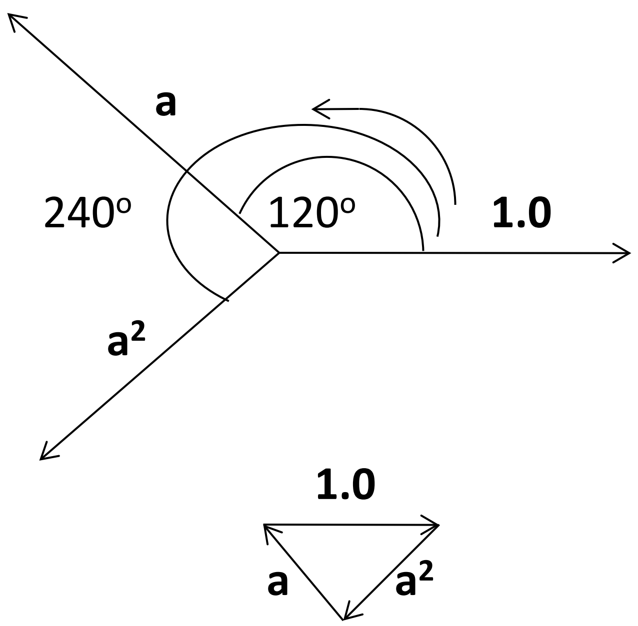




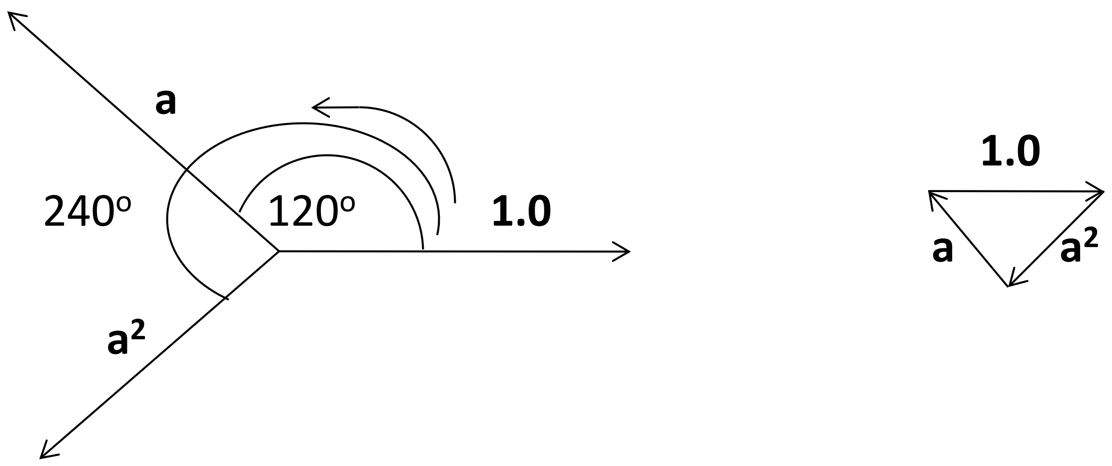
Symmetrical Components Theory
Unit Vector or Operator ‘a’

- Just as the operator j rotates the vector by 90°, we define a unit vector or operator ‘a’ , which when multiplied to a vector rotates the vector through 120° in anticlockwise direction

$$a = e^{j120} = \cos 120 + j \sin 120$$
$$= -0.5 + j0.866$$
$$= 1.0 \angle 120$$
$$a^2 = 1.0 \angle 120 \times 1.0 \angle 120$$
$$= 1.0 \angle 240$$
$$= -0.5 - j0.866$$
$$1 + a + a^2 = 0$$



- If a vector is multiplied by operator ‘a’ the vector is rotated by 120°
- If a vector is multiplied by operator ‘a^2’ the vector is rotated by 240°



Symmetrical Components Theory
Voltage & Current Equations

$$V_{A1} = \frac{1}{3}.\left(V_A + aV_B + a^2V_C\right)$$

$$V_{A2} = \frac{1}{3}.\left(V_A + a^2V_B + aV_C\right)$$

$$V_{A0} = \frac{1}{3}.\left(V_A + V_B + V_C\right)$$

$$I_{A1} = \frac{1}{3}.\left(I_A + aI_B + a^2I_C\right)$$

$$I_{A2} = \frac{1}{3}.\left(I_A + a^2I_B + aI_C\right)$$

$$I_{A0} = \frac{1}{3}.\left(I_A + I_B + I_C\right)$$

$$V_A = V_{A1} + V_{A2} + V_{A0}$$

$$V_B = a^2V_{A1} + aV_{A2} + V_{A0}$$

$$V_C = aV_{A1} + a^2V_{A2} + V_{A0}$$

$$I_A = I_{A1} + I_{A2} + I_{A0}$$

$$I_B = a^2I_{A1} + aI_{A2} + I_{A0}$$

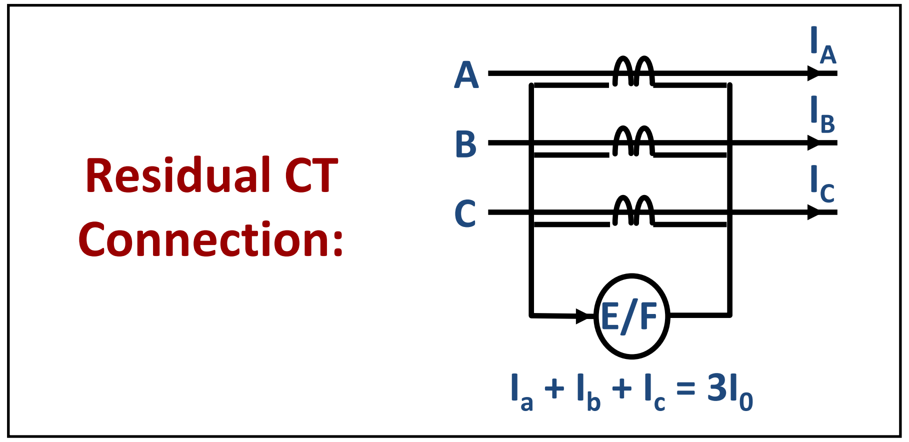
$$I_C = aI_{A1} + a^2I_{A2} + I_{A0}$$

Symmetrical Components Practical Considerations

- Under balanced conditions the system generates only positive sequence currents and voltages
  - normal operation
  - three-phase faults
- Negative sequence currents and voltages occur as a result of unbalance on the system
  - unbalanced loading
  - unbalanced faults
- Zero sequence currents and voltages occur as a result of an earth fault on the system

