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Introduction to Grid Modelling

23rd March 2021

IRRP
INTEGRATED RESOURCE AND RESILIENCE PLANS

Team

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Learning Outcomes

- Appreciate grid modelling fundamentals.
- Appreciate the requirements to build a power system model in software.
- Appreciate steady state studies (power flow and short circuit analysis) and transient analysis.
- Identify the data requirements for accurate modelling and analyses.

Power Systems Basics

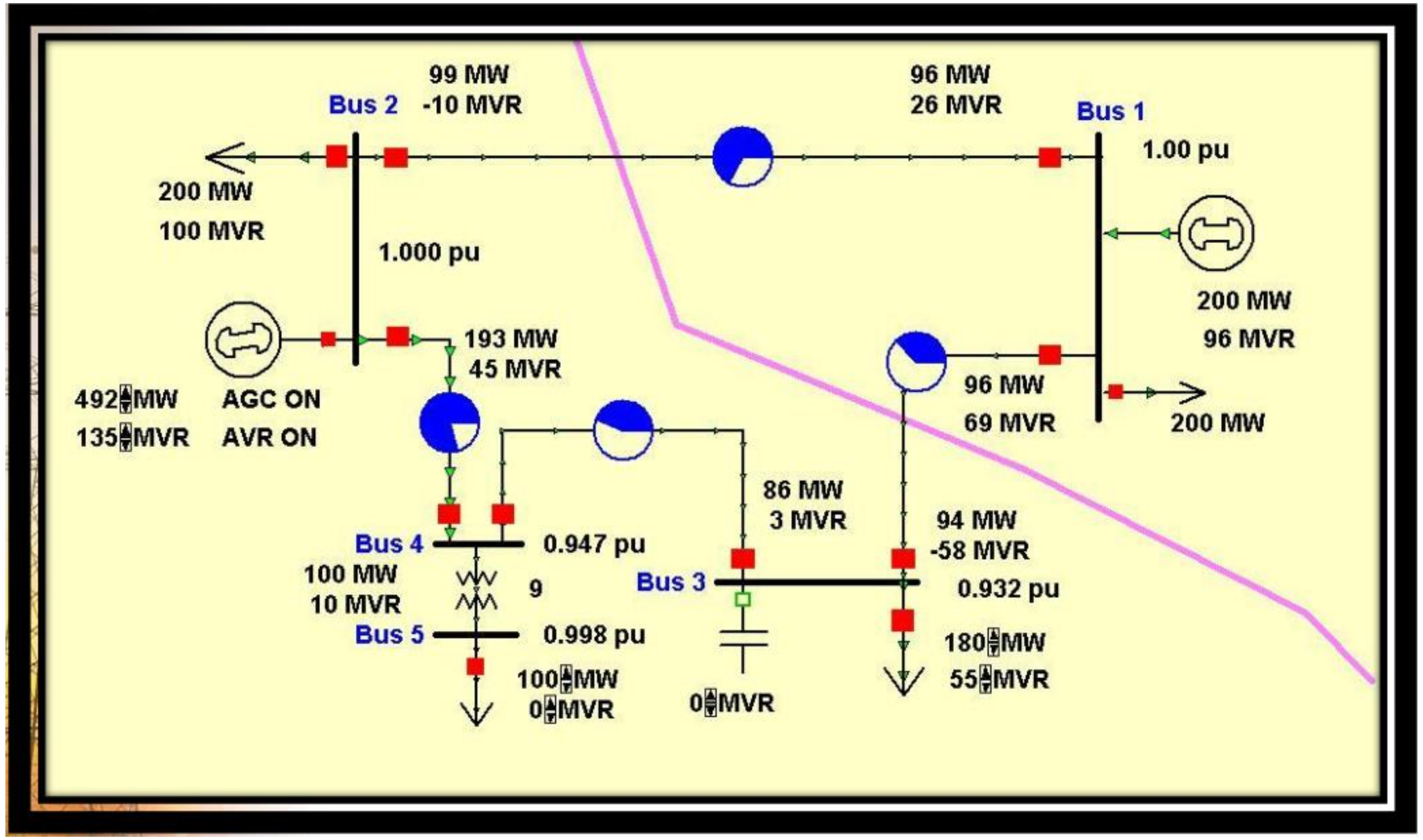
Simple Power System

Every power system has three major components

- Generation: source of power, ideally with a specified voltage and frequency
- Transmission system: transmits power; ideally as a perfect conductor
- Load: consumes power; ideally with a constant resistive value

Modelling Power Systems

Why model Power Systems?



Need to simulate real system to evaluate designs and operation tasks.

Simpler and more cost effective to implement.

Power Systems Analysis

CCREEE
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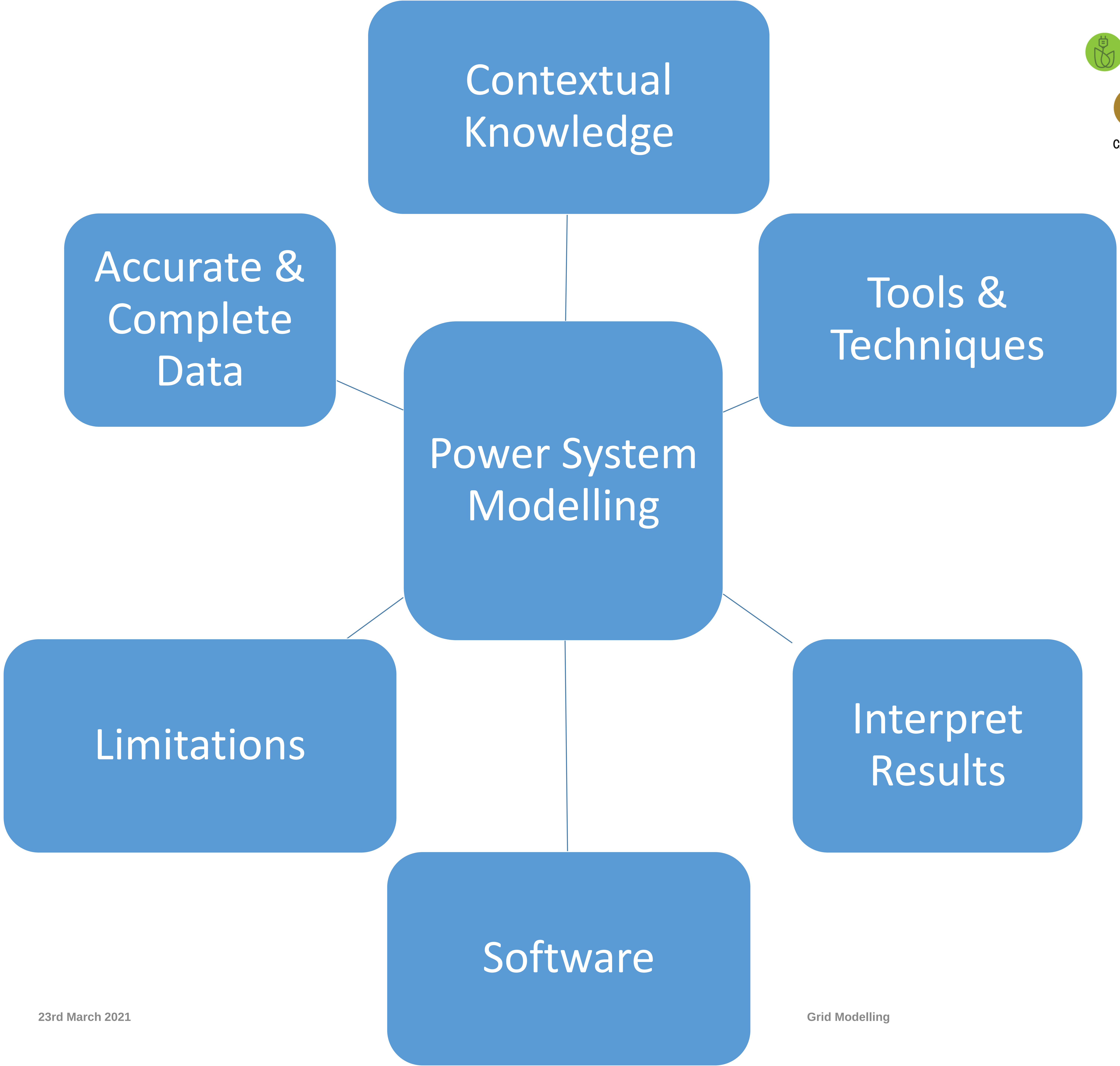
Practical Power Systems

- Safe
- Reliable
- Economical

Modelling Power Systems

- Planning & Expansion
- Operations
- Types of analysis
  - Transmission line performance
  - Power flow analysis
  - Contingency analysis
  - Economic generation scheduling
  - Fault analysis
  - Transient studies
- Requires component modeling



Contextual Knowledge

Accurate & Complete Data

Tools & Techniques

Power System Modelling

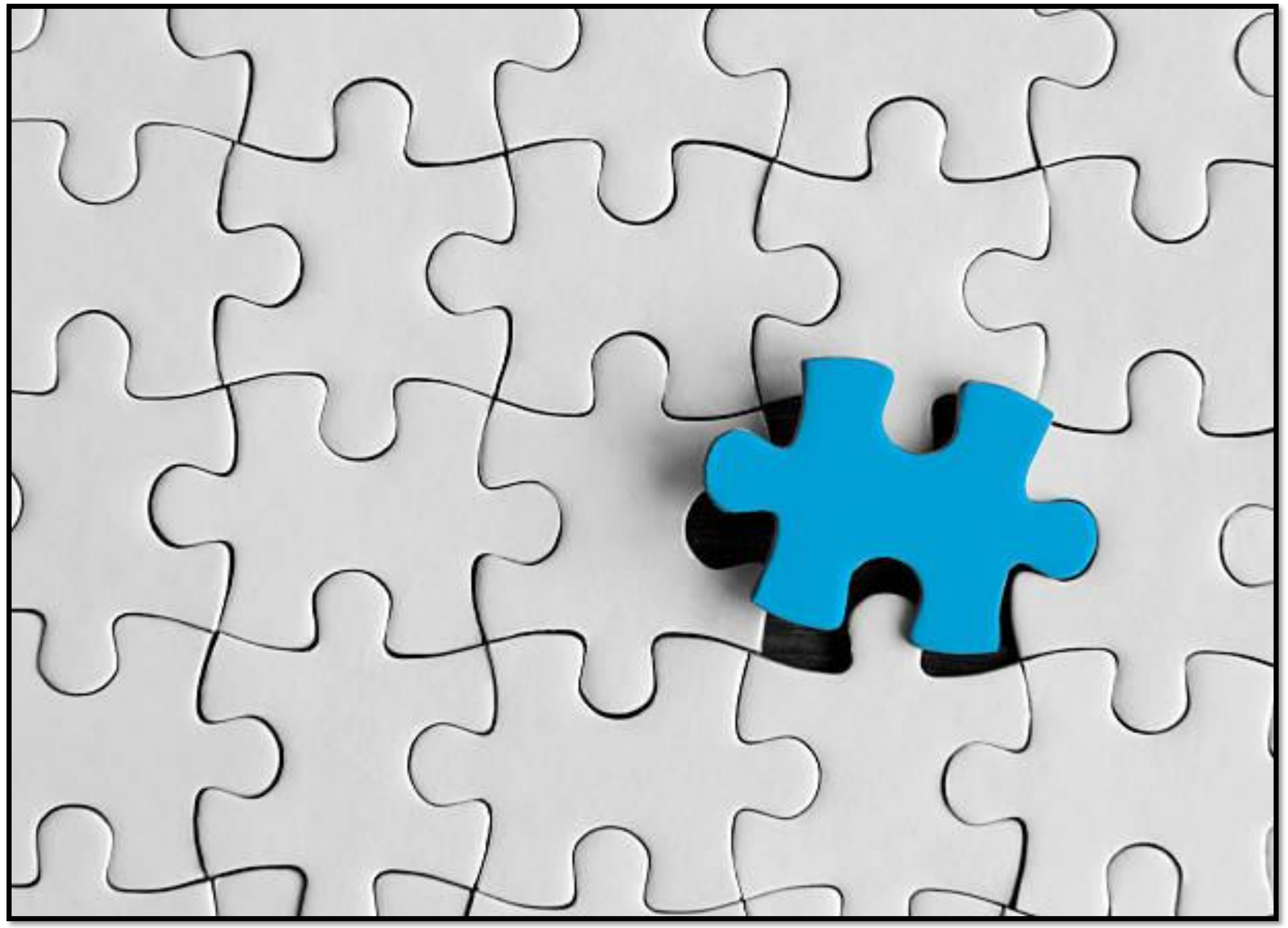
Limitations

Interpret Results

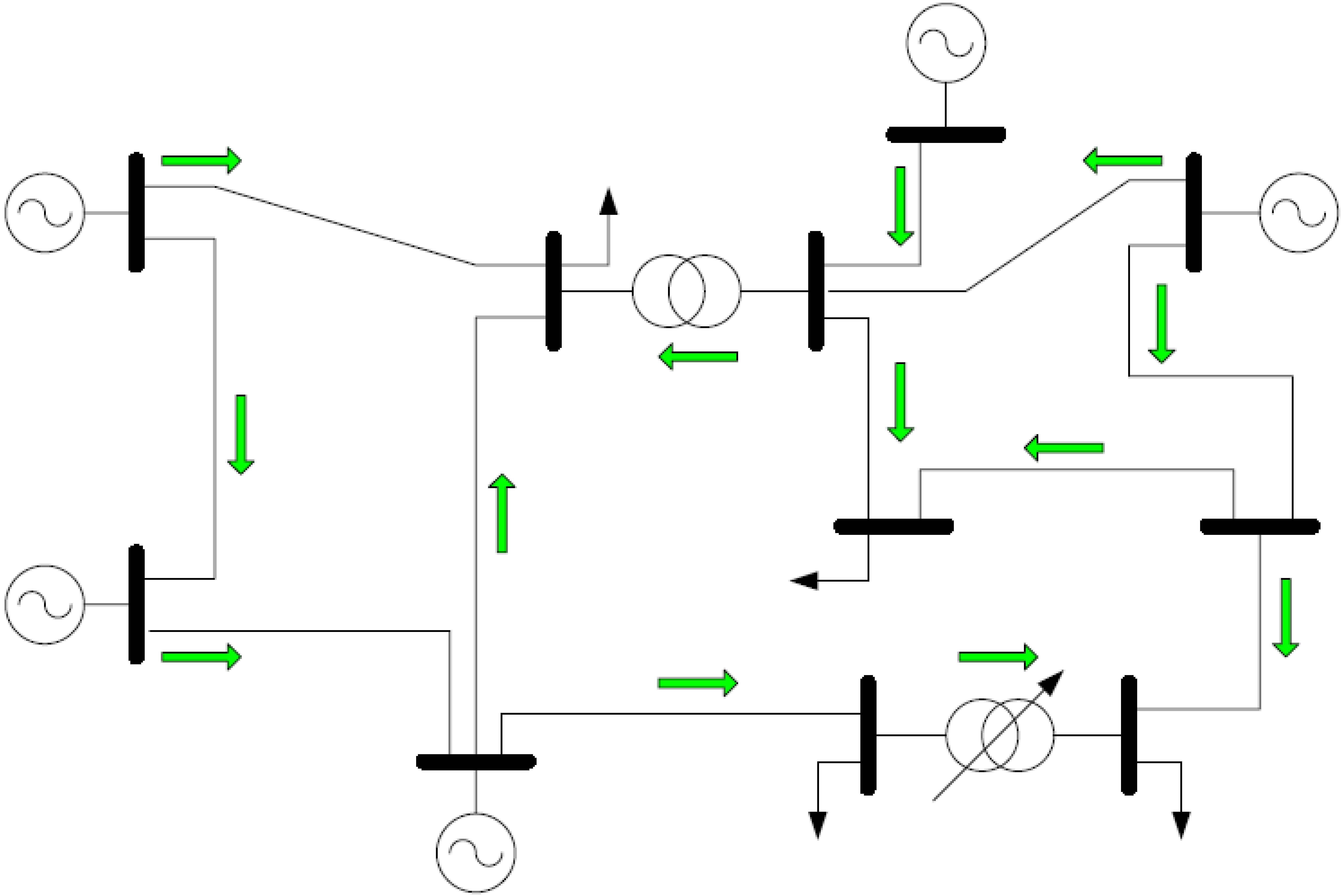
Software

Develop Technical Capacity

- Planning
  - Software familiarity
  - Missing data for models
- Operational
  - Data capture
  - Data analysis
  - Optimize
- Reduce outsourcing costs