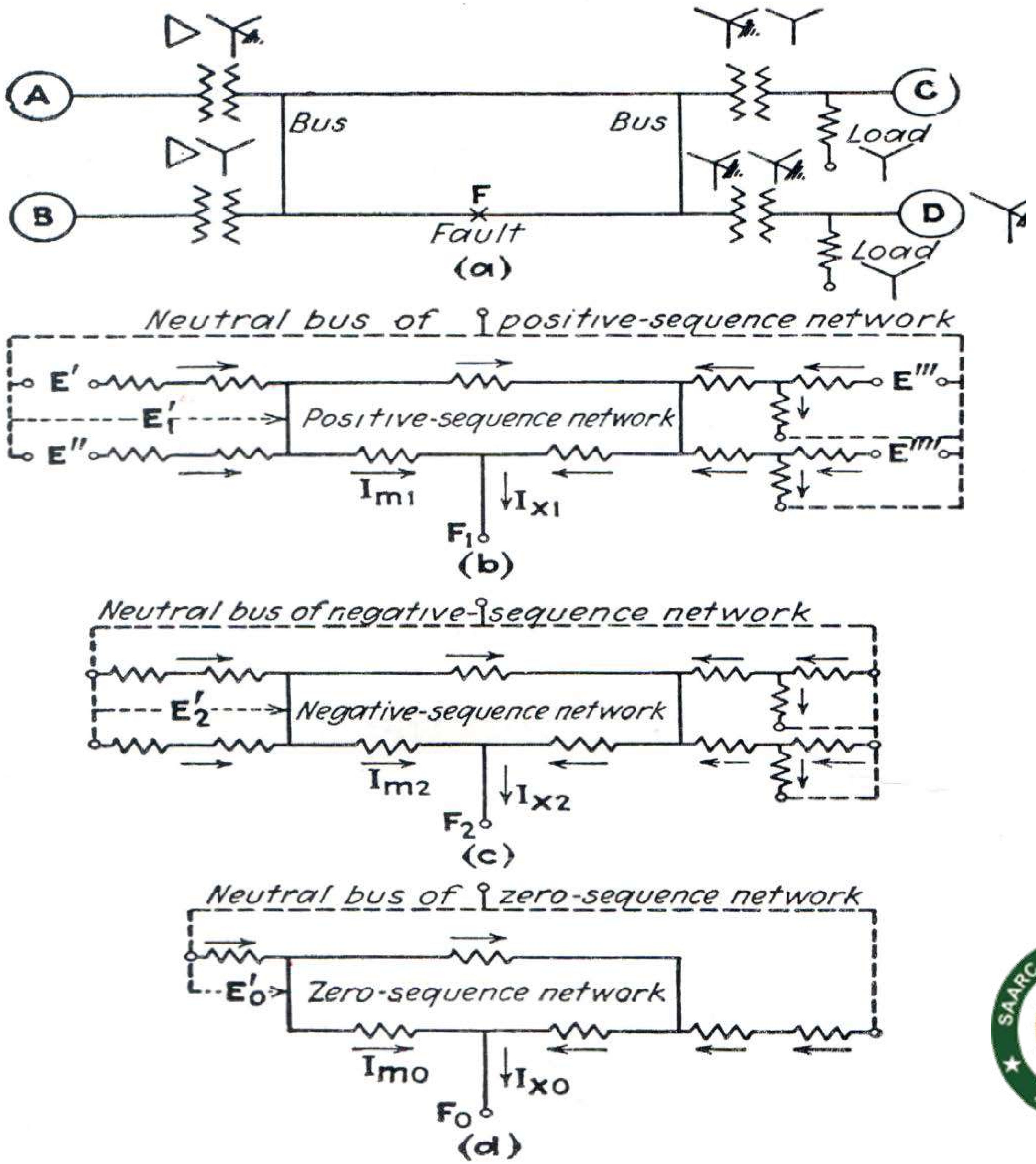
$$I_0 = \frac{1}{3}.\left(I_A + I_B + I_C\right)$$

$$I_0 = \frac{1}{3}.\left(\text{Residual Current}\right)$$



Network Modeling with Symmetrical Components

- Generators A, B, C and D
- GSU of A Δ-Y grounded
- GSU of B Δ-Y ungrounded
- TF1 receiving end Y-Y (G/UG)
- TF 2receiving end Y-Y (G/G)
- Gen C ungrounded
- Gen D grounded
- Loads: Y ungrounded
- Transmission line: double circuit



Single-Phase to Ground Fault (L-G)

- The conditions will be

$$E_x = 0 \qquad I_y = 0 \qquad I_z = 0$$

- The symmetrical components of current are

$$I_{x0} = \frac{1}{3}(I_x + I_y + I_z) = \frac{1}{3}(I_x)$$

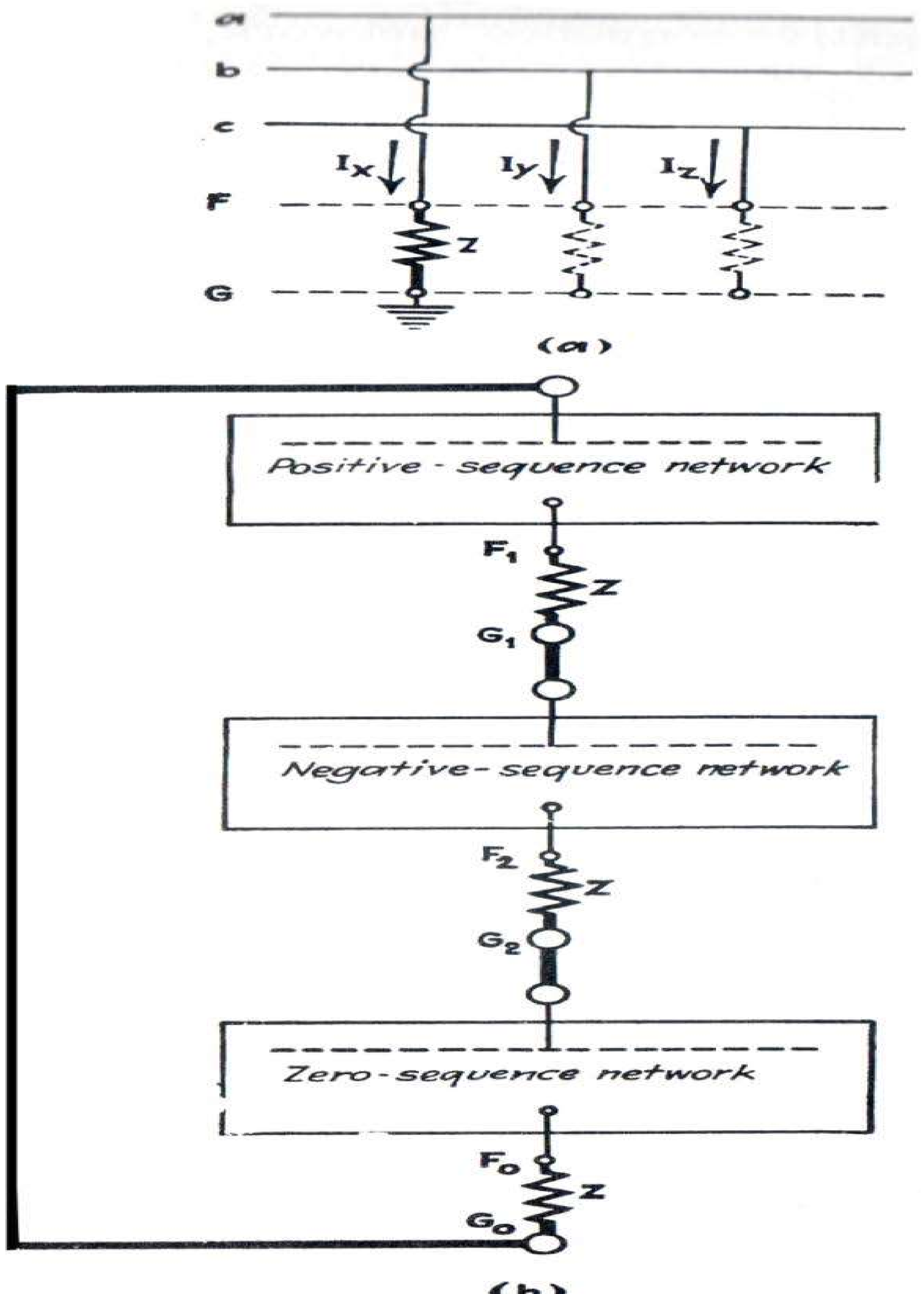
$$I_{x1} = \frac{1}{3}(I_x + aI_y + a^2 I_z) = \frac{1}{3}(I_x)$$