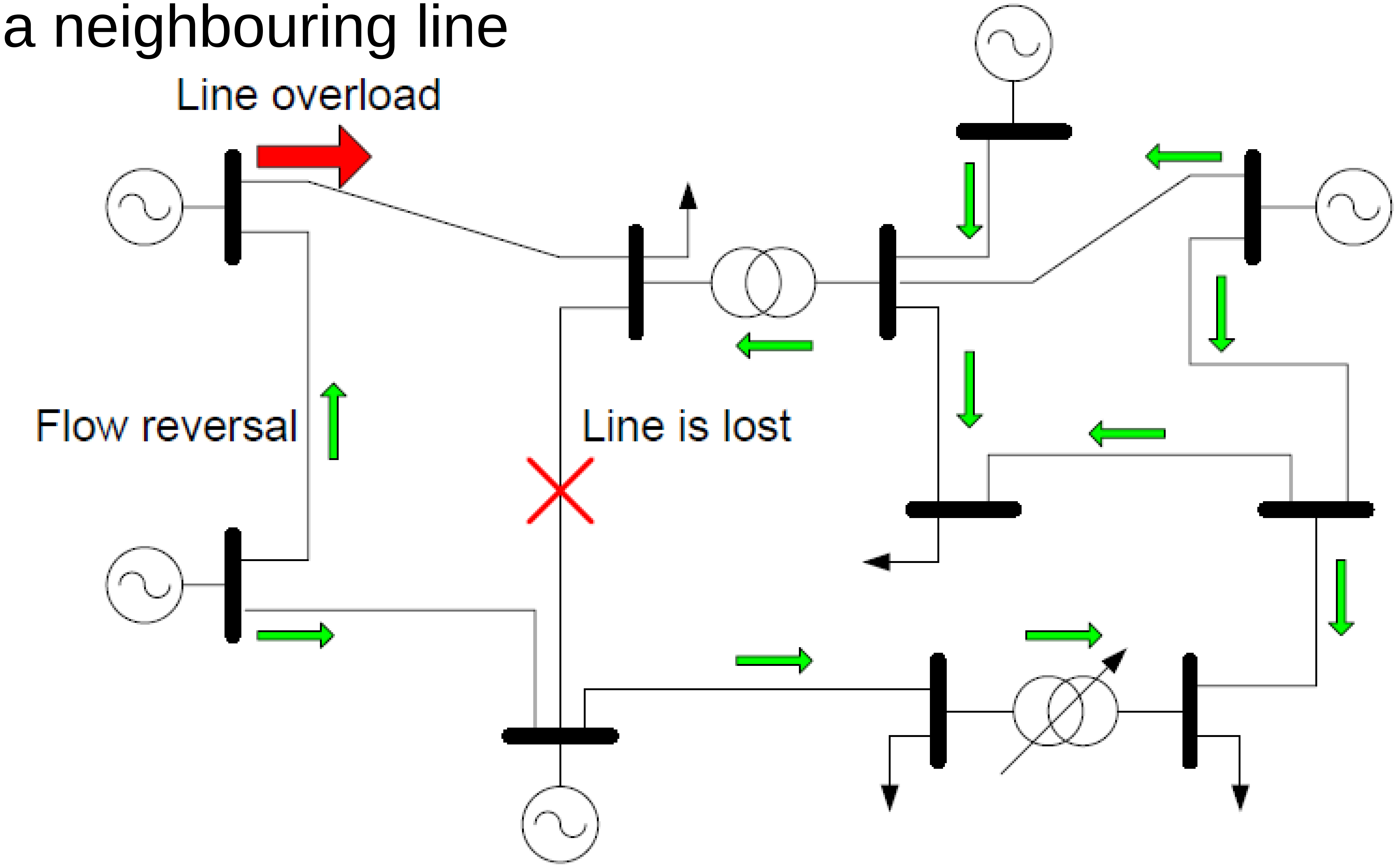


A Story of Cascading Outages



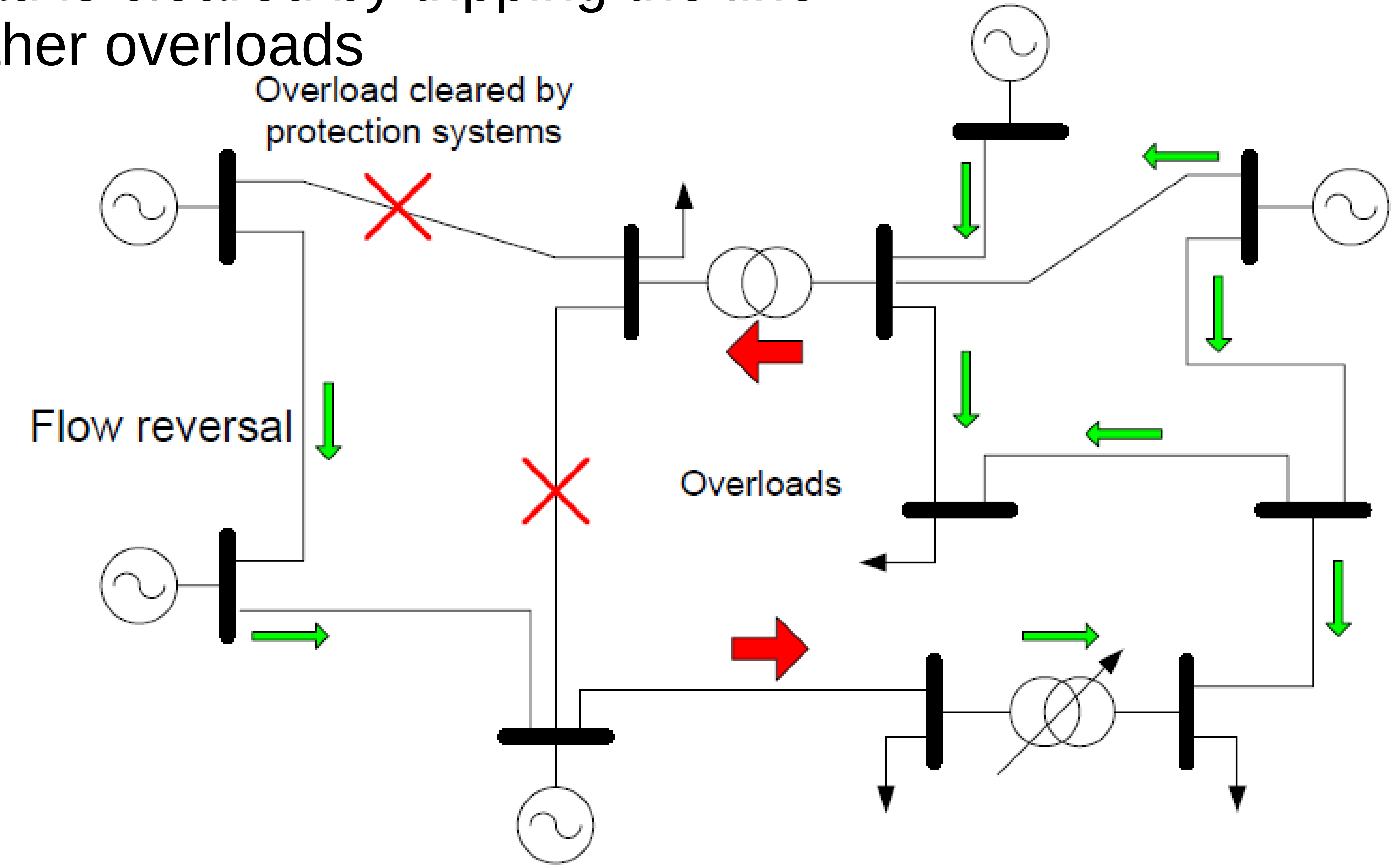
A Story of Cascading Outages

A line failure occurs and causes and overload on a neighbouring line



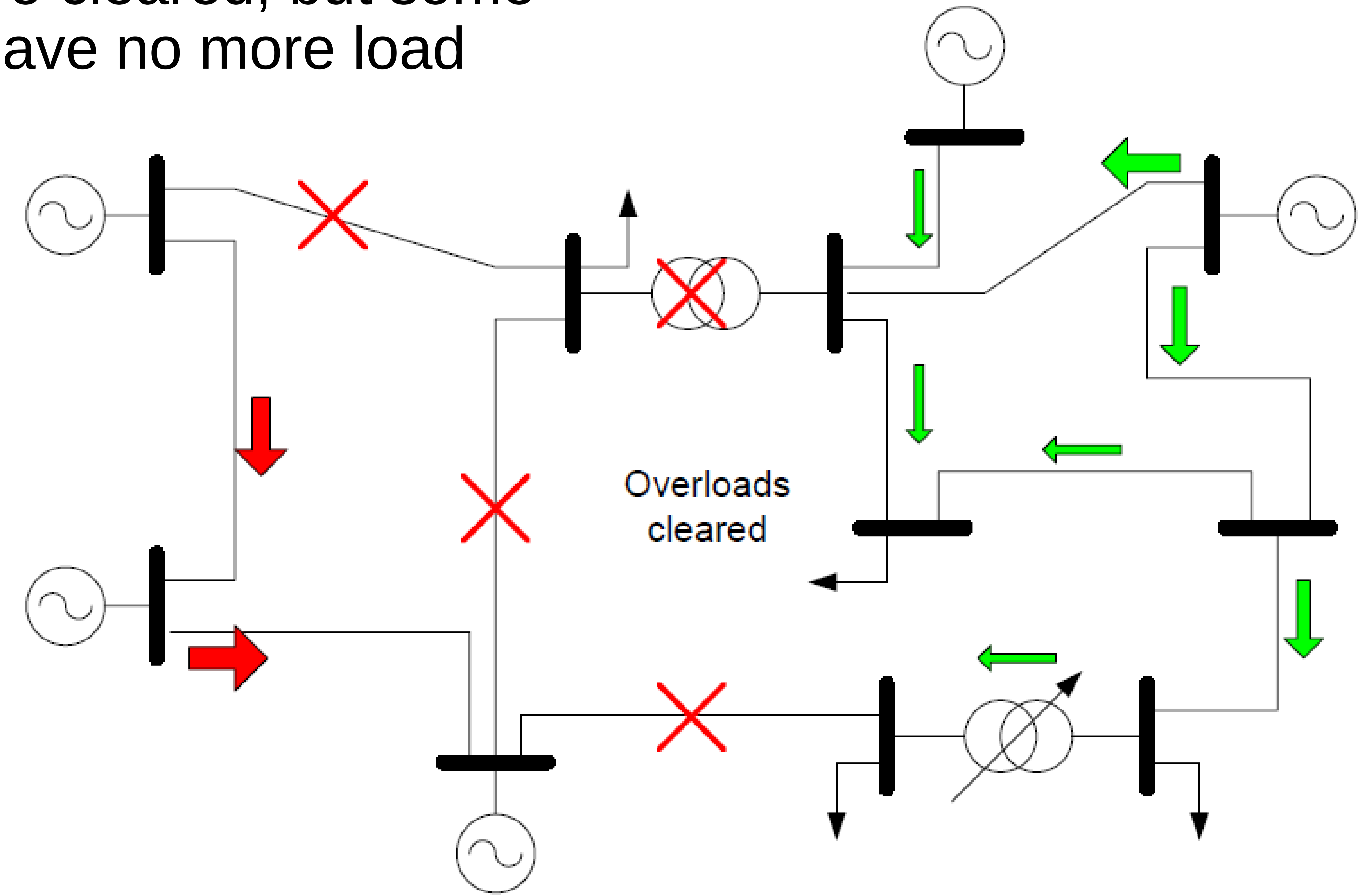
A Story of Cascading Outages

The overload is cleared by tripping the line causing further overloads



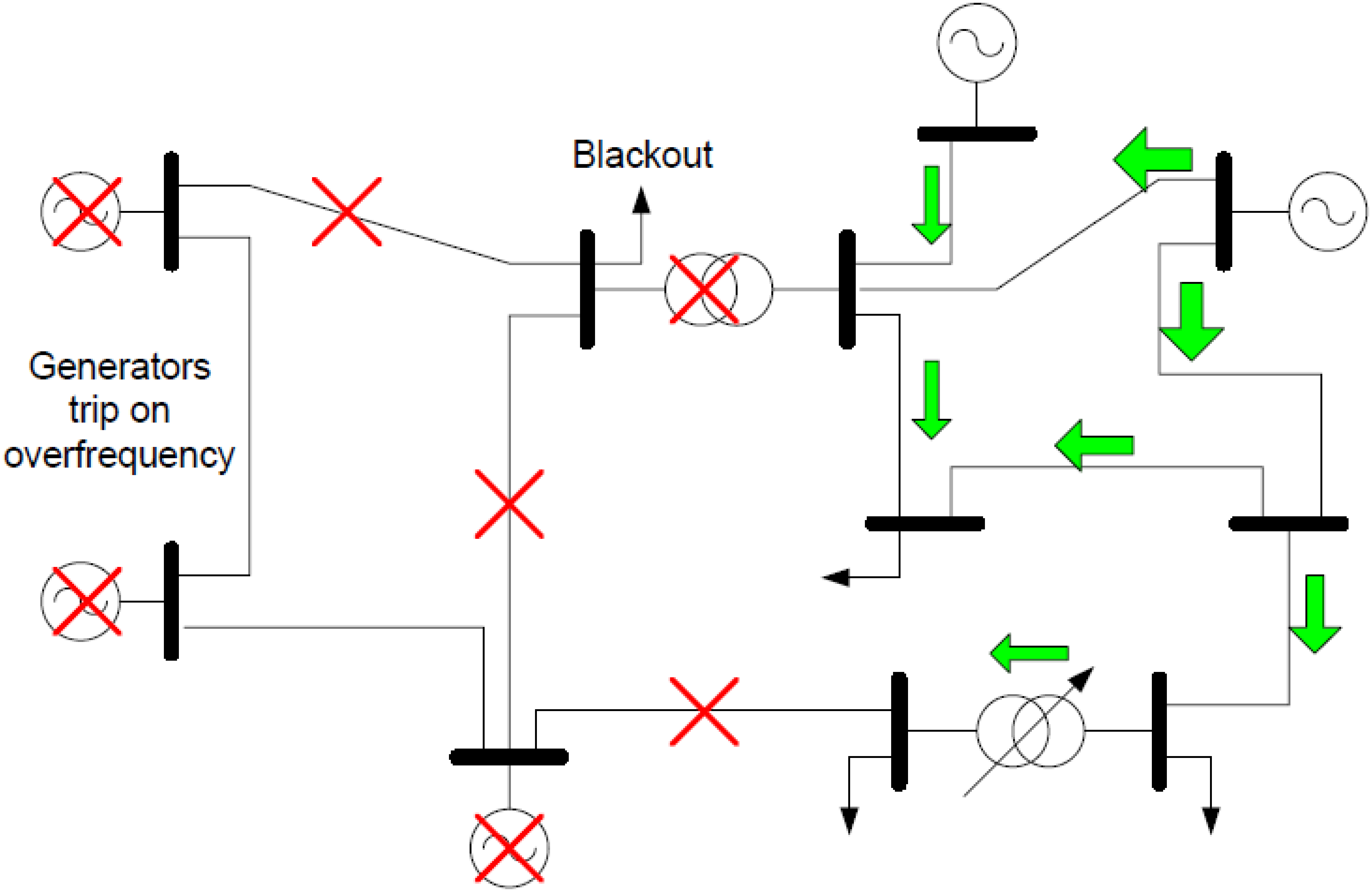
A Story of Cascading Outages

Overloads are cleared, but some generators have no more load



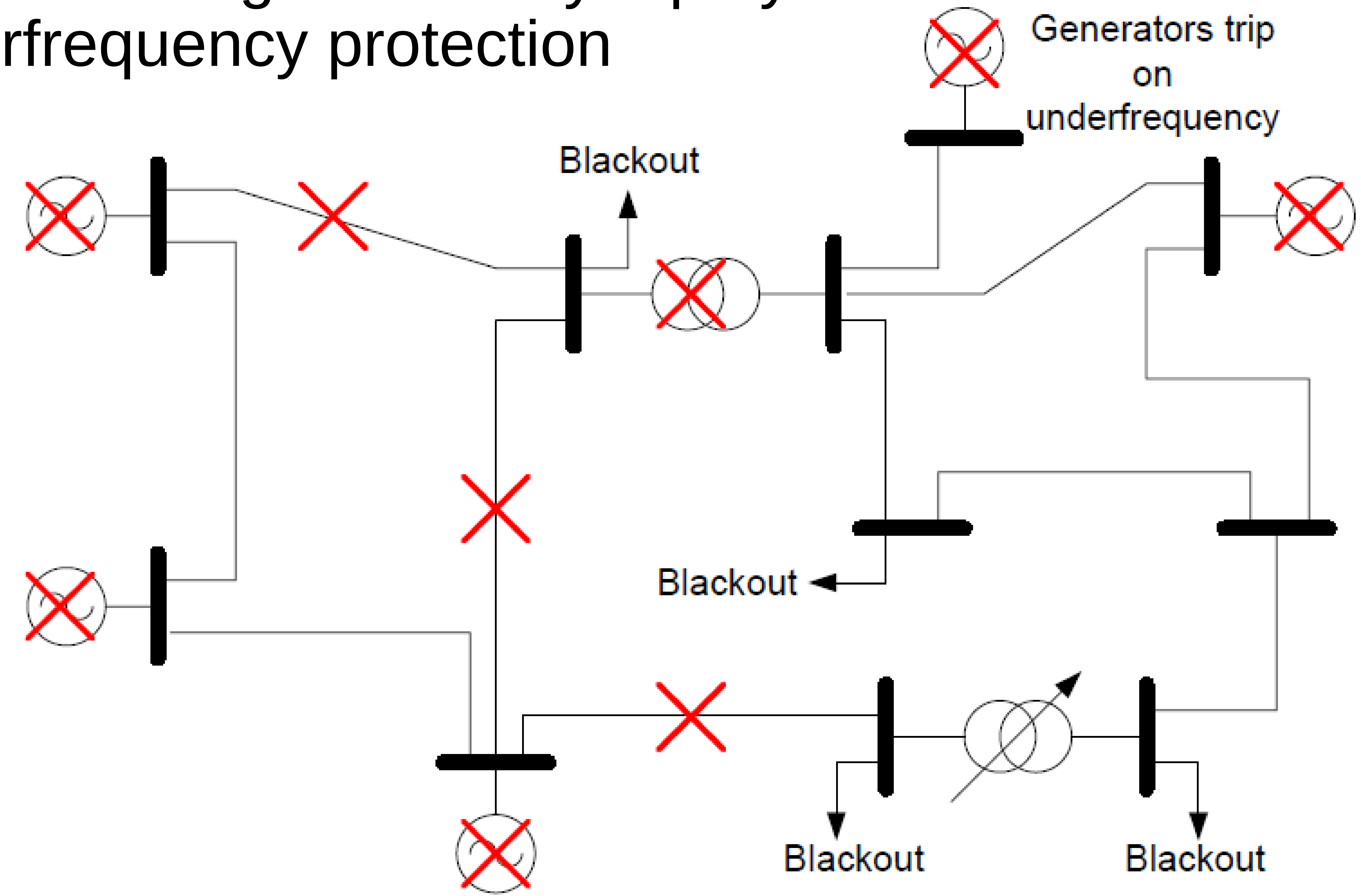
A Story of Cascading Outages

Generators



A Story of Cascading Outages

The remaining generators are not enough to supply all the remaining load. They trip by the action of underfrequency protection



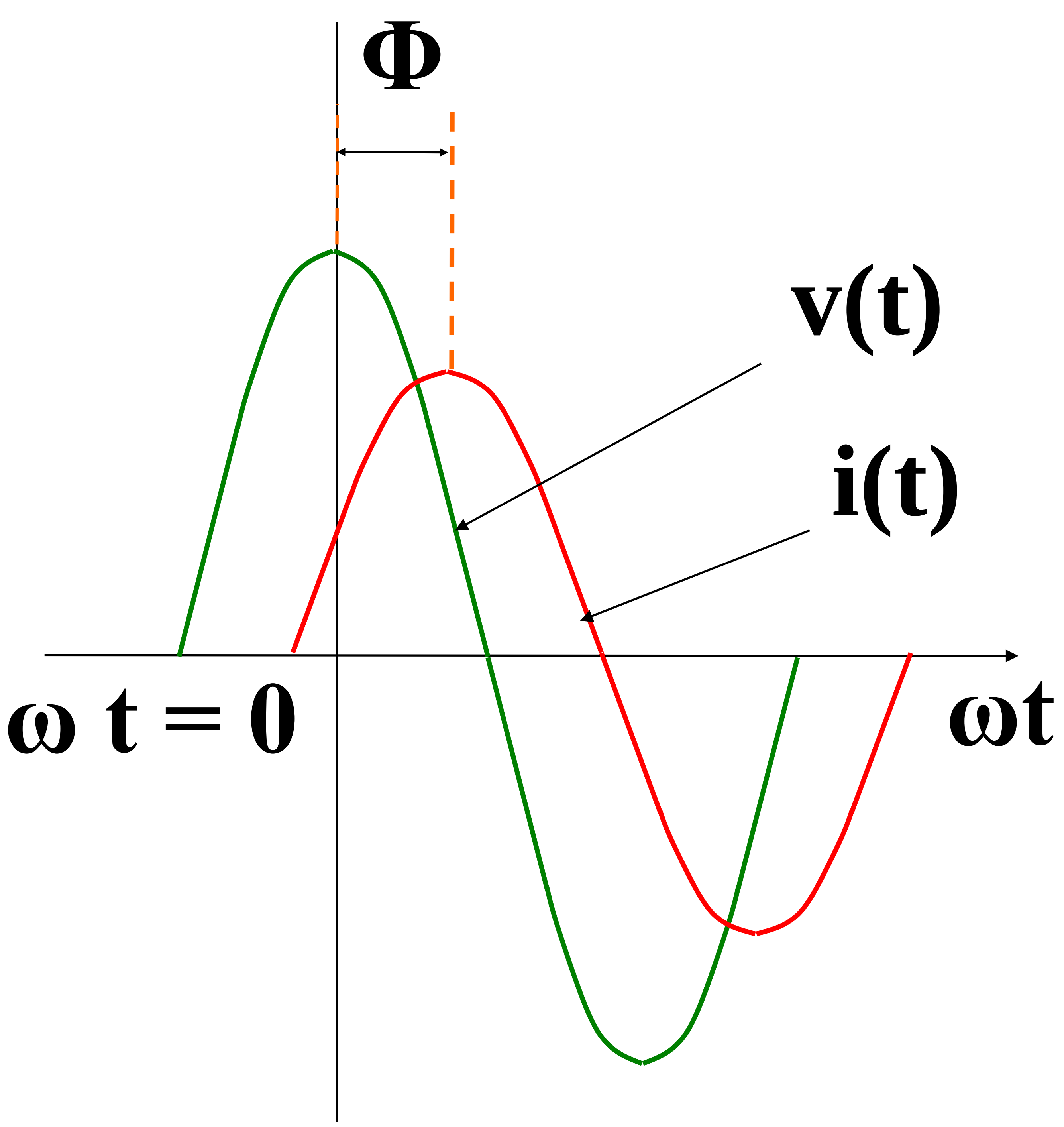
A Story of Cascading Outages

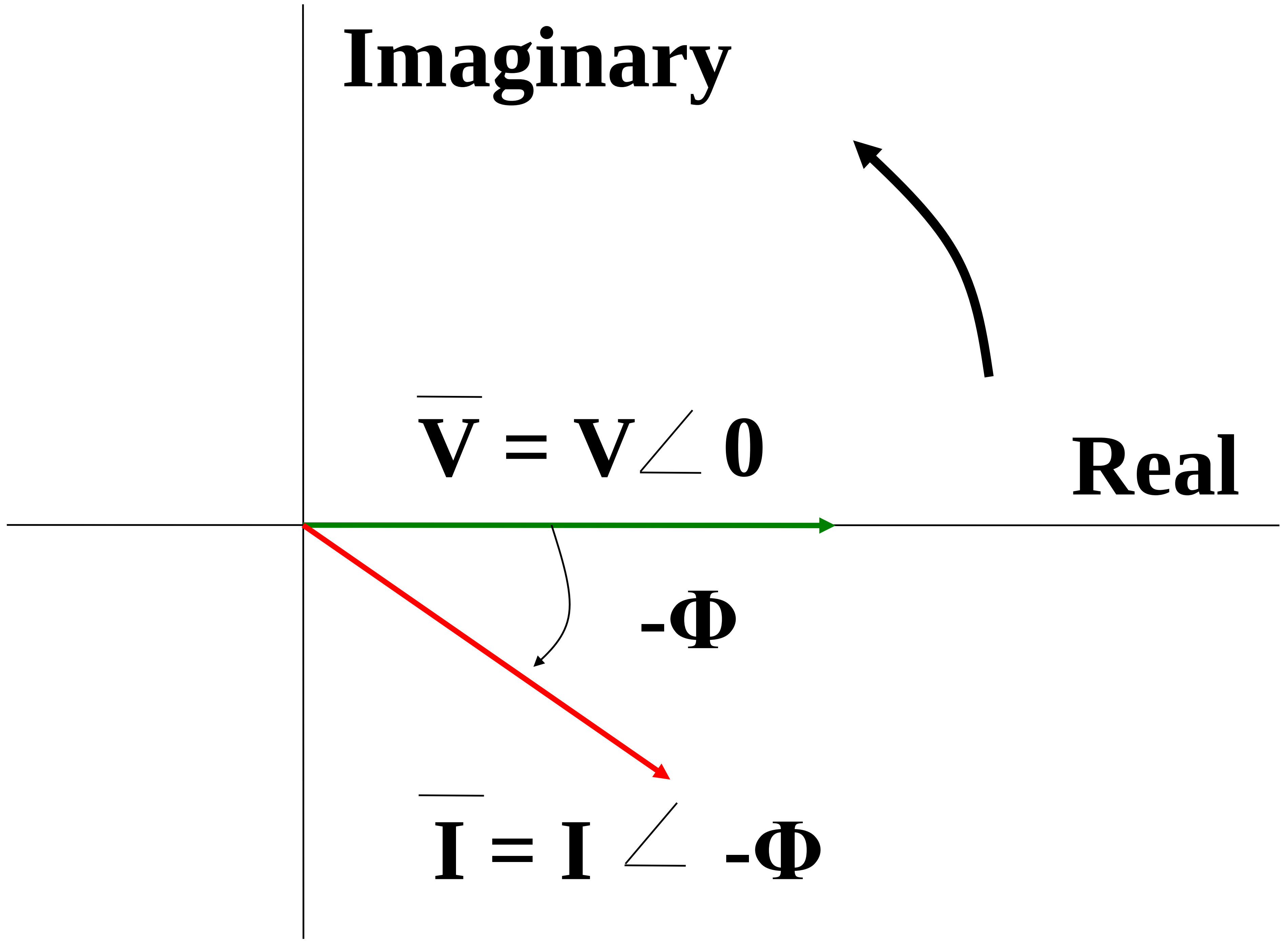
The moral of the story is. . .

- *The initial generation dispatch should always be checked and modified to avoid any overload in the system following the loss of any component.*
- *Protection settings should be reviewed.*

Circuit Analysis

Phasor Domain Representation for AC





$v(t) = \sqrt{2}\ V\cos(\omega t) \iff \overline{V} = V\angle 0$

$i(t) = \sqrt{2}\ I\cos(\omega t - \Phi) \iff \overline{I} = I\angle -\Phi$

Power Definitions

- P → Real power
  - It is the usable power and depends strongly on power factor (cosϕ) .
  - It is the average of the first term (Watts)

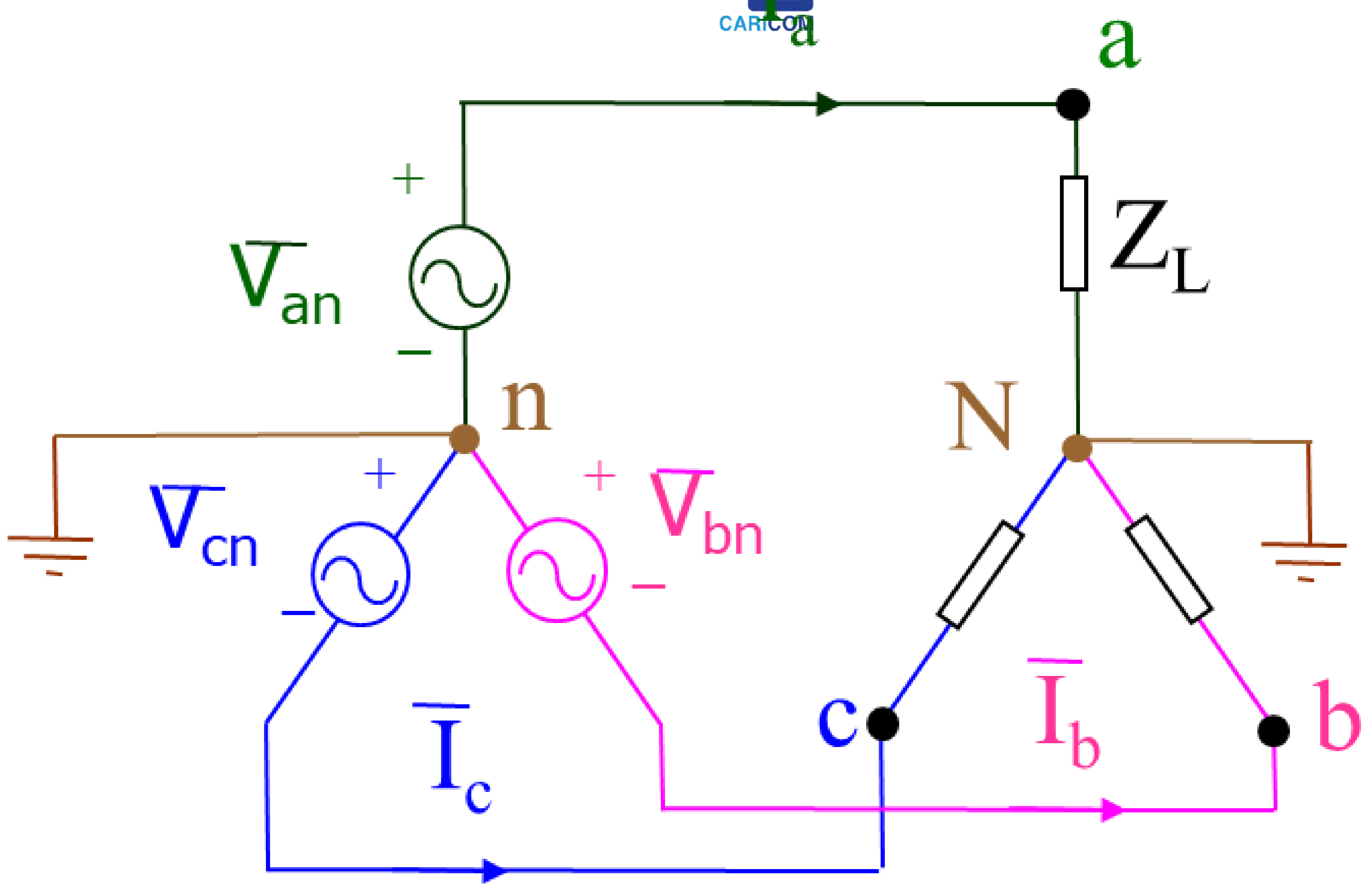
- Q → Reactive power
  - Charges and discharges components that store energy in magnetic and electric fields.
  - It is the peak value of the second term (Vars)