$$I_{x2} = \frac{1}{3}(I_x + a^2 I_y + a I_z) = \frac{1}{3}(I_x)$$

- Therefore

$$I_{x0} = I_{x1} = I_{x2}$$

- For same current to flow through Positive, Negative and Zero Sequence networks, they are to be connected in series



Line-to-Line Fault (L-L)

- The conditions will be

$$I_x = 0 \qquad I_y = -I_z \qquad E_y = E_z$$

- The symmetrical components of current are

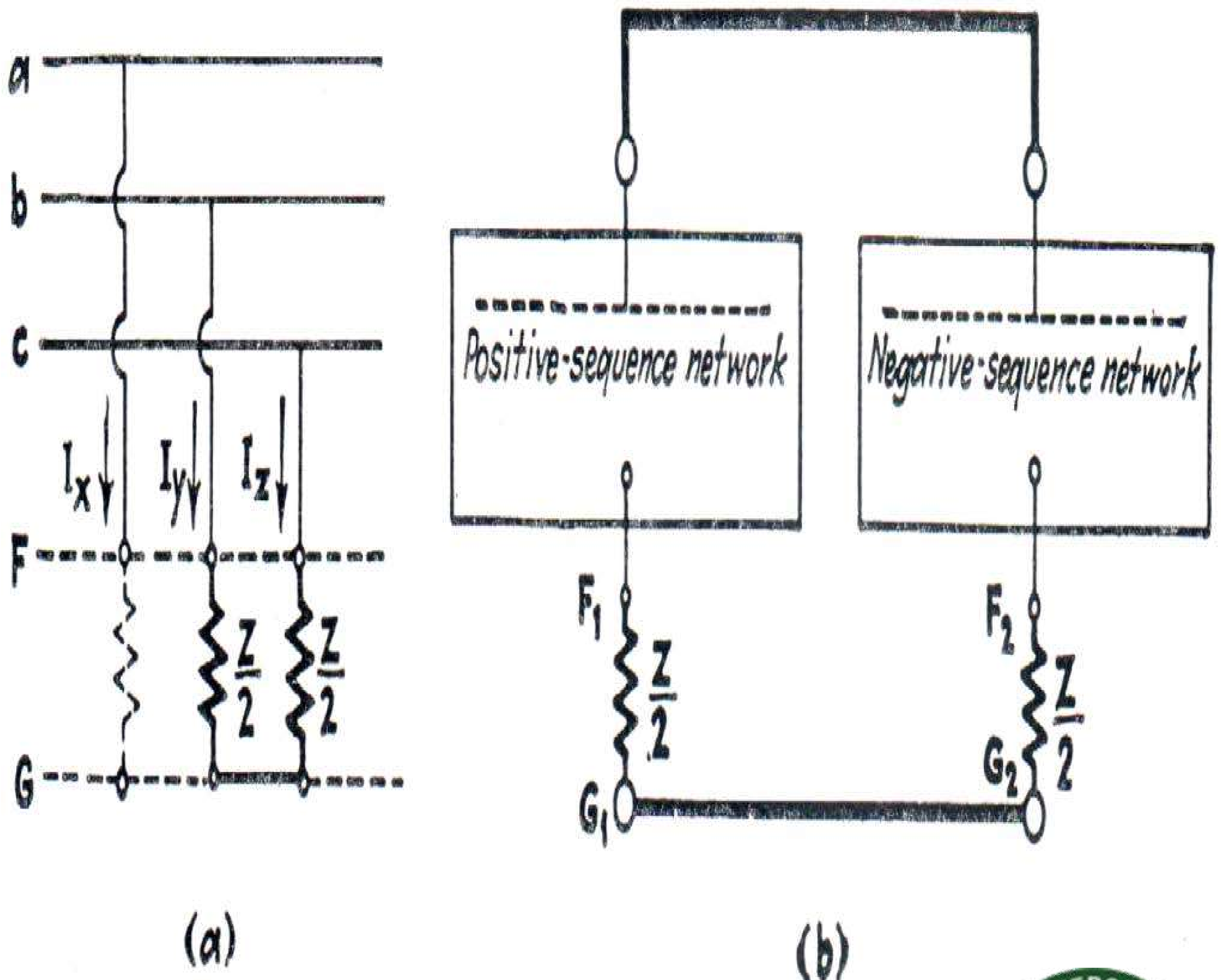
$$I_{x0} = \frac{1}{3}(I_x + I_y + I_z) = \frac{1}{3}(0 - I_z + I_z) = 0$$

- Substitute

$$E_{x1} = \frac{1}{3}(E_x + aE_y + a^2 E_z) = \frac{1}{3}(E_x + (a + a^2)E_z$$

$$E_{x2} = \frac{1}{3}(E_x + a^2 E_y + a\, E_z) = \frac{1}{3}(E_x + (a + a^2)E_z$$

- Therefore $E_{x1} = E_{x2}$
- Since $I_{x0} = 0$
- Zero Sequence Network will not be considered
- Positive and Negative Sequence networks are to be connected in parallel



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Line-to-Line-to-Ground Fault (L-L-G)

- The conditions will be

$$I_x = 0 \qquad E_y = 0 \qquad E_z = 0$$

- The symmetrical components of Voltages are

$$E_{x0} = \frac{1}{3}(E_x + E_y + E_z) = \frac{1}{3}(E_x)$$

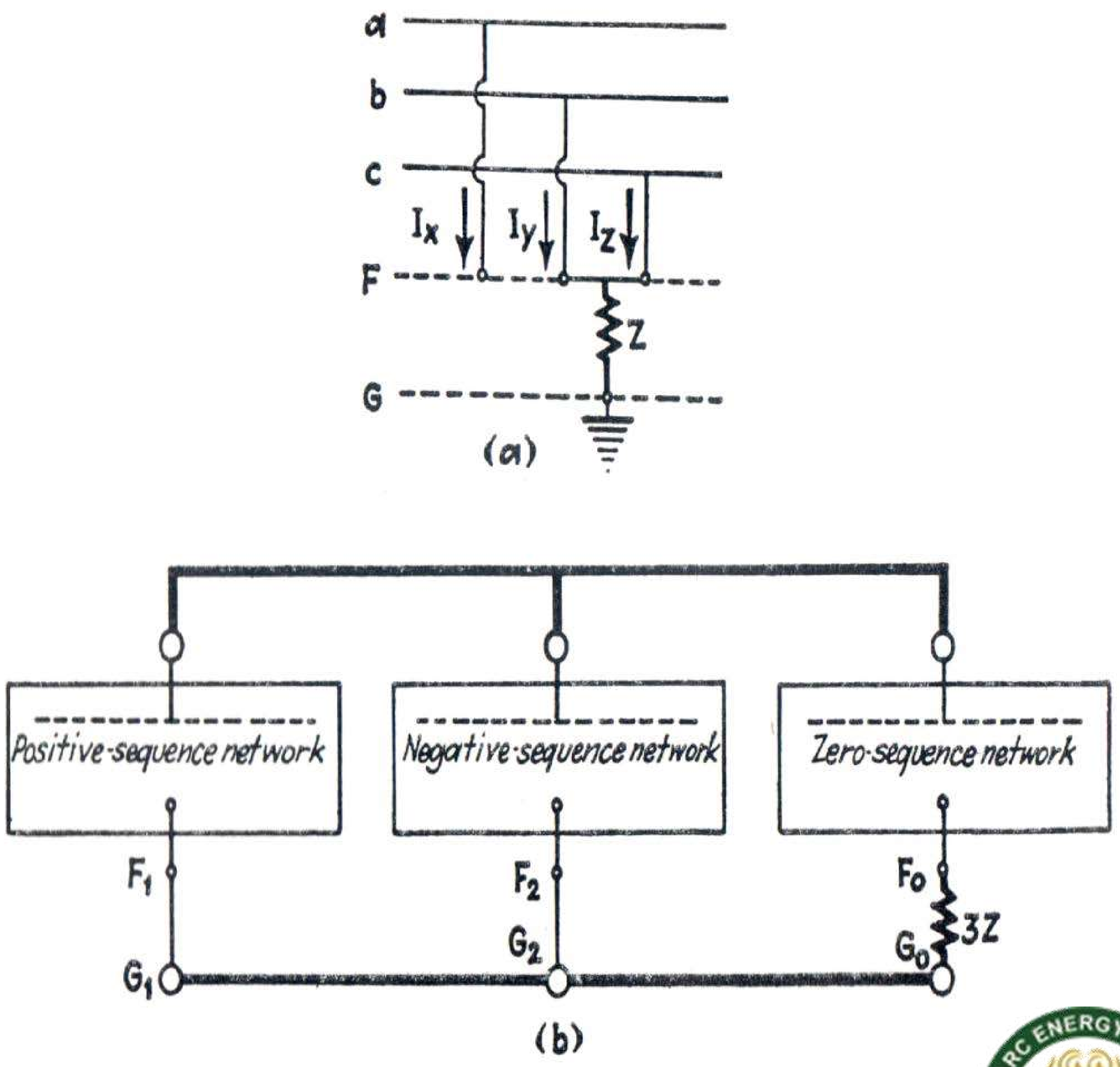
$$E_{x1} = \frac{1}{3}(E_x + aE_y + a^2 E_z) = \frac{1}{3}(E_x)$$

$$E_{x2} = \frac{1}{3}(E_x + a^2E_y + a\, E_z) = \frac{1}{3}(E_x)$$

- Therefore

$$E_{x0} = E_{x1} = E_{x2}$$

- For same voltage across Positive, Negative and Z
Sequence networks, they are to be connected in para

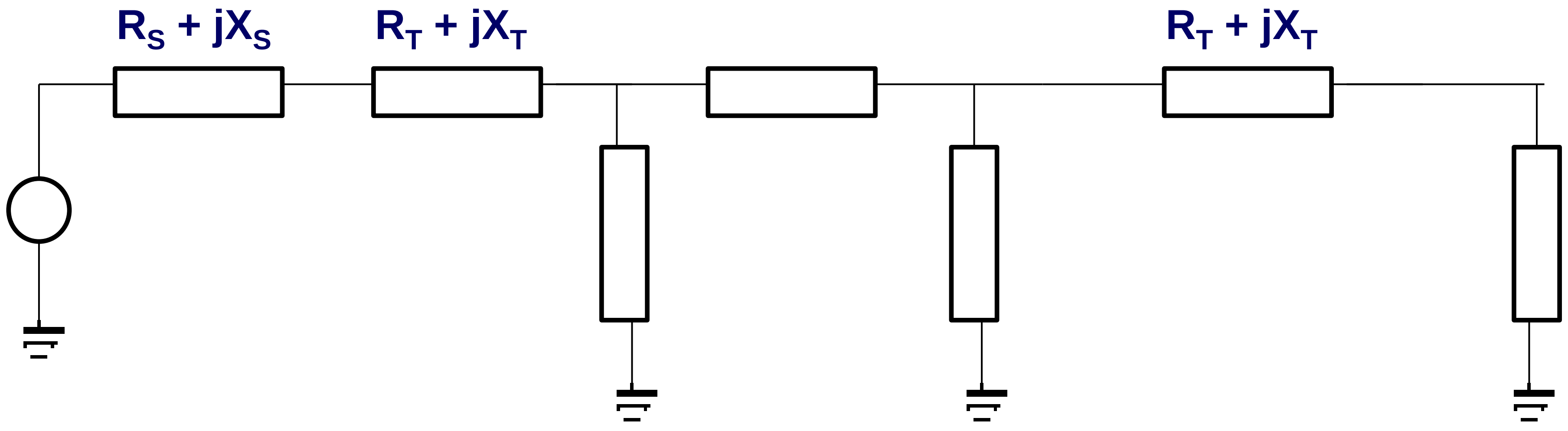


Equivalent Model of a Simple Power System Under Symmetrical Fault

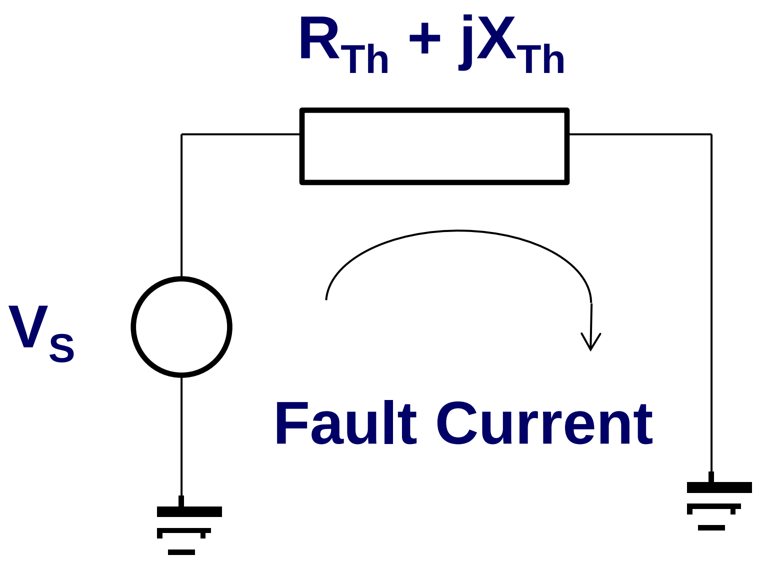
- Thevenin Equivalent for 3-Phased Symmetrical Faults
- Thevenin Impedance,

$$Z_{Th} = R_{Th} + jX_{Th}$$

- Pre-Fault Source Voltage = V_S
- Symmetrical 3-Phase Fault Current = $V_S / R_{Th} + jX_{Th}$
- Short Circuit MVA = $V_S * I_{Fault} = (V_S)^2 / Z_{Th}$