Analysis of Balanced 3 Phase Circuits

$$\bar{I}_a = \frac{\bar{V}_{an}}{|Z_L|} = \frac{V_s}{|Z_L|} \angle -\Phi$$

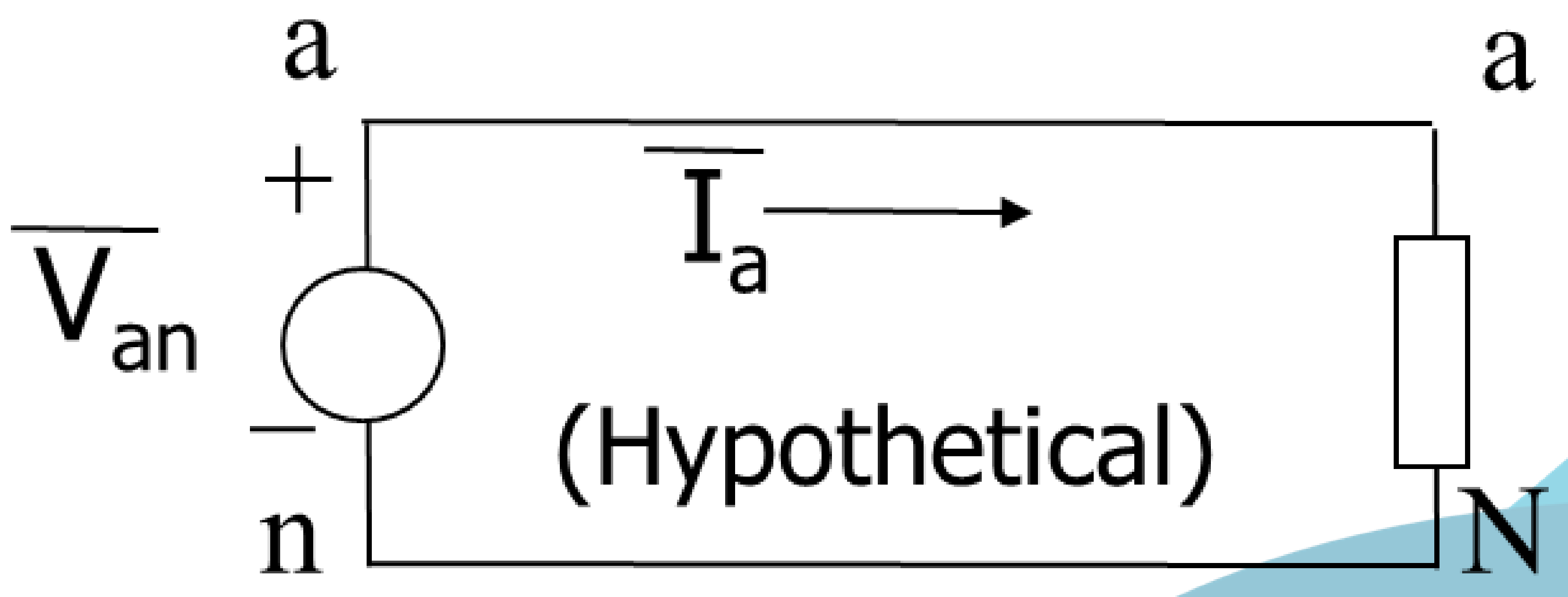
$$\bar{I}_b = \frac{\bar{V}_{bn}}{|Z_L|} = \frac{V_s}{|Z_L|} \angle -2\pi/3 -\Phi$$

$$\bar{I}_c = \frac{\bar{V}_{cn}}{|Z_L|} = \frac{V_s}{|Z_L|} \angle -4\pi/3 -\Phi$$



$$\bar{I}_n = \bar{I}_a + \bar{I}_b + \bar{I}_c = 0 \Longrightarrow$$

$$i_n(t) = [\, i_a(t) + i_b(t) + i_c(t) \,] = 0$$

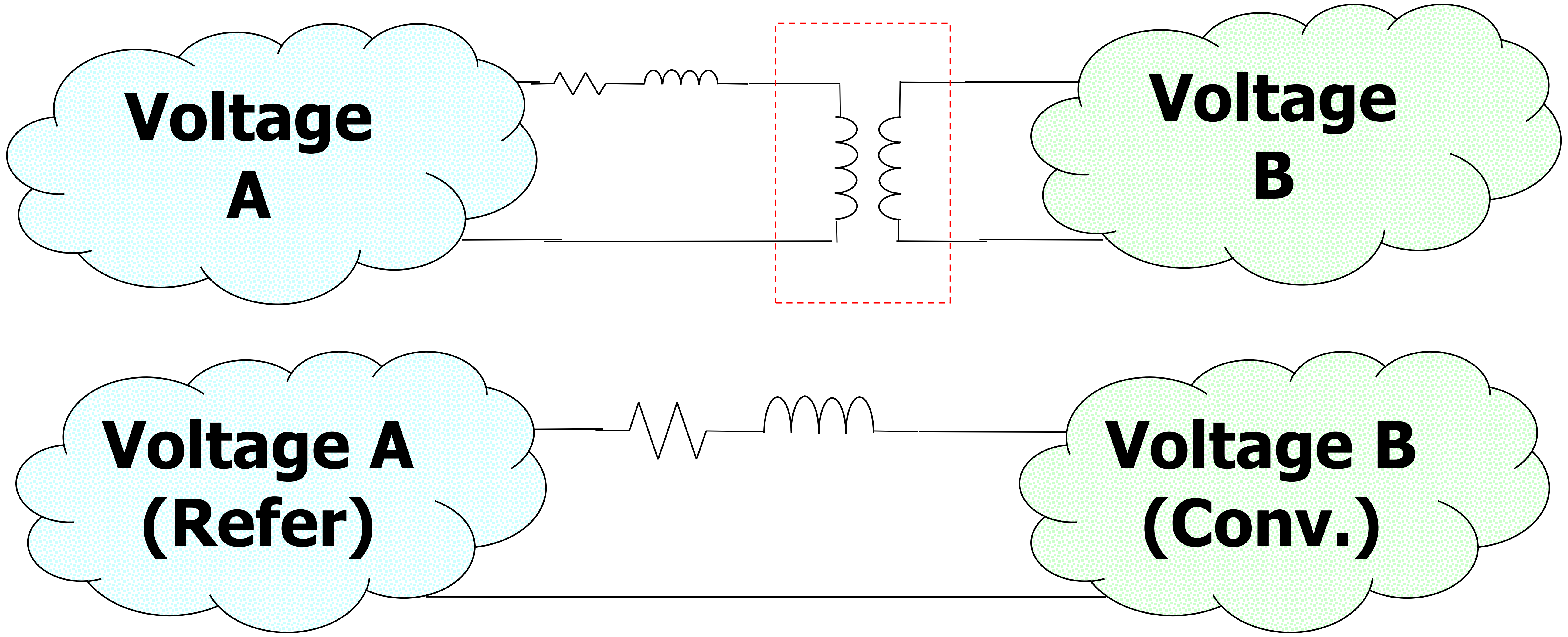


Per Unit, Loads, Synchronous Machine, Transformer, Overhead Conductors, Cables, Towers & Transmission Lines

Per- Unit Quantities

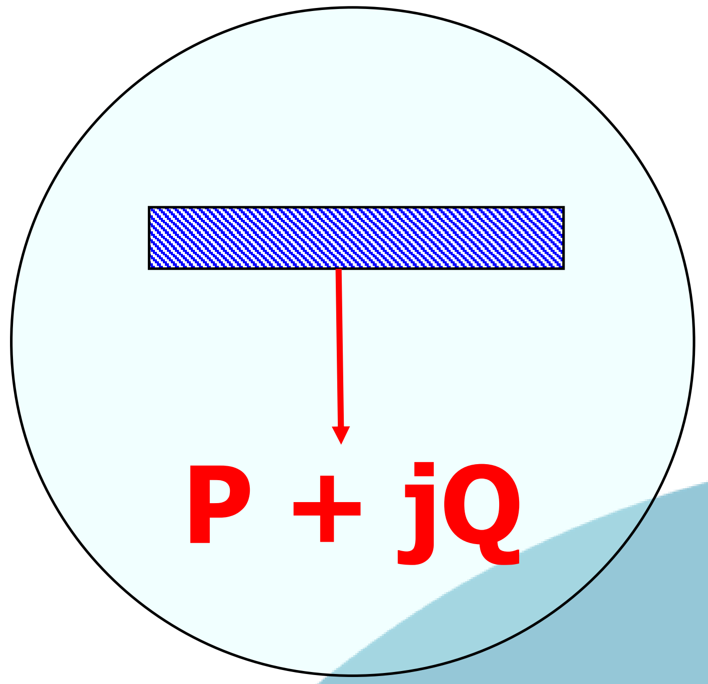
Fraction (Unit is a reference quantity)

- Some quantities in P.U. system become comparable (Voltage Level)
- Equipment Rating.
- Transformers → Simplify.
- Simplify Calculations.

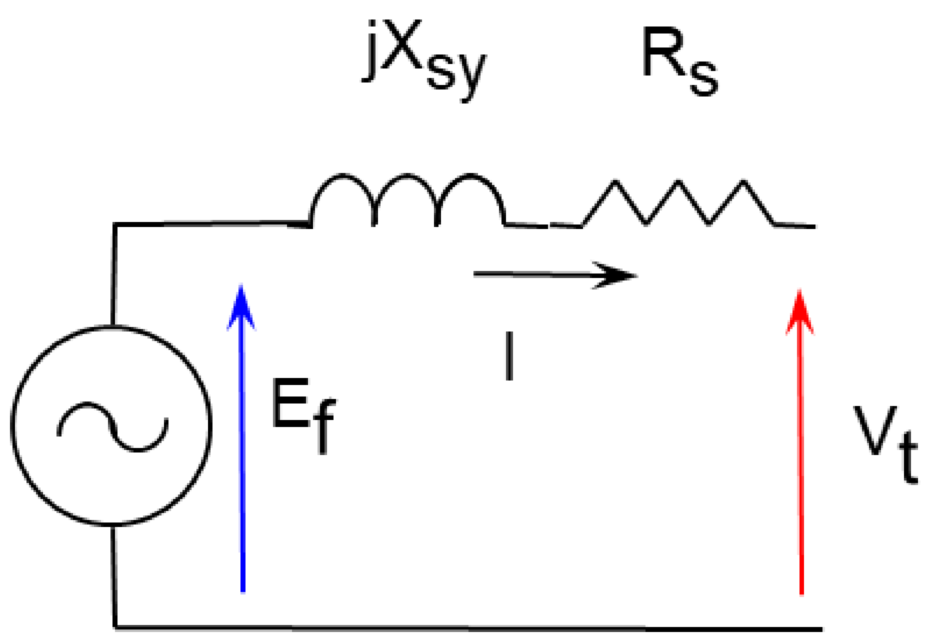


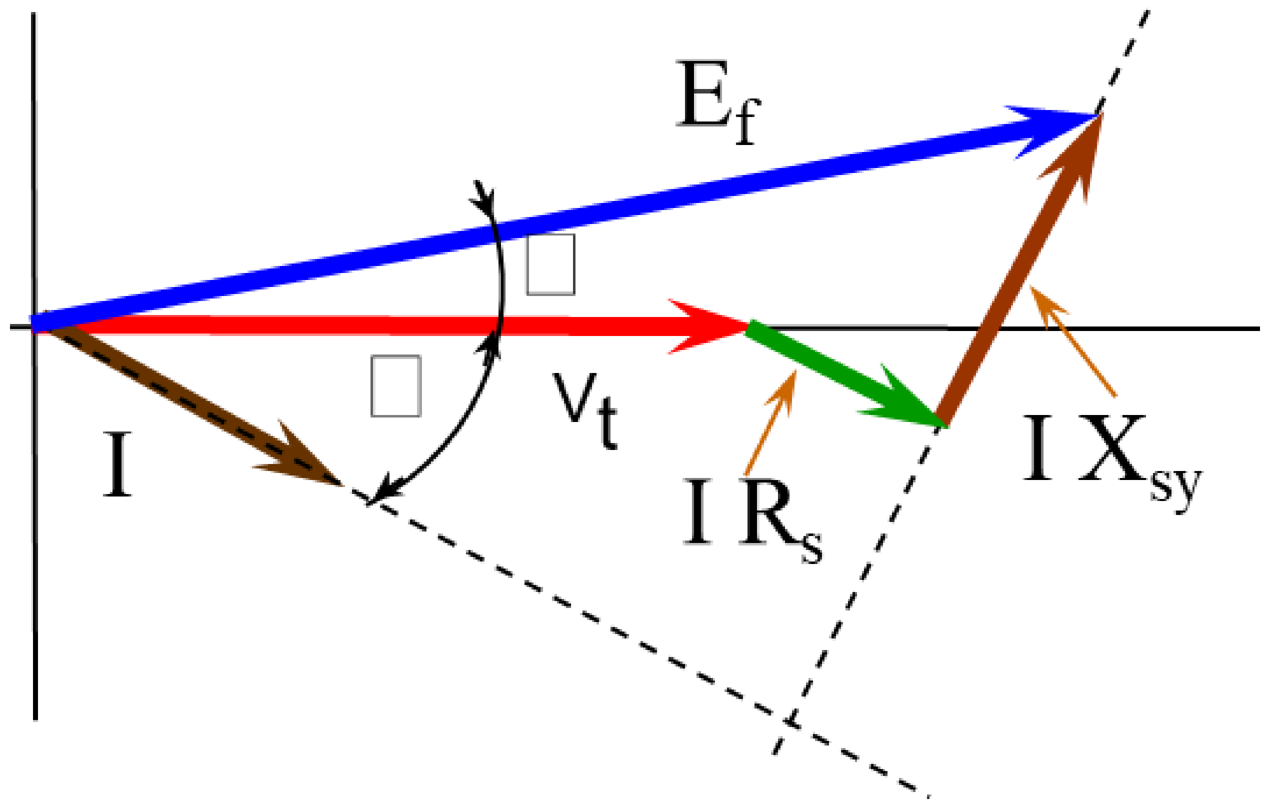
Challenges of Load Modelling

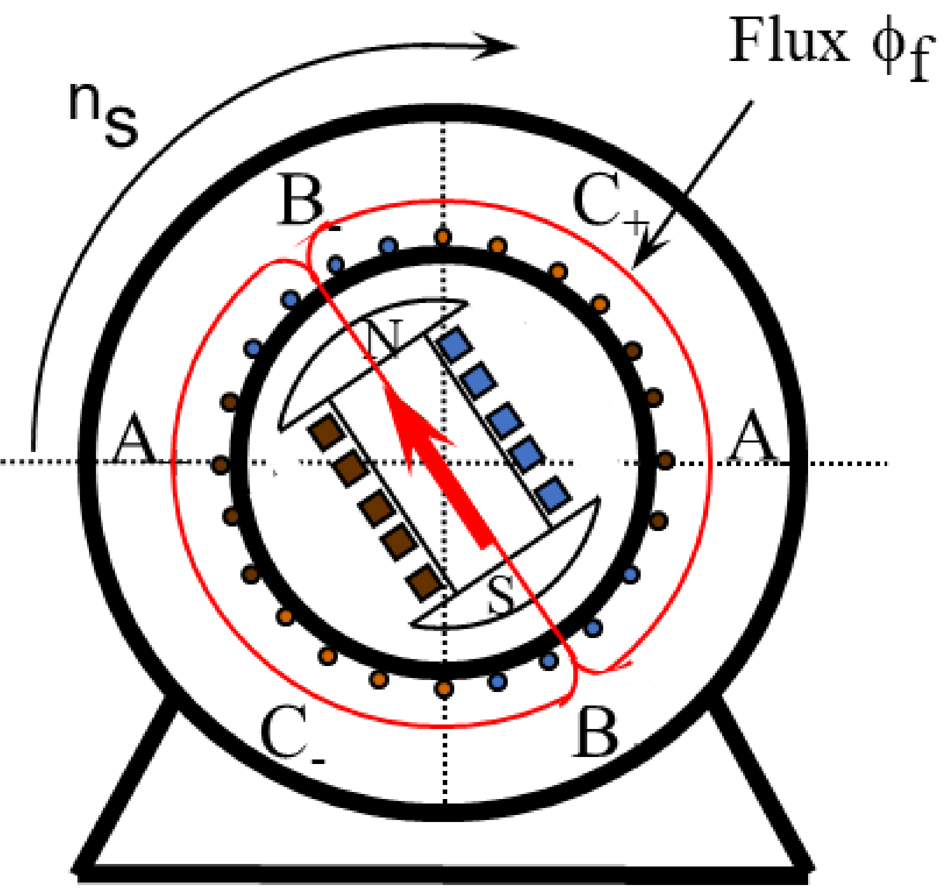
- Composition (lights, refrigerators, motors, furnaces, etc.)
- Composition changes (time, weather, economy)
- Need to simplify.
- Represent a composite load characteristic as seen from bulk power delivery points (Includes loads, substation step-down transformers, subtransmission feeders, distribution transformer and feeders, etc.)
- Specific models for particular loads.