Transmission Line

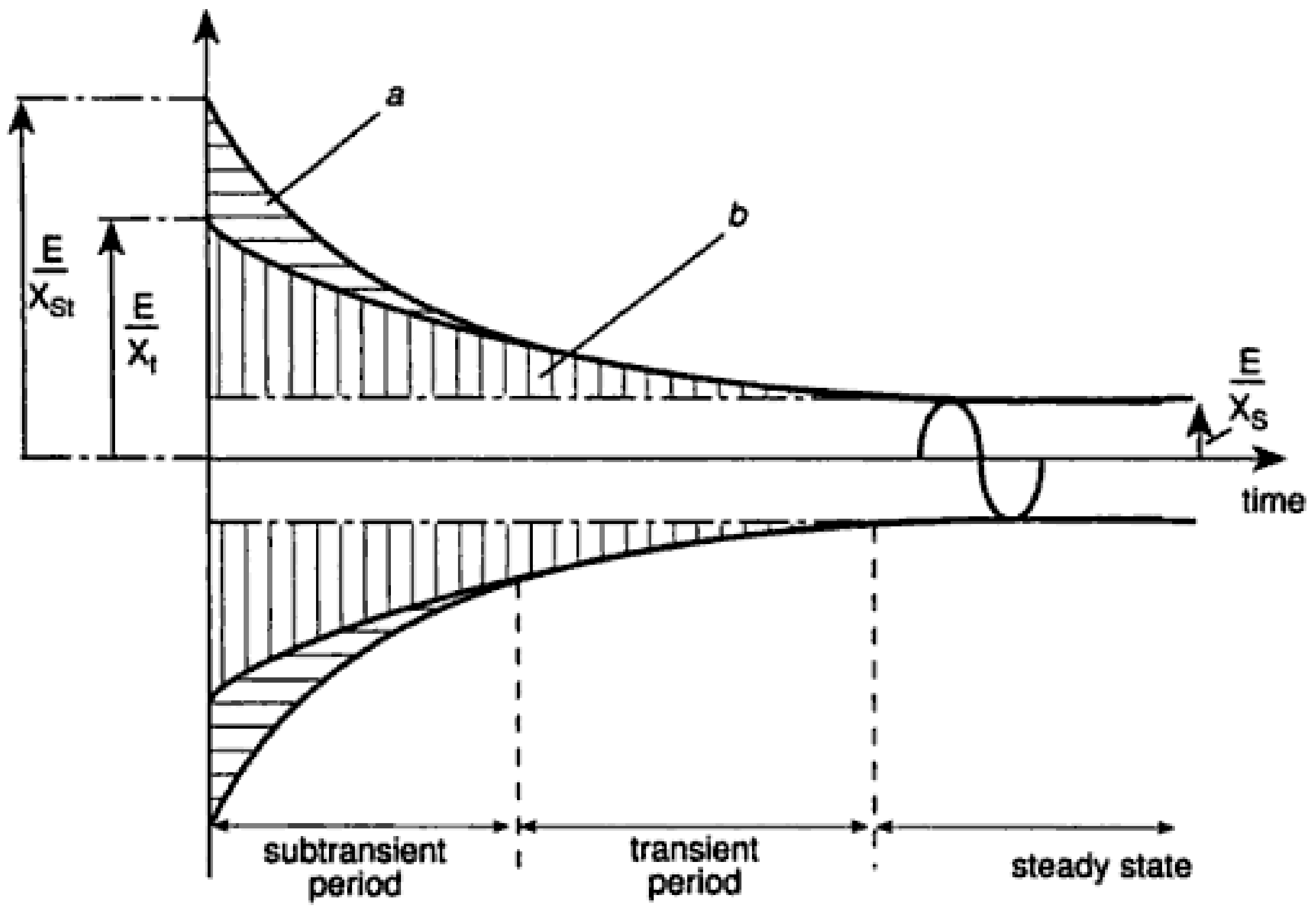


Generator under 3-Phase Symmetrical Fault

- Post Fault Scenario
- Sub-Transient period
  - Lasts few cycles
  - Current amplitude decays rapidly, say with a time constant of 20 ms (1 cycle)
- Transient period
  - Lasts 2-5 seconds
  - Current amplitude decays slowly, say with a time constant of 1 second
- Steady state period

  Current amplitude remains constant

  Symmetrical current envelop for 3-Phase fault as shown in Figure.



- Shaded area a = sub transient current decay
- Shaded area b = transient current decay

Generator under 3-Phase Symmetrical Fault

- At the instant of fault occurrence, the fault current is limited by sub transient reactance X_{st} or X'' or more appropriately X''_d

$$I_{SC} = I'' = \frac{E''}{X''_d}$$

- During transient period, the transient current is limited by transient reactance X_t or X' or X'_d

$$I' = \frac{E'}{X'_d}$$

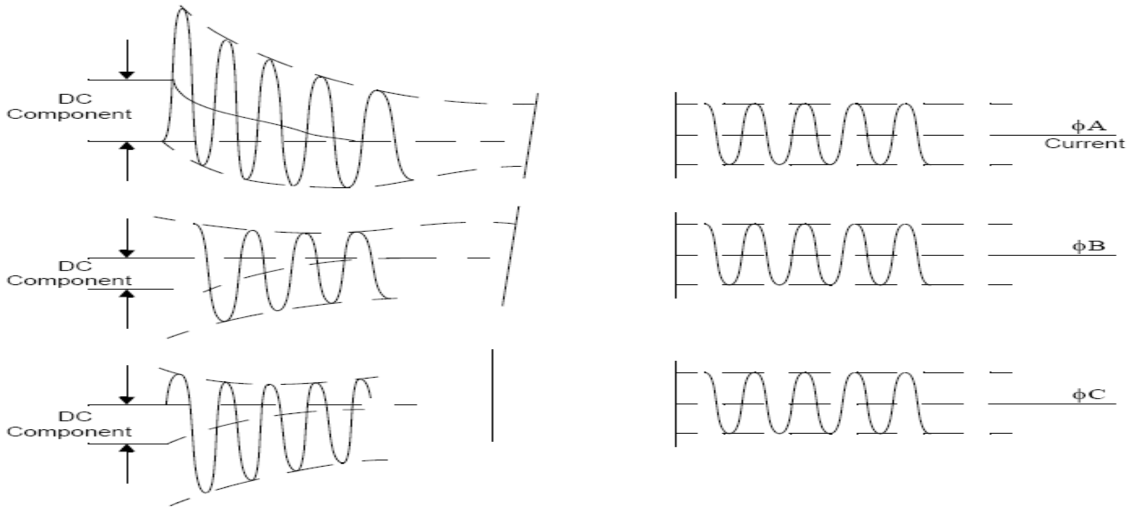
- During steady state the current is determined by synchronous reactance X_s or X_d

$$I = \frac{E}{X_d}$$

- For close-up faults the current supplied by the generator decays exponentially
- Generator is represented by different equivalent circuits depending on time elapsed since fault occurred
- Equivalent circuit used depends upon instant after fault for which analysis is required