Synchronous Machine







Operation concept

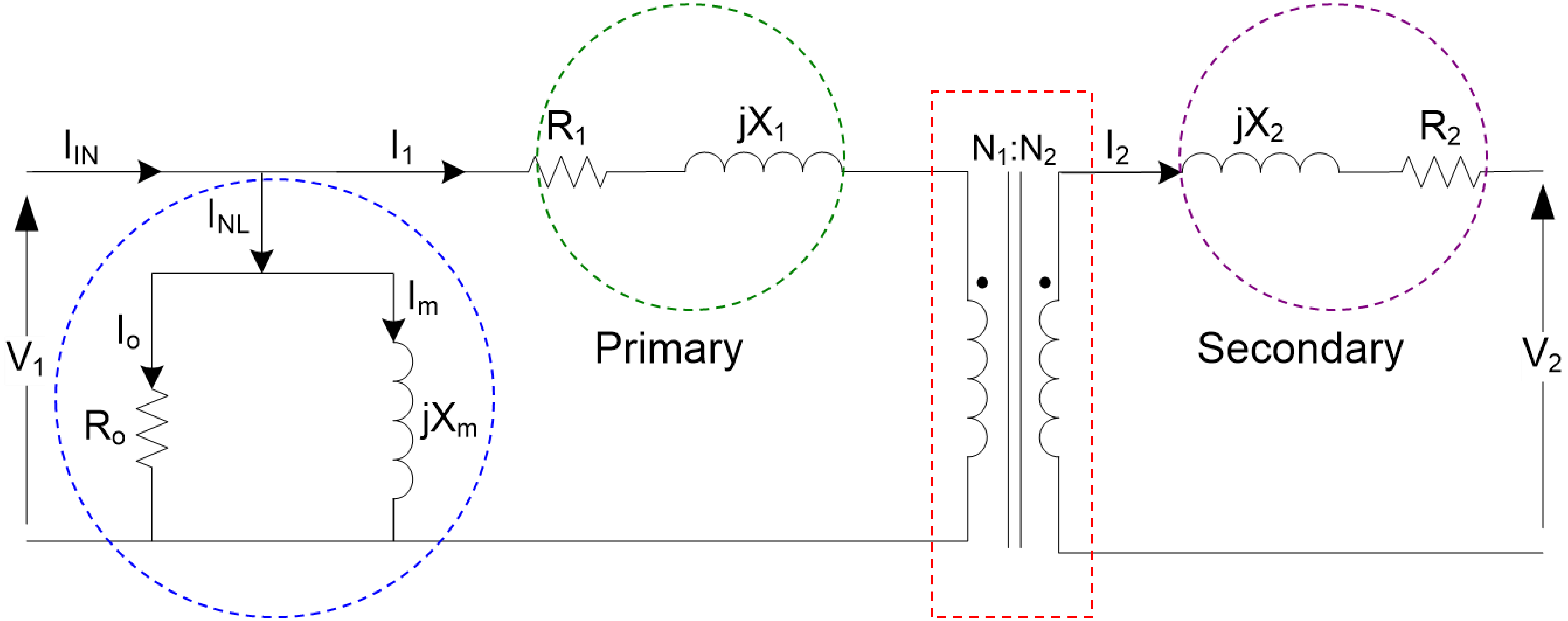
- The terminal voltage is: $V_t = E_f - E_s = E_f - I_a \, j X_{ar}$
- The synchronous reactance is given in percent x_{syn}. The ohm value is calculated by:

$$X_{syn} = x_{syn\_pu} \, (V^2/S)$$

where: **V** and **S** are the rated voltage in kV and MVA of the generator.

- Typically generators have several equivalent reactances. The synchronous reactance is used for steady-state analysis.
- Reactances are usually measured by manufacturer under standard testing of the machine.
- The generator is classified as a synchronous machine because it is only at synchronous speed that it can develop constant electromagnetic torque.
- The $X_{ar} + X_{leakage}$ is called synchronous reactance X_{syn}.

Transformer



Joule heating and leakage in primary winding

Joule heating and leakage in secondary winding

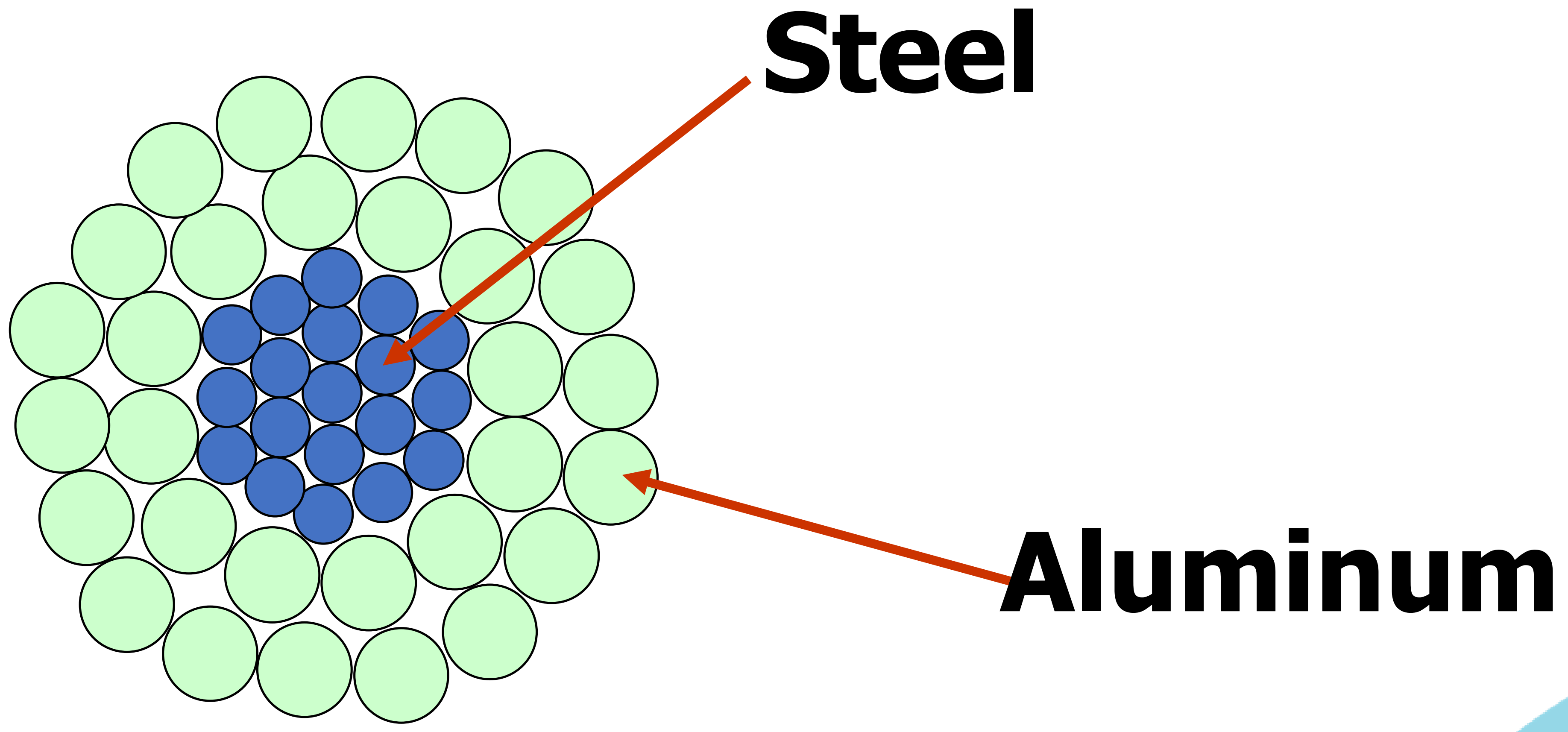
Turns Ratio

Hysteresis & Eddy Current Losses as well as magnetizing losses in core

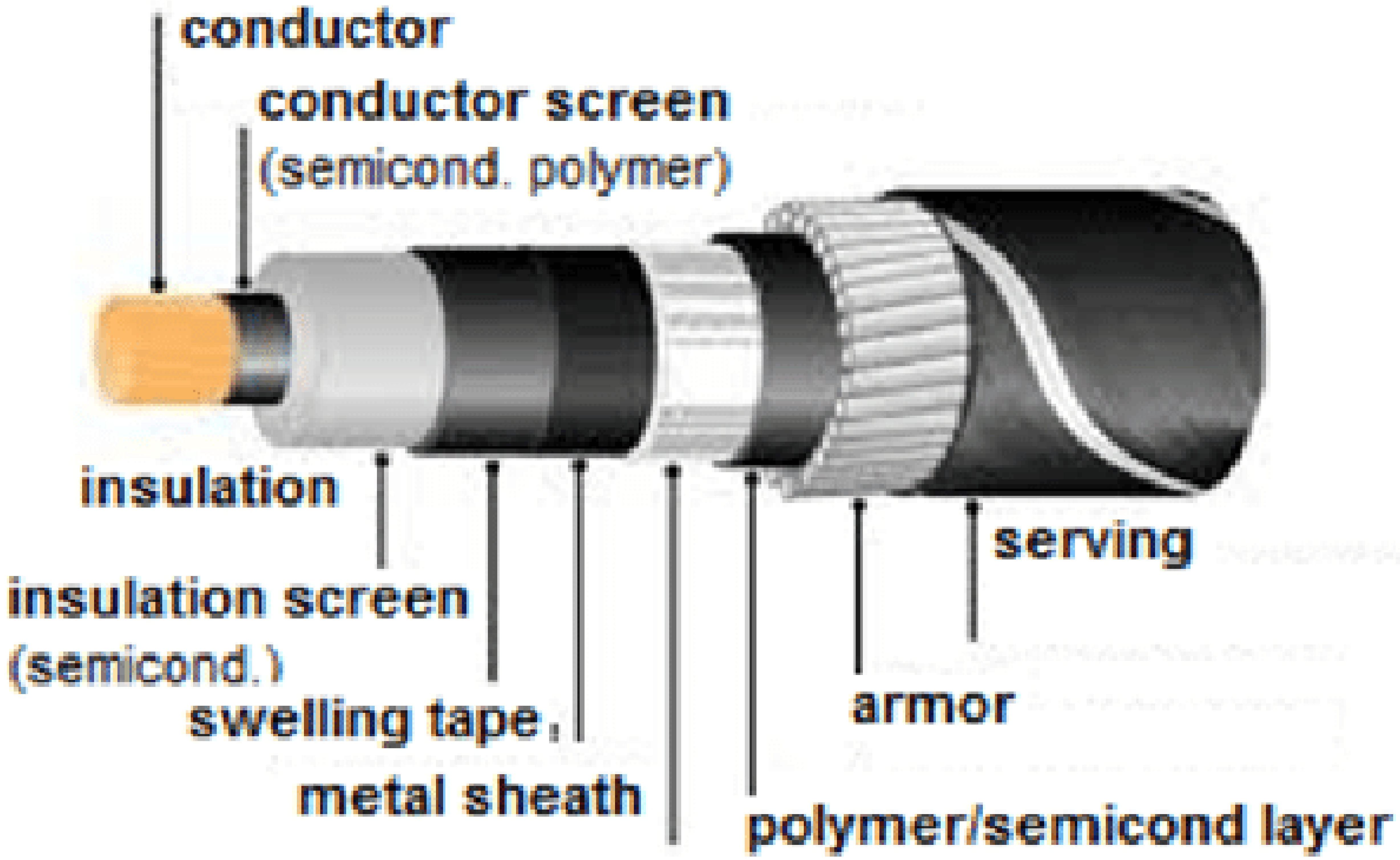
Overhead Conductors

Homogeneous conductors

Non-homogeneous conductors

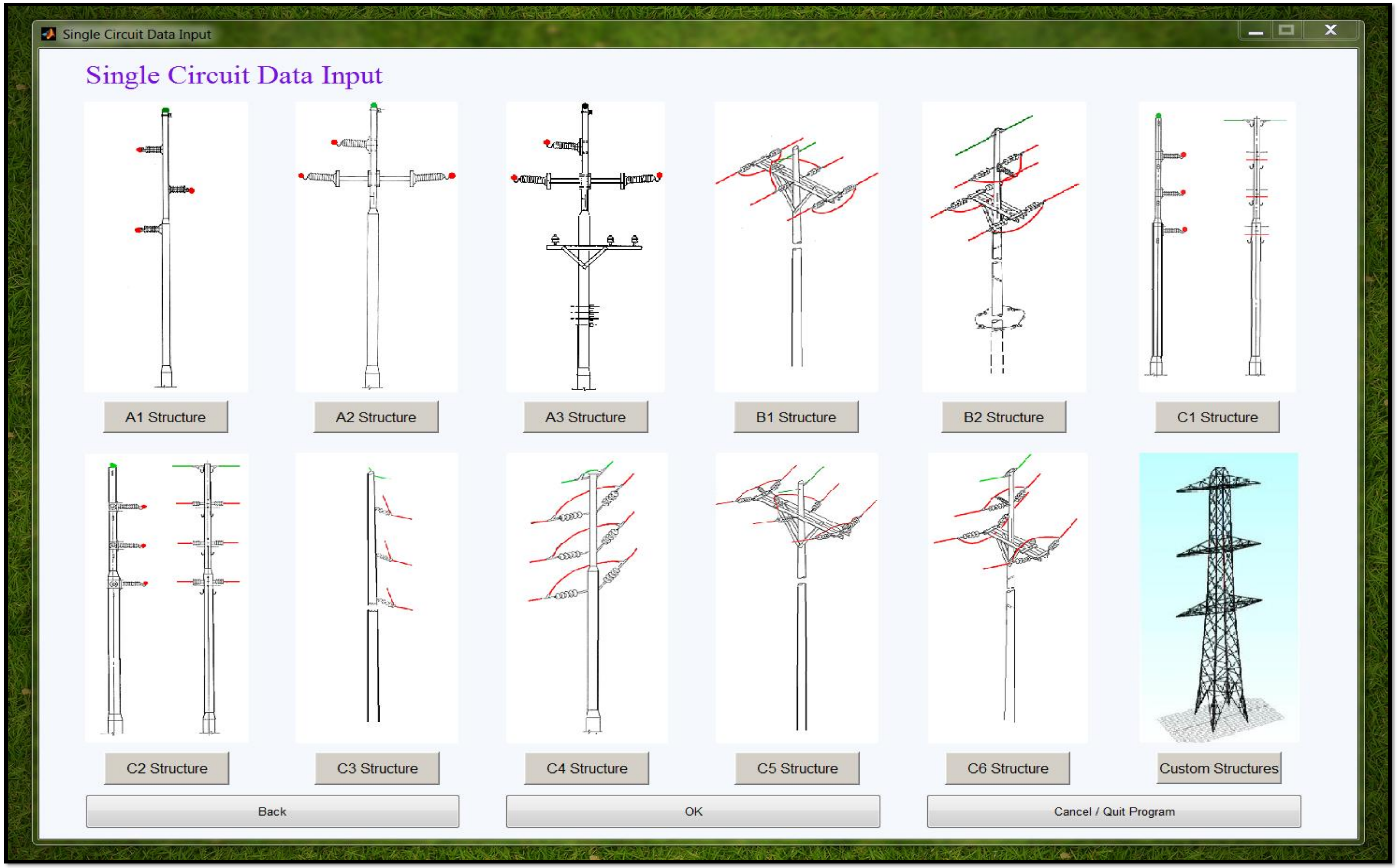


Cables

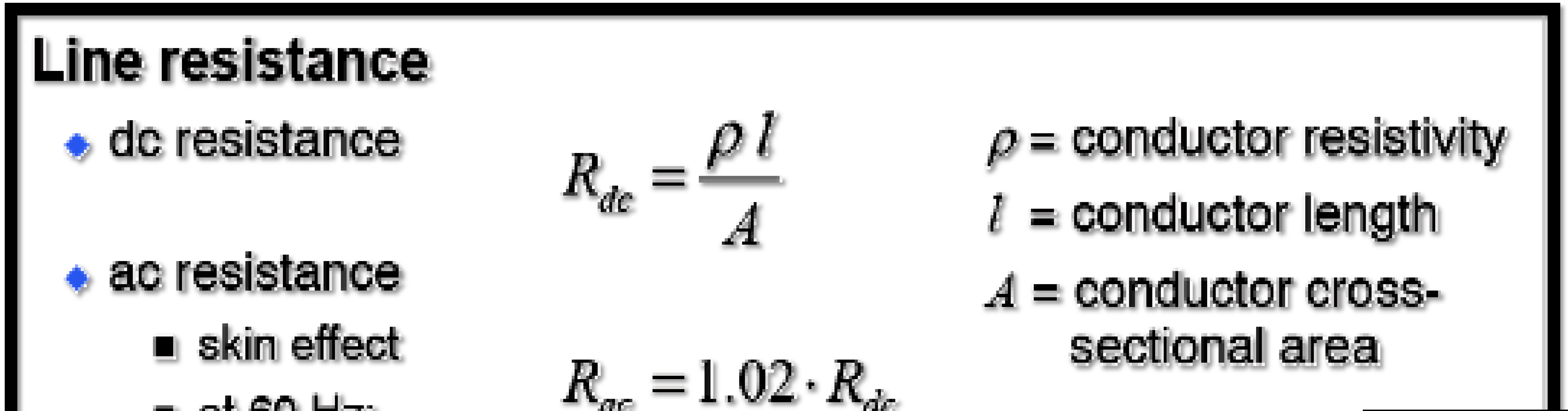


A Novel Approach to Design Cathodic Protection System for High Voltage Transmission Cables - Scientific Figure on ResearchGate. Available from:
https://www.researchgate.net/figure/Arrangement-of-a-single-core-HV-XLPE-submarine-power-cable-III-APPLICATION_fig1_273912822 [accessed 18 Mar, 2021]