AC and DC Components and Circuit Breaker Duty

- Sudden fault to a power system produces currents whose transient form as shown in figure
- Total fault current in each phase consists of:
  - An alternating component that decays from an
  - initial sub transient value to a final steady-state valu
  - A decaying unidirectional component



- Determination of circuit breaker duty requires the calculation of either of these values:
  - The maximum instantaneous value of current in any phase at the instant, a few milliseconds after fault initiation, when the circuit breaker contacts separate
  - The root-mean-square (rms) value of current wave consisting of sinusoidal component of constant amplitude equal to the instantaneous amplitude of the decaying alternating component at an instant, superimposed on a constant unidirectional component of amplitude equal to that of the decaying unidirectional component at the same instant

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AC and DC Components and Circuit Breaker Duty

- To determine these current amplitudes, the following data must be considered:
  - The alternating current component results from decaying machine internal flux linkages behind constant sub transient impedances of the machines
  - The unidirectional component is, at the instant of fault application, determined by the value of the alternating component
- Amplitude of the alternating and unidirectional (DC) components of current flowing in symmetrical faults and in the branches in the network
- The alternating and DC components are calculated for the instant of fault application and for a specified time after the fault initiation

AC and DC Components and Circuit Breaker Duty

- DC Current $I_{\mathrm{dc}} = I_{\mathrm{rms}} \times e^{-\omega t R/X}$
- AC Fault Current $I_{\mathrm{rms}} = I''_{\mathrm{k}}$
- Time from initiation of fault to start of breakers contacts opening For 220 and 500 kV

$$t = 0.03\ s$$

- For 132 kV and Below $t = 0.04\ s$
- X/R Ratio

$$\frac{X}{R} = \tan\theta$$

θ = Angle of I''_k

Asymmetrical Current

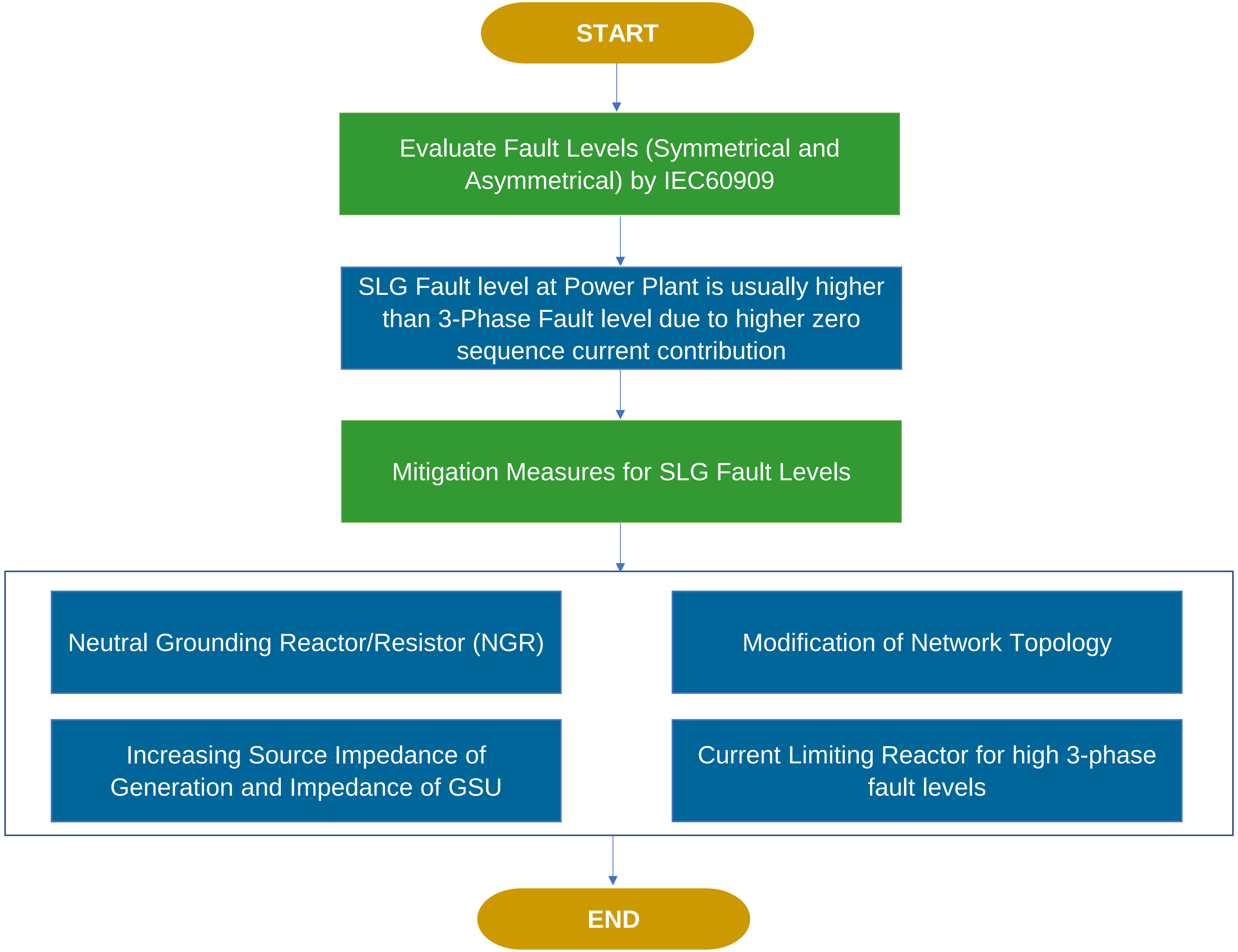
$$I_{total\ peak} = I_{dc} + I_{ac}$$

$$\text{Asymmetrical } I_{total\ rms} = \text{sqrt}\ (I_{dc}^2 + I_{rms}^2)$$

- I_{dc} – Instantaneous amplitude of unidirectional component
- I_{ac} – Peak amplitude of alternating component

$$I_{rns} = I_{ac} / \text{sqrt}(2)$$

Fault Currents Mitigation Measures



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Capacity Building on Advance & Innovative Transmission System Design and Optimization

Principle of Power Flow Study
Tools of Power Flow Analysis
(Day 1.2 D)

By

Hassan Jafar Zaidi

CEO, Power Planners International, Pakistan

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Under SAARC Energy Center

14th-16th October 2025 Thimphu, Bhutan

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Agenda

1. Basic Known Inputs to Power Flow Analysis
2. Why Iterative Method
3. Gauss Siedel Method
4. Newton Raphson Method
5. Solution Convergence Issues

Basic Known Inputs to Power Flow Calculations

1. Transmission line impedances (R+jX) and charging admittances (jB).
2. Transformer impedances and tap ratios (jX and Tap).
3. Admittances of shunt-connected devices such as static capacitors and reactors (jB or –jB).
4. Load-power consumption at each bus of the system (PL)
5. Real-power output of each generator or generating plant (PG).
6. Either voltage magnitude at each generator bus or reactive power output of each generating plant (|V| or MVAR).
7. Maximum and minimum reactive power output capability of each generating plant (MVARMAX and MVARMIN).

Basic Known Outputs of Power Flow Calculations

1. The magnitude of the voltage at each bus that this is not specified in the input data ($|V_i|$).
2. The phase of the voltage at every bus (θ_i).
3. The reactive power output of each plant that it is not specified (MVAR).
4. The real power (P_{ik}), reactive power (Q_{ik}), and current flow (I_{ik}) in each transmission line and transformer

Power Flow Solution

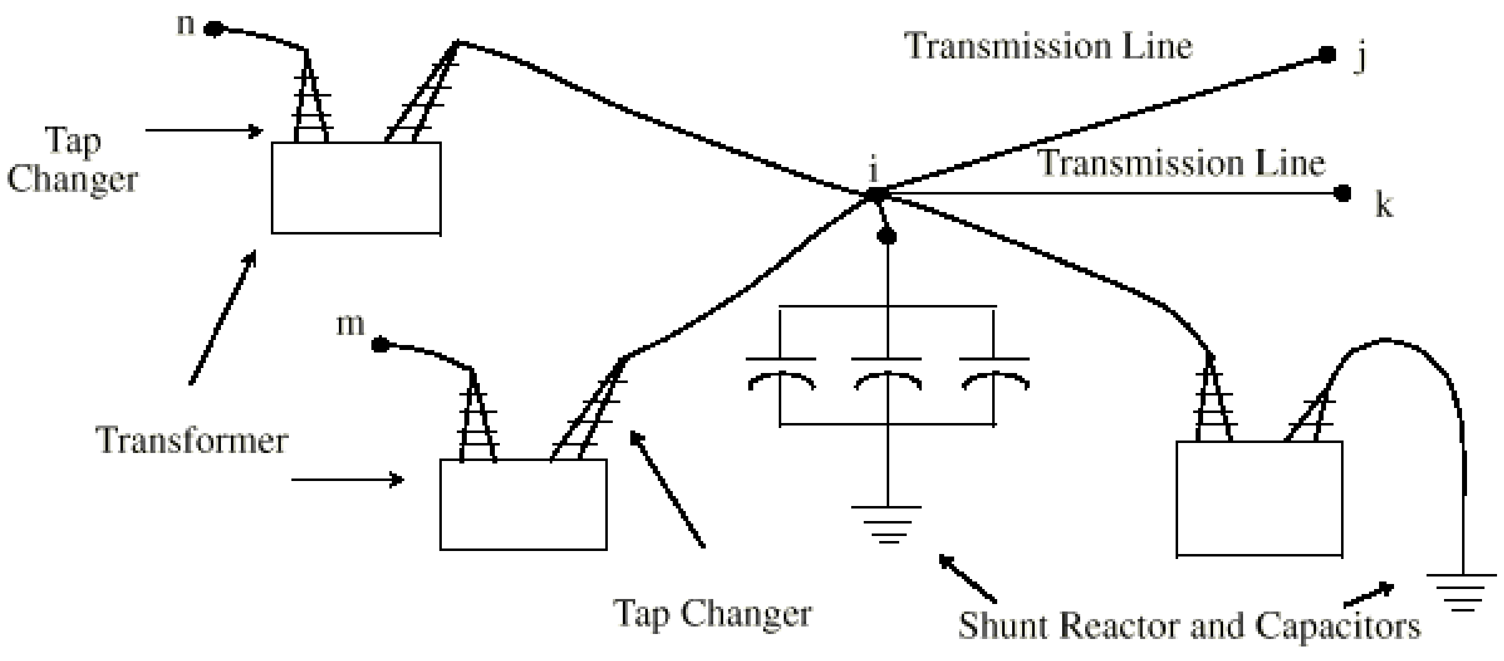
The network of transmission lines and transformers is described by the linear algebraic equation:

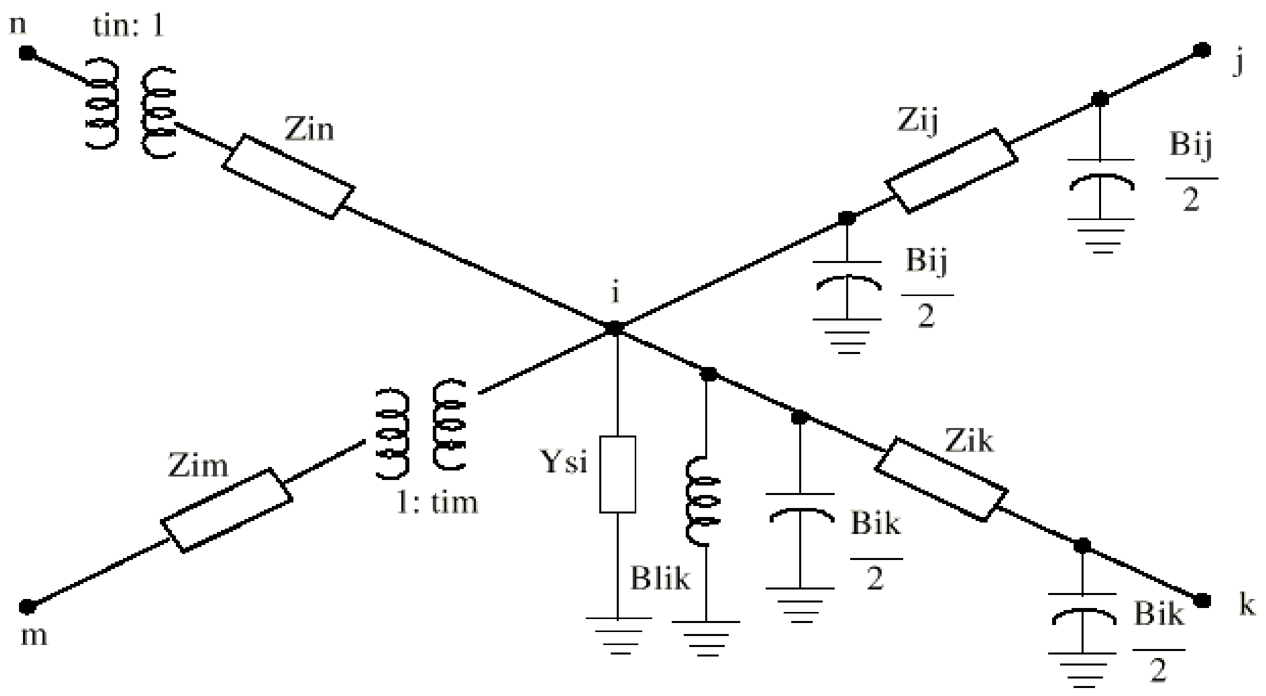
$$I_n = Y_{nn}V_n$$

where,

- I_n- Vector of positive-sequence currents flowing into the network at its buses.
- V_n- Vector of positive-sequence voltages at the network buses.
- Y_{nn} - Network admittance matrix.
- If either In or Vn is known, the power flow calculation is straightforward.
- In practice, neither In nor Vn is known and the task of the power flow program is to devise successive trials of both In and Vn such that the algebraic linear equation is satisfied