Transmission Towers



Resistance



Line resistance

- dc resistance

$$R_{dc} = \frac{\rho\, l}{A}$$

- ac resistance
  - skin effect
  - at 60 Hz:

$$R_{ac} = 1.02 \cdot R_{dc}$$

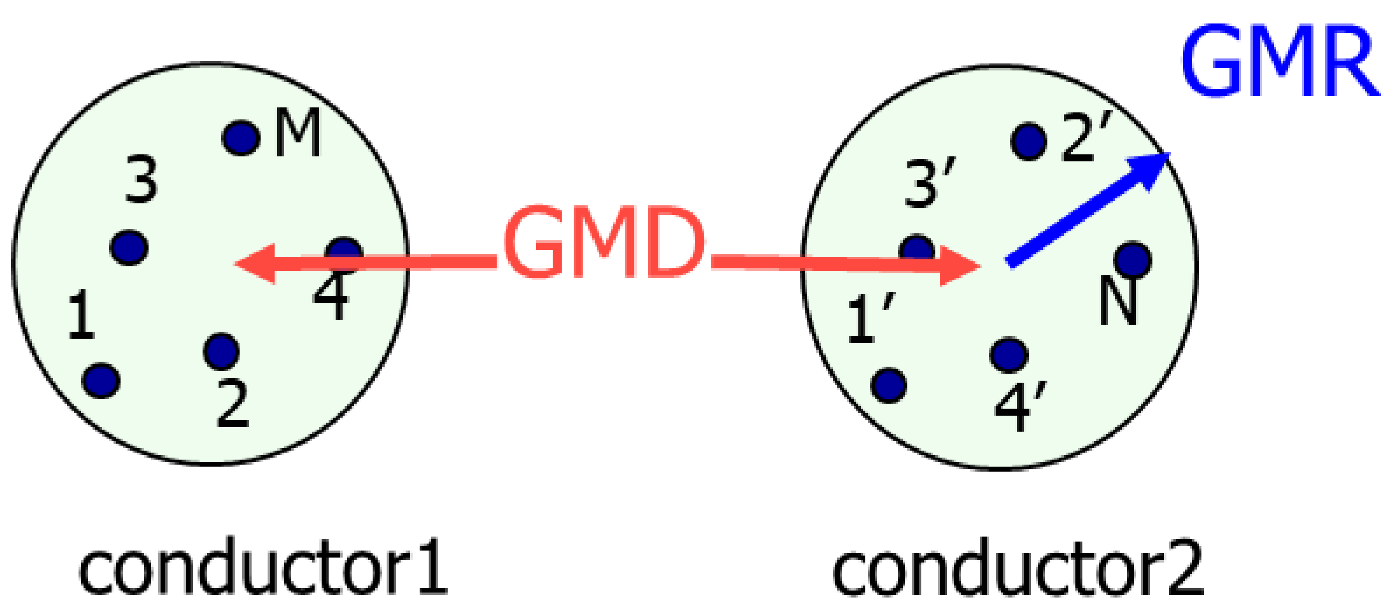
ρ = conductor resistivity

l = conductor length

A = conductor cross-sectional area

- Manufacturer gives dc, 50 Hz, 60 Hz
- Affected by:
  - Material, stranding, spiraling, temperature and frequency.

Bundle Conductors – GMR and GMD



GMR = Geometric Mean Radius

- GMD = Geometric Mean Distance.
  - Average distance between centre of the bundles.

$$GMR = \sqrt[n]{r'\prod_{i=2}^{n} d_{1i}}$$

$$r' = e^{-1/4} r = 0.7788r$$

$$\sqrt{r'd}$$

(For capacitance calculations use r)

Transmission Line Parameters

- All lines are made up of distributed series inductance and resistance, and shunt capacitance and conductance (per km)
- Line parameters: *R*, *L*, *C*, & *G*
- Calculated parameters (Hand equations-assumed totally transposed).
- Resistance – tables.
- Inductance

$$L_a = 2 \times 10^{-7} \ln (D/r') \quad \text{H/m} \quad \text{per phase}$$

- Capacitance

$$C_{an} = \frac{2\pi\varepsilon}{\ln(D/r)} \quad \text{F/m} \quad \text{line-to-neutral}$$

Transmission Line Models

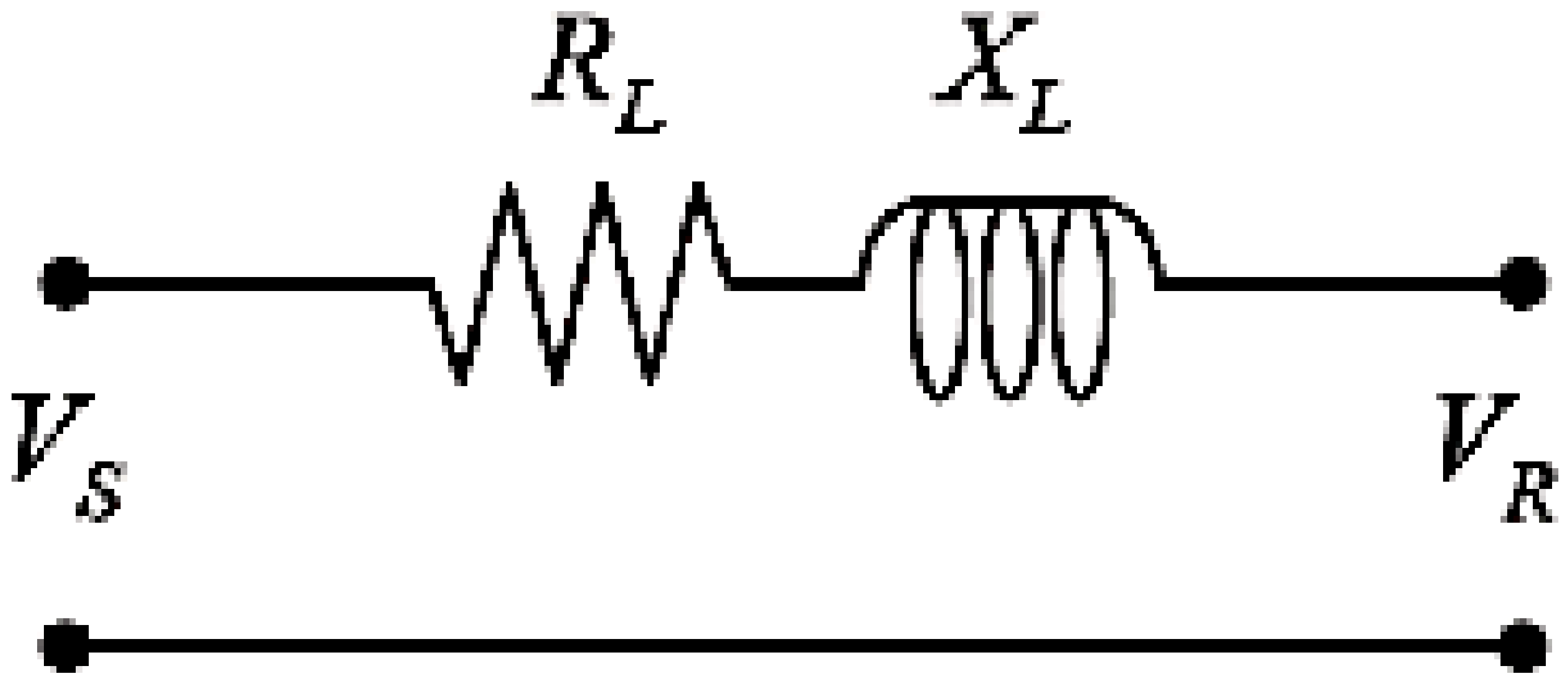
- **Transmission lines are represented by an equivalent circuit with parameters on a per-phase basis**
  - Voltages are expressed as phase-to-neutral.
  - Currents are expressed for one phase.
  - The three phase system is reduced to an equivalent single-phase.

- **Three types of models**
  - Depend on the length (and frequency ~ 60 Hz).
  - Short, medium, and long length line models.

Short Transmission Line Model

- **The short transmission line model may be used when**
  - The line length is less than 80 km.

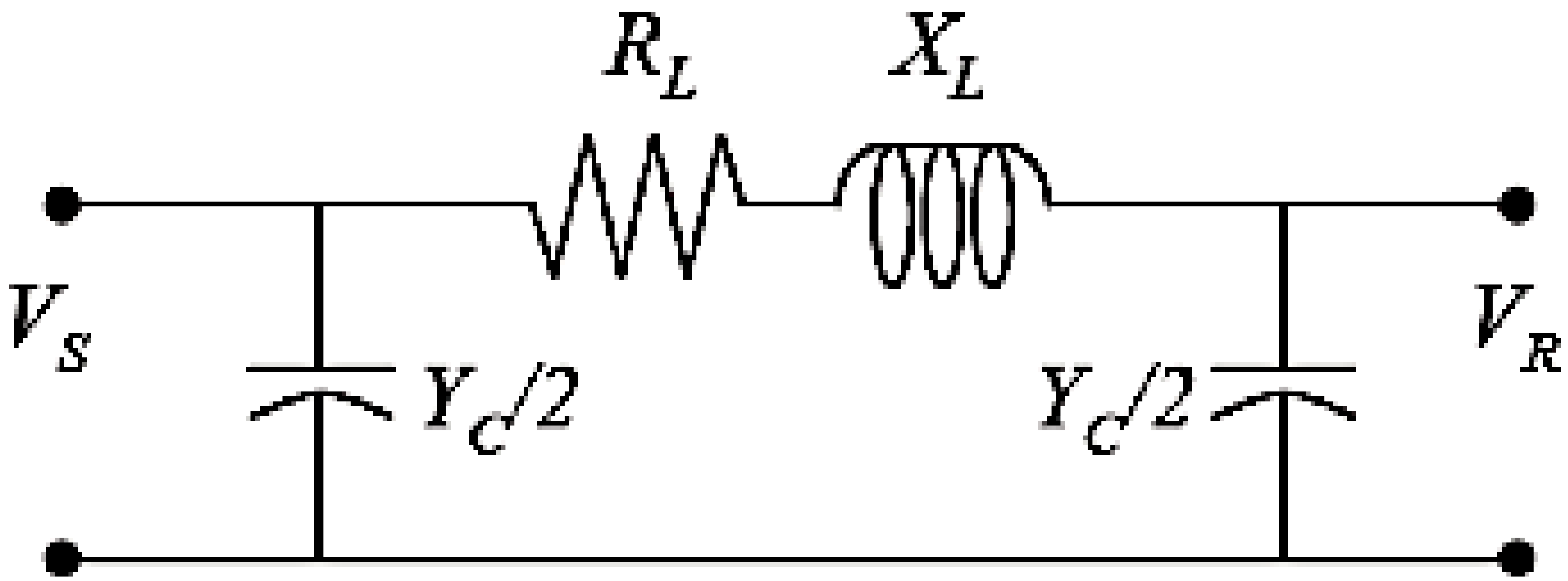
- **Modelling of the transmission line parameters**
  - The shunt capacitance and conductance are ignored.
  - The line resistance and reactance are treated as lumped parameters.
  - The line length is l [km] and the line series impedance is : z = R + j X [Ω/km]
  - The total series impedance is Z = z l [Ω]



Medium Transmission Line Model

- **The medium transmission line model may be used when**
  - The line length is greater than 80 km and less than 250 km.

- **Modelling of the transmission line parameters**
  - Half of the shunt capacitance is considered to be lumped at each end of the line (shunt admittance is y = jB = jωC; total shunt admittance Y = y l [S]).
  - The line resistance and reactance are treated as lumped parameters (The total series impedance Z = z l [Ω]).
  - Nominal PI.



Fault Analysis

Fault Analysis (Short Circuit Analysis)

Fault → Failure which interferes with normal flow of current.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SHORT CIRCUIT

- **Lightning (most common)**
- Dirt/salt on insulators
- Flashover line-line (wind)
- Flashover to tree
- Tower/pole or conductor falls
- Objects fall on conductors
- Cable insulation failure

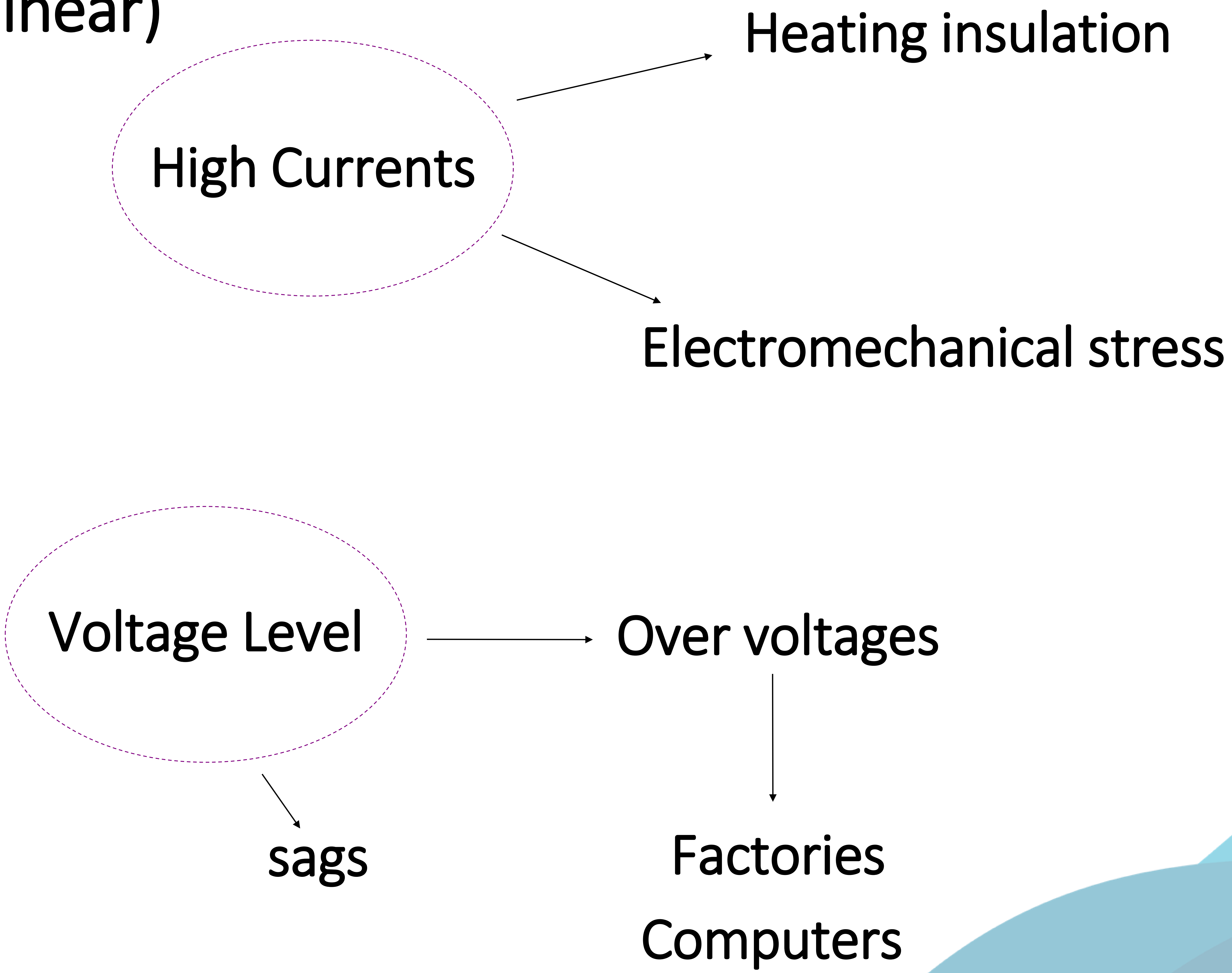
OPEN CIRCUIT

Faults will occur ⇨ Try to control the effects

Fault Analysis

Main Effects (Non-linear)