Network Admittance Matrix - Y_{nn}





- Node i connected to two transmission lines, two transformers, a shunt capacitor and a shunt reactor.
- Each element can be represented by per unit equivalent circuit

Network Admittance Matrix - Y_{nn}

- There are two elements in the admittance matrix:
  - Diagonal element $\mathbf{Y_{nn}}$ is summing of all line or transformer impedance that are connected to the particular bus m.
  - Non-diagonal element $\mathbf{Y_{jk}}$ is negative of the line or transformer impedance that connected between bus **i** and **k**
- The impedance matrix can be expressed as follows:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix}$$

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Network Admittance Matrix - Y_{nn}

- The total current, i_i , flowing into node i when voltages, v_i, v_j, v_k, v_m, and v_n are applied to the network may be determined by adding up the flow into each leg at its connection to node i.

$$
\begin{aligned}
i_i = {} & v_i Y_{si} \\
& + (v_i - v_j)/z_{ij} + \frac{v_i B_{ik}}{2} \\
& + (v_i - v_k)/z_{ik} + \frac{v_i B_{ik}}{2} + v_i B_{lik} \\
& + \left(\frac{v_i}{t_{im}} - v_m\right)/(z_{im} t_{im}) \\
& + \left(v_i - \frac{v_n}{t_{im}}\right)/z_{in}
\end{aligned}
$$

- Other nodes can be calculated by the same procedure

Network Admittance Matrix - Y_{nn}

- Expansion of the i-th element of I_n , which is i_i , gives

$$i_i = \sum_{n=1}^{n} y_{ih} v_h$$

- where, y_{ih} are the elements of Y_{nn} and v_h are the elements of the node voltage vector, v_n
- The construction of the individual elements, y_{ih} , of the network admittance matrix from the line and transformer data is a key section of all power flow solution procedures of PSS/E.

Usually there are 2 or 3 transmission lines or transformers that are connected to a node.

A transmission network of 2000 buses might, therefore, be expected to have approximately 4000 branches and, correspondingly, 8000 nonzero off-diagonal elements in its admittance matrix.

This typical bus-to-branch ratio results in very sparse admittance matrices.

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Network Admittance Matrix - Y_{nn}

- The admittance matrix is symmetrical, sparse, and constant since they contain only network admittances.
- This is less or more important according to the power-system size and computing environment platform.
- Therefore, many methods are proposed to handle the sparse matrix.
- The sparse matrix method is used principally in the majority of power system analyses.
- Using sparsity technique, only non-zero elements are stored; thus, the storage requirements can be minimized.
- The linear equations can also be solved using sparsity technique such as in the LU decomposition method proposed by Tinney and Walker.

Network Admittance Matrix - Y_{nn}

- Modern power flow calculation programs, including PSS/E, take advantage of this sparsity in their management of computer storage.
- The sparsity techniques are designed to be:
  - partial inverse forms which have similar sparsity properties
  - but whose number of nonzero off-diagonal elements is typically two to three times the number of such elements in the original Y_{nn} matrix
  - manipulated into triangular factor

If the allocation of number of nonzero elements exceed the program's allocated capacity, the program results in an error condition that prevents the use of some, but not all, of the available power flow iteration algorithms.

Y-matrix iterative methods: There were the first practical methods applied to automatic digital solution. Although they perform satisfactorily on many problems, requiring minimal computer storage, they converge relatively slowly and are sensitive to system parameters and conditions.

Z-matrix iterative methods: These methods are more reliable than the Y-matrix methods but require very much more computer storage.

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Iterative Power Flow Solutions

The power flow problem is nonlinear and requires an iterative trial and error process for its solution. One simple but effective iterative scheme can be given as follows:

- Step 1: Make an initial estimate of the voltage at each bus.
- Step 2: Build up an estimated current inflow vector, In, at each bus from a boundary condition such as:

$$P_k + jQ_k = V_k I_k^*$$

- Step 3: Obtain a new estimate of the bus voltage vector, Vn.
- Step 4: Return to Step 2 and repeat the cycle until it converges on an unchanging estimate of Vn.

While this scheme is useful in some specific situations, it does not work well for the general power flow calculation where the terminal voltage magnitude, rather than reactive power output, is specified for many generators.

Iterative Power Flow Solutions

PSS/E (Software of Siemens-PTI) allows the user to choose from five different AC power flow iteration schemes:

- Gauss-Seidel iteration
- Modified Gauss-Seidel iteration suitable for series capacitors
- Fully coupled Newton-Raphson iteration
- Decoupled Newton-Raphson iteration
- Fixed slope Decoupled Newton-Raphson iteration

Gauss-Seidel Controls

ACCP - Acceleration factor for the real part of the voltage adjustment

ACCQ - Acceleration factor for the imaginary part of the voltage adjustment

TOL - Convergence tolerance in pu

ITMX - Default limit on number of iterations

BLOWUP - Largest voltage change threshold

Gauss-Seidel Rules and Convergence Characteristics

- Negative reactance branches causes divergence of the solution
- The presence of very low impedance branches (e.g., jumpers with an impedance of j0.0001 pu) cause slow convergence as the voltage adjustments get small, and in mismatches at the buses involved
- The number of iterations required to reach the convergence tolerance increases as the system size increases
- Can be used if the initial voltage estimate is poor
- Is tolerant of data errors and insoluble conditions in local areas of the network. It is generally well converged everywhere except in the problem areas
- When it diverges, it usually fail gently

Newton-Raphson Power Flow Solution Methods

Differences from the Gauss method are:

- Tap and phase adjustment options are broken out to be independent
- Imposition of VAR limits has more options
- A non-divergent solution is available only for the full Newton and fixed slope decoupled Newton solutions

Newton-Raphson Solution Controls

ACCN - the acceleration factor

TOL - the largest mismatch in MW and Mvar

ITMXN - the maximum number of iterations

DVLIM - the largest change in bus voltage

NDVFCT - the non-divergence improvement factor

Fully Coupled Newton Raphson Method Rules and Characteristics

Continues its iteration until one of the following occurs:

- No active or reactive component of bus mismatch exceeds the bus power mismatch convergence tolerance, and all FACTS devices are satisfactory solved
- The iteration limit is exceeded
- The non-divergent solution option is disabled and the "blown up" condition is detected
- The non-divergent solution option is enabled and applying the current iteration's change vectors does not significantly reduce the system mismatch level

Continues its iteration until one of the following occurs:

- The user issues the "AB" interrupt control code
- A diagonal element of Jacobian matrix is near zero, indicating a singular matrix(Floating Point Error)

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