Anchor damage on Baltic Cable



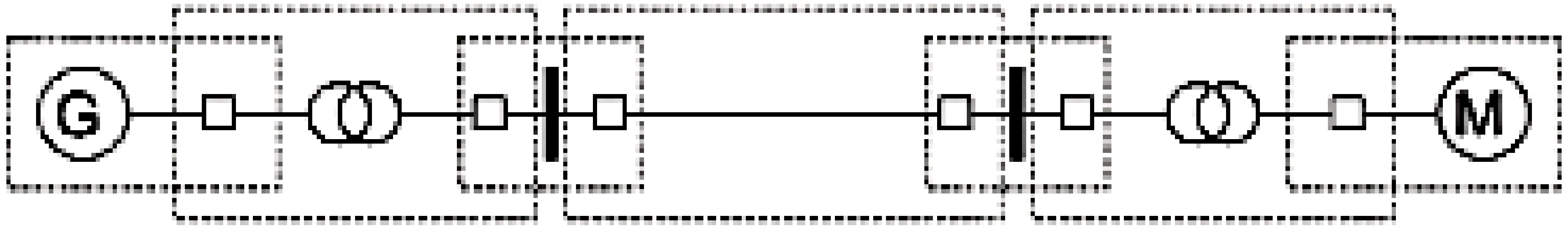
High Currents → Heating insulation

High Currents → Electromechanical stress

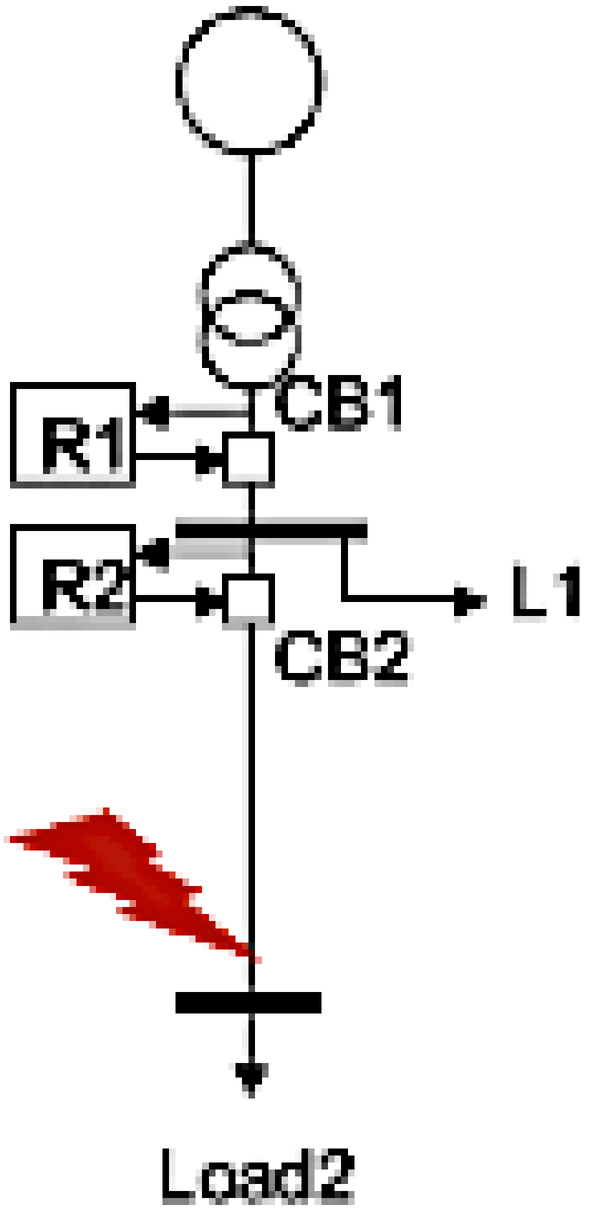
Voltage Level → Over voltages → Factories, Computers

Voltage Level → sags

Fault Analysis

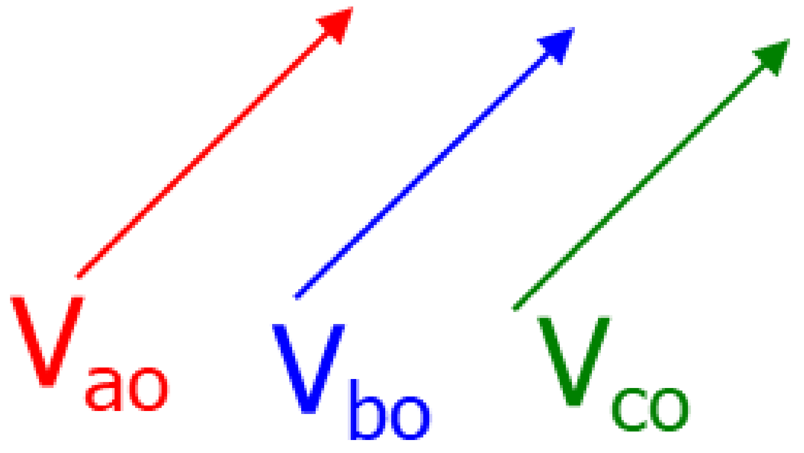


- Control
  - Protection devices
    - Relays, breakers
  - Other
    - Switching schemes, grounding mesh, etc



- Short circuit analysis
  - Protection coordination
  - Selection of breakers
  - Selection of current transformers
  - Selection of other protective devices
  - Contributions from generators and motors
  - Calculation of grounding mesh

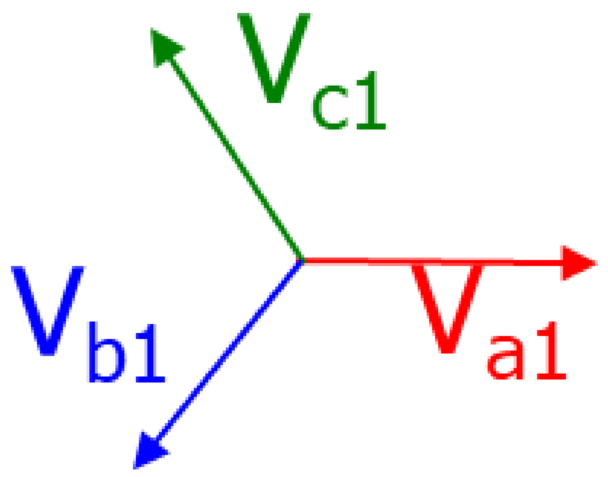
Symmetrical Components



Zero Sequence Components

Equal magnitude

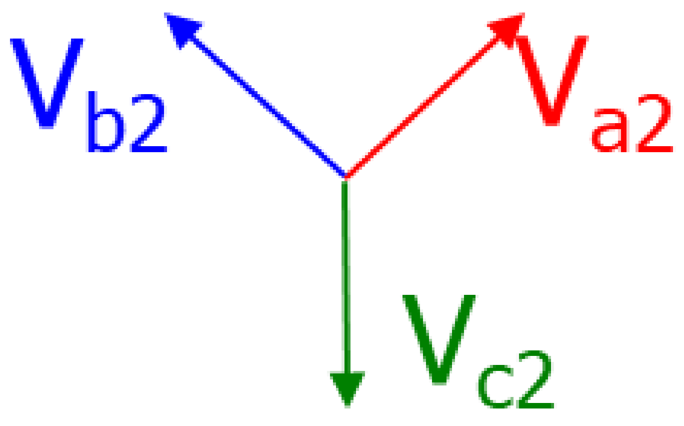
Zero phase displacement



Positive Sequence Components

Equal magnitude and 120^0 phase displacement

Same phase sequence as original (positive)

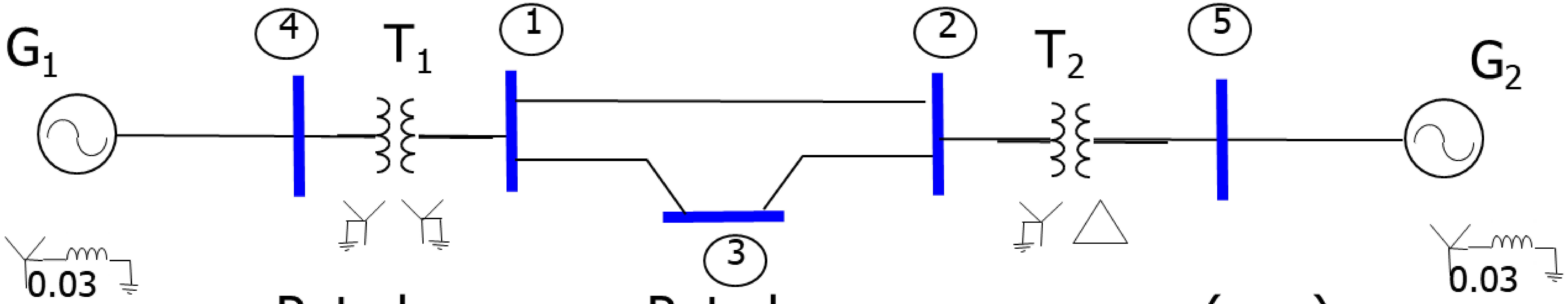


Negative Sequence Components

Equal magnitude and 120^0 phase displacement

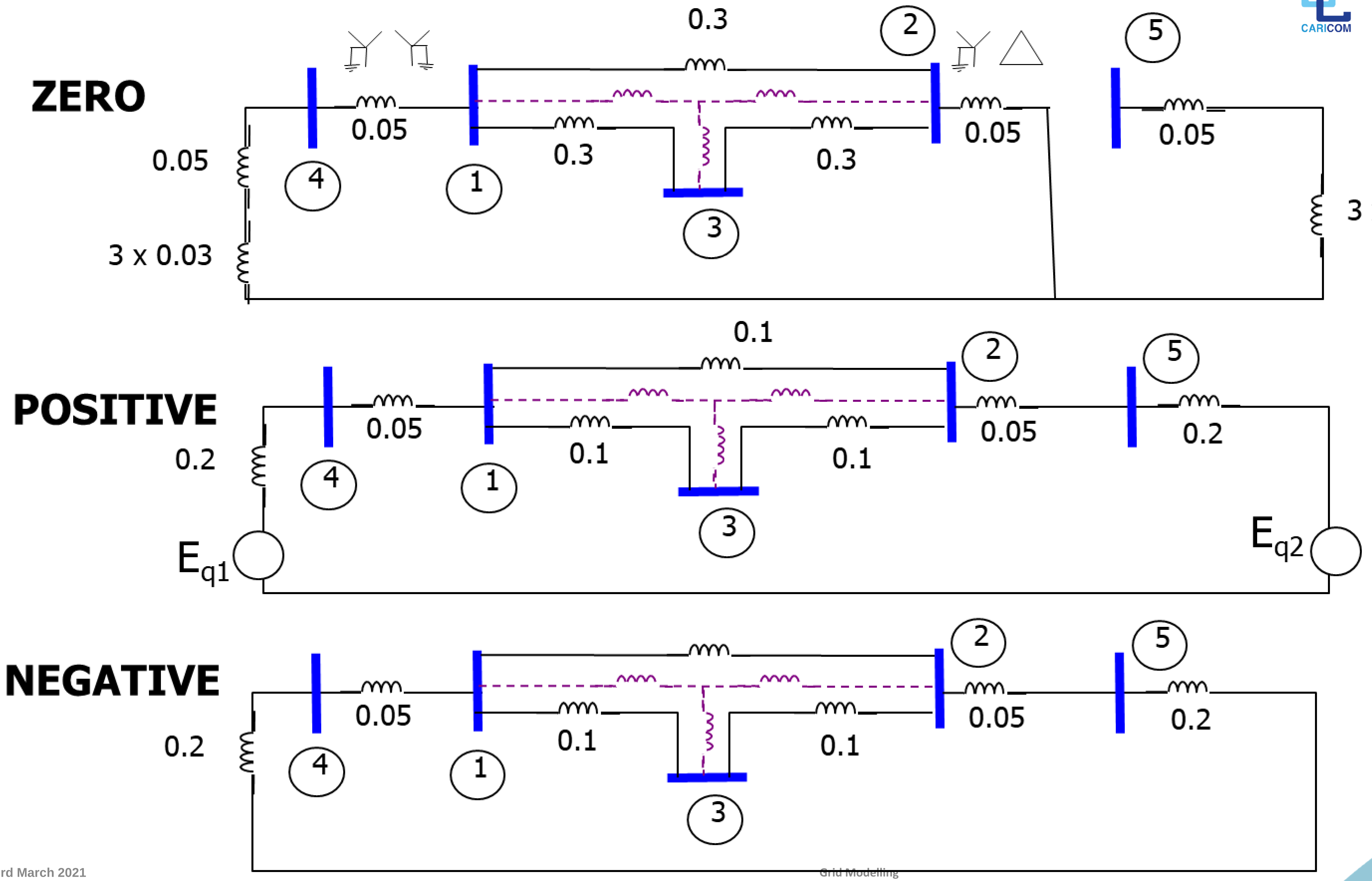
Opposite phase sequence as original (positive)

Network for Short Circuit Studies



	Rated	Rated		(p.u.)	
	MVA	Voltage	X_1	X_2	X_0
G_1	100	25kV	0.2	0.2	0.05
G_2	100	13.8kV	0.2	0.2	0.05
T_1	100	25/230kV	0.05	0.05	0.05
T_2	100	13.8/230kV	0.05	0.05	0.05
TL_{12}	100	230kV	0.1	0.1	0.3
TL_{23}	100	230kV	0.1	0.1	0.3
TL_{13}	100	230kV	0.1	0.1	0.3

Sequence Networks



A Short Break

Before we switch presenters

Power Flow

Power Flow Main Objectives

- **To calculate P&Q flow through elements.**
  - Observe power flow and check overloads.
  - Effects of contingencies.
  - Effects of configuration changes.

- **To calculate voltage magnitude and angle on buses.**
  - Quality of service.
  - Strategies to operate elements with voltage control (Taps, Exc. Generator , Capacitors.)

- **To design the optimal operation & distribution of loads.**

- **To define operation guidelines.**

Power Flow

- Operation point of the system.
- Steady State.
- Given conditions of generation, load & configuration: Operation Point

Buses **$(V\underline{/\theta})$**

Branches **(P, Q)**

Solve Equations (Balance generation and load)

The Power Flow Problem

Solving the power flow problem amounts to finding the combination of nodal voltage angles and magnitudes which can simultaneously support the specified real and reactive power injections throughout a network

Observation

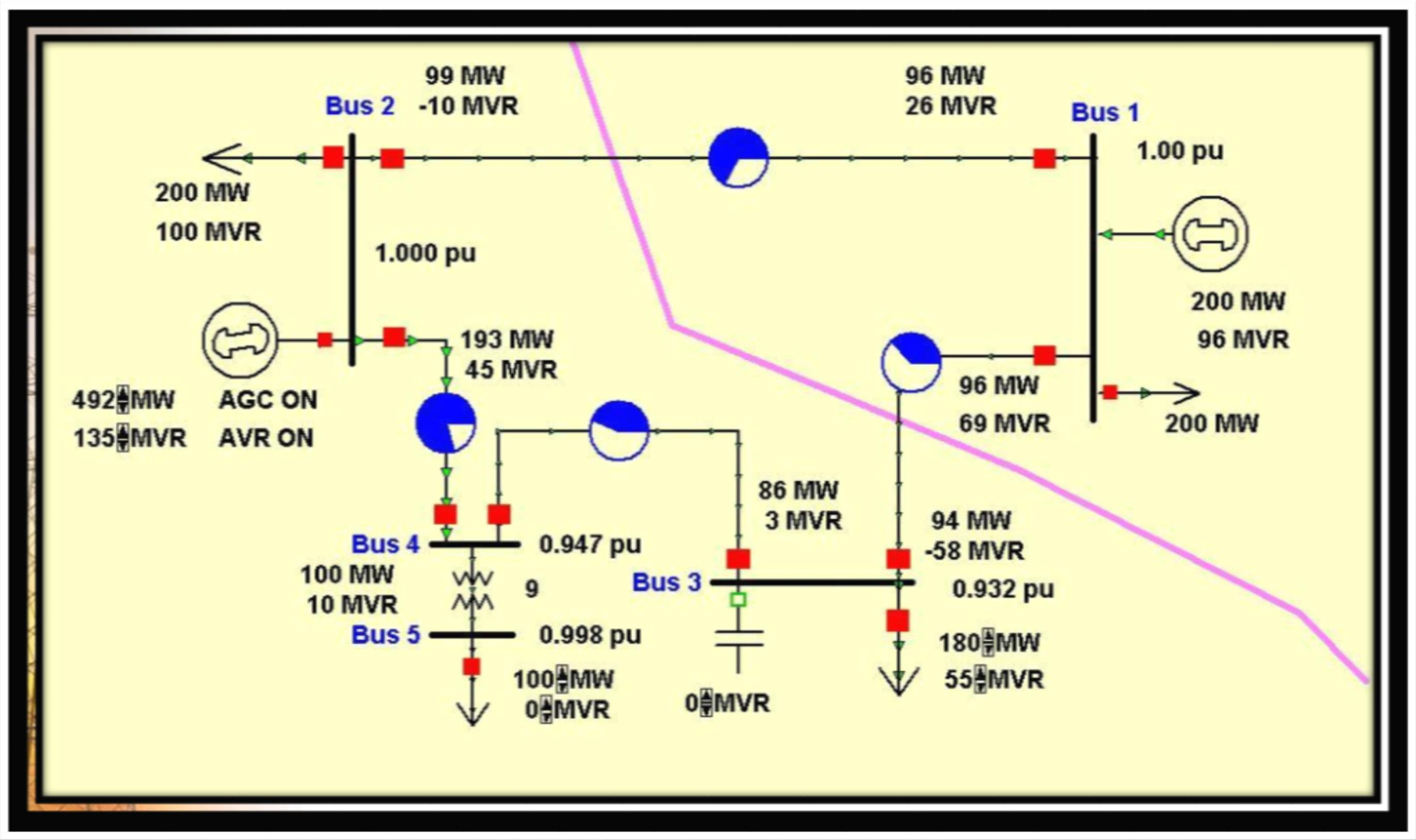
- **We have a system of 2n coupled equations in 2n unknowns**
- **The system of equations is *nonlinear***
- **This means that finding a solution to the power problem is not trivial for realistically-sized power systems with thousands of nodes**
- **Hence, it is not possible to obtain analytical solutions**
  - **Possible only for two-node systems**
  - **We will have to resort to specialized iterative numerical methods**

Power Flow

- If load P increases δ increases
- If load Q increases V reduces
- Real power flow

  $\delta_{\text{sending end}} > \delta_{\text{receiving end}}$
- Reactive power flow

  $|V_{\text{sending end}}| > |V_{\text{receiving end}}|$



Power Flow – Bus Types

- LOAD (PQ)
  - Given: P_k, Q_k
  - Unknown: V_k, δ_k
  - Example: Loads, transformer buses

- VOLTAGE CONTROLLED (PV)
  - Given: P_k, V_k
  - Unknown: Q_k, δ_k
  - Example: Generation buses, reactive power compensation buses

- SLACK(V δ)
  - Given: V_k, δ_k
  - Unknown: P_k, Q_k

Power Flow Tools

- Gauss-Seidel
- Newton Raphson
- Decoupled
- Fast Decoupled
- DC

Gauss-Seidel

Simple Iterative Methods
Gauss-Seidel method

Example (in one variable)

Compute the fixed point of $\cos\theta$ for $\theta \in [0, \frac{\pi}{2}]$

- Let us start with an initial guess for the fixed point $\theta^0 = 0.5$, we get

$$\theta^1 = \cos\theta^0 = \cos(0.5) = 0.8775\ldots$$

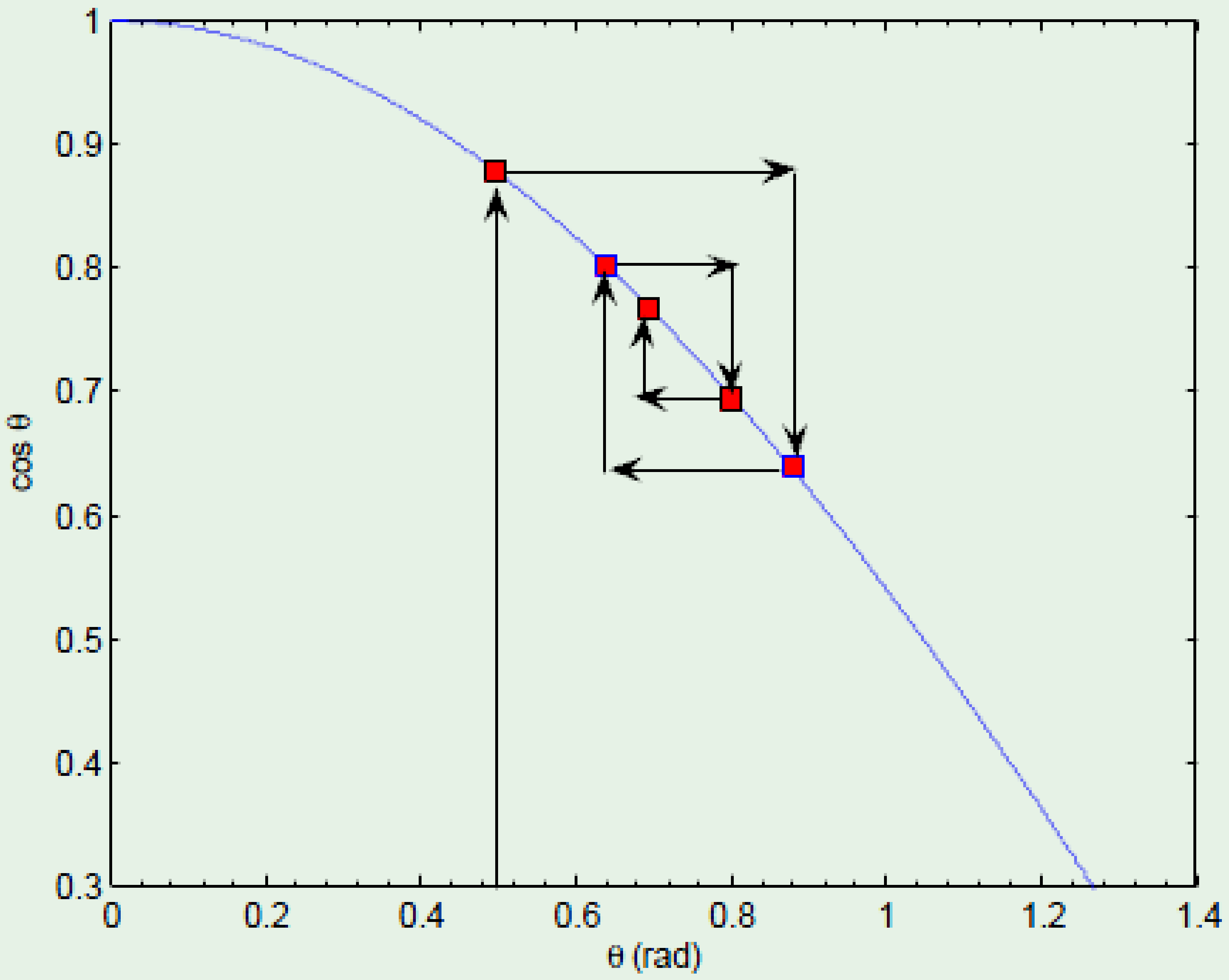
- Applying the fixed point principle again

$$\theta^2 = \cos\theta^1 = \cos(0.8775\ldots) = 0.6390\ldots$$

and so on.

- In the limit as $k \to \infty$, $\cos\theta^k - \theta^{k+1} = 0$ and $\theta^k \to 0.7390\ldots$

Graphically this looks like



Newton Raphson

Newton-Raphson Method
Basic principle for single-variable functions

We recall Taylor's theorem for functions of a single variable

$$f(x + \Delta x) = f(x) + f'(x)\Delta x + \frac{1}{2!}f''(x)\Delta x^2 + \cdots$$

retaining only the first two terms of the series expansion for x small enough, we can say

$$f(x + \Delta x) \approx f(x) + f'(x)\Delta x$$

The above is the tangent line approximation of the function f about the point x

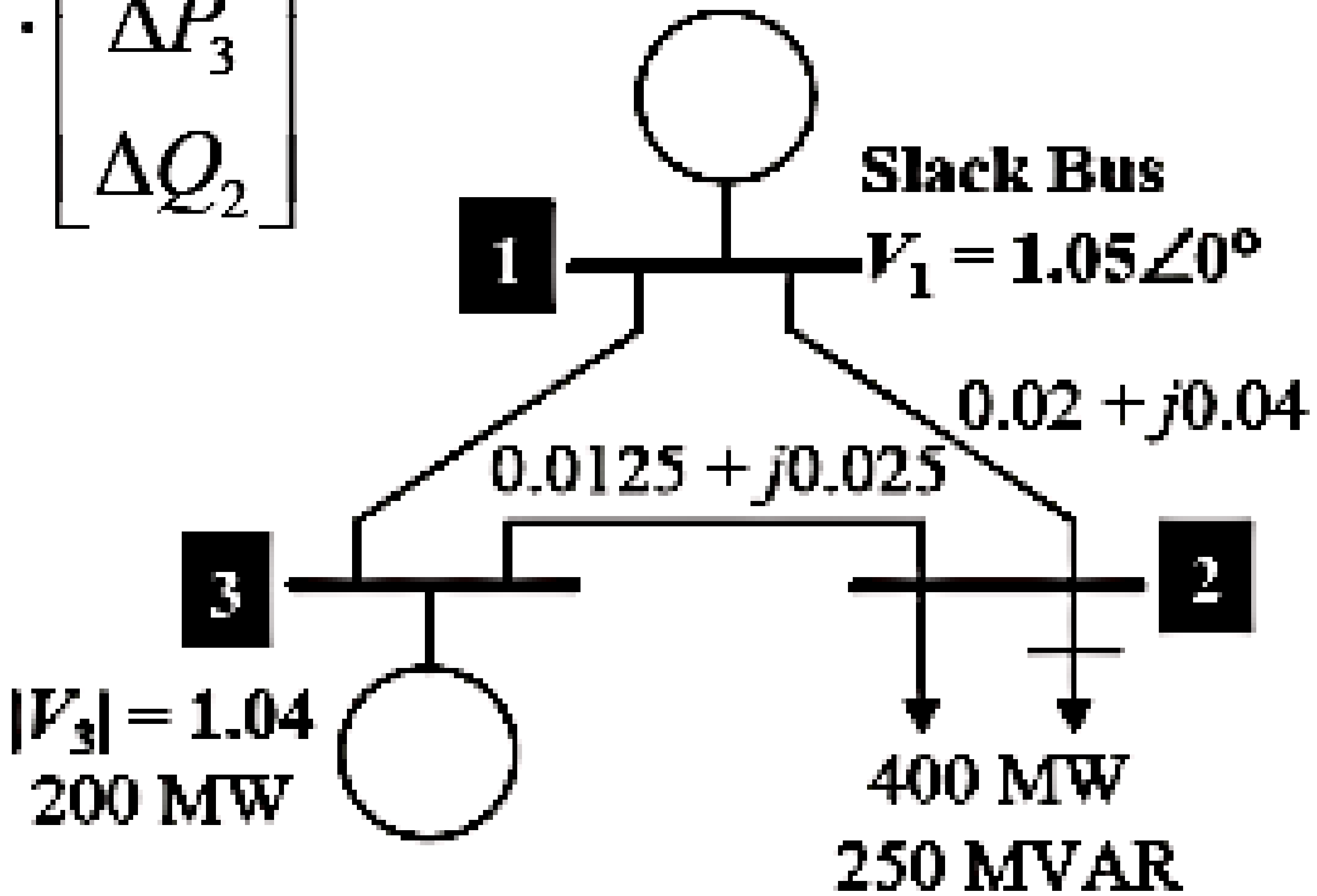
Newton Raphson - Example

$$f(x+\Delta x) \approx f(x) + f'(x)\Delta x$$

$$\bar{x}^{[k+1]} = \bar{x}^{[k]} + J^{-1} \cdot \Delta c^{[k]}$$

$$= \begin{bmatrix} \bar{\delta}_2 \\ \bar{\delta}_3 \\ \bar{V}_2 \end{bmatrix}^{[k+1]} = \begin{bmatrix} \bar{\delta}_2 \\ \bar{\delta}_3 \\ \bar{V}_2 \end{bmatrix}^{[k]} + \begin{bmatrix} \partial P_2/\partial\delta_2 & \partial P_2/\partial\delta_3 & \partial P_2/\partial V_2 \\ \partial P_3/\partial\delta_2 & \partial P_3/\partial\delta_3 & \partial P_3/\partial V_2 \\ \partial Q_2/\partial\delta_2 & \partial Q_2/\partial\delta_3 & \partial Q_2/\partial V_2 \end{bmatrix}^{-1} \cdot \begin{bmatrix} \Delta P_2 \\ \Delta P_3 \\ \Delta Q_2 \end{bmatrix}^{[k]}$$

Jacobian Matrix



Newton Raphson - Example

$$Y_{bus} = \begin{bmatrix} 20-j50 & -10+j20 & -10+j30 \\ -10+j20 & 26-j52 & -16+j32 \\ -10+j30 & -16+j32 & 26-j62 \end{bmatrix}$$

$$= \begin{bmatrix} 53.9\angle -1.90 & 22.4\angle 2.03 & 31.6\angle 1.89 \\ 22.4\angle 2.03 & 58.1\angle -1.11 & 35.8\angle 2.03 \\ 31.6\angle 1.89 & 35.8\angle 2.03 & 67.2\angle -1.17 \end{bmatrix}$$

angles are in radians

$$P_2 = |V_2||V_1||Y_{21}|\cos(\theta_{21}-\delta_2+\delta_1)+|V_2|^2|Y_{22}|\cos(\theta_{22})+|V_2||V_3||Y_{23}|\cos(\theta_{23}-\delta_2+\delta_3)$$

$$P_3 = |V_3||V_1||Y_{31}|\cos(\theta_{31}-\delta_3+\delta_1)+|V_3||V_2||Y_{32}|\cos(\theta_{32}-\delta_3+\delta_2)+|V_3|^2|Y_{33}|\cos(\theta_{33})$$

$$Q_2 = -|V_2||V_1||Y_{21}|\sin(\theta_{21}-\delta_2+\delta_1)-|V_2|^2|Y_{22}|\sin(\theta_{22})-|V_2||V_3||Y_{23}|\sin(\theta_{23}-\delta_2+\delta_3)$$

Newton Raphson - Example

$$\bar{x} = \begin{bmatrix} \bar{\delta}_2 \\ \bar{\delta}_3 \\ \bar{V}_2 \end{bmatrix} \qquad f(\bar{x}) = \begin{bmatrix} P_2(\bar{\delta}_2, \bar{\delta}_3, \bar{V}_2) \\ P_3(\bar{\delta}_2, \bar{\delta}_3, \bar{V}_2) \\ Q_2(\bar{\delta}_2, \bar{\delta}_3, \bar{V}_2) \end{bmatrix}$$

$$= \begin{bmatrix} |\bar{V}_2||1.05||22.3|\cos(2.03 - \bar{\delta}_{21}) + |\bar{V}_2|^2|58.1|\cos(-1.11) + |\bar{V}_2||1.04||35.8|\cos(2.03 - \bar{\delta}_2 + \bar{\delta}_3) \\ |V_3||1.05||31.6|\cos(1.89 - \bar{\delta}_3) + |1.04||\bar{V}_2||35.8|\cos(2.03 - \bar{\delta}_3 + \bar{\delta}_2) + |1.04|^2|67.2|\cos(-1.17) \\ -|\bar{V}_2||1.05|22.3|\sin(2.03 - \bar{\delta}_2) - |\bar{V}_2|^2|58.1|\sin(-1.11) - |\bar{V}_2||1.04||35.8|\sin(2.03 - \bar{\delta}_2 + \bar{\delta}_3) \end{bmatrix}$$

$$\Delta c = \begin{bmatrix} \Delta P_2 \\ \Delta P_3 \\ \Delta Q_2 \end{bmatrix} = c - f(\bar{x}) = \begin{bmatrix} P_2^{sch} \\ P_3^{sch} \\ Q_2^{sch} \end{bmatrix} - \begin{bmatrix} P_2(\bar{\delta}_2, \bar{\delta}_3, \bar{V}_2) \\ P_3(\bar{\delta}_2, \bar{\delta}_3, \bar{V}_2) \\ Q_2(\bar{\delta}_2, \bar{\delta}_3, \bar{V}_2) \end{bmatrix} = \begin{bmatrix} -4.0 \\ 2.0 \\ -2.5 \end{bmatrix} - \begin{bmatrix} P_2(\bar{\delta}_2, \bar{\delta}_3, \bar{V}_2) \\ P_3(\bar{\delta}_2, \bar{\delta}_3, \bar{V}_2) \\ Q_2(\bar{\delta}_2, \bar{\delta}_3, \bar{V}_2) \end{bmatrix}$$

Newton Raphson - Example

$$\bar{x}^{[0]} = \begin{bmatrix} 0.0 \\ 0.0 \\ 1.0 \end{bmatrix} \quad \Delta c^{[0]} = \begin{bmatrix} P_2^{sch} \\ P_3^{sch} \\ Q_2^{sch} \end{bmatrix} - \begin{bmatrix} P_2^{[0]} \\ P_3^{[0]} \\ Q_2^{[0]} \end{bmatrix} = \begin{bmatrix} -4.0 \\ 2.0 \\ -2.5 \end{bmatrix} - \begin{bmatrix} -1.14 \\ 0.562 \\ -2.28 \end{bmatrix} = \begin{bmatrix} -2.86 \\ 1.438 \\ -0.22 \end{bmatrix}$$

$$\Delta x^{[0]} = J^{-1} \Delta c^{[0]}$$

$$\Delta x^{[0]} = \begin{bmatrix} \Delta\delta_2^{[0]} \\ \Delta\delta_3^{[0]} \\ \Delta\left|V_2^{[0]}\right| \end{bmatrix} = \begin{bmatrix} 54.28 & -33.28 & 24.86 \\ -33.28 & 66.04 & -16.64 \\ -27.14 & 16.64 & 49.72 \end{bmatrix}^{-1} \begin{bmatrix} -2.86 \\ 1.438 \\ -0.22 \end{bmatrix} = \begin{bmatrix} -0.04526 \\ -0.00772 \\ -0.02655 \end{bmatrix}$$

$$\bar{x}^{[1]} = \begin{bmatrix} \delta_2^{[1]} \\ \delta_3^{[1]} \\ \left|V_2^{[1]}\right| \end{bmatrix} = \begin{bmatrix} 0.0 + (-0.04526) \\ 0.0 + (-0.00772) \\ 1.0 + (-0.02655) \end{bmatrix} = \begin{bmatrix} -0.04526 \\ -0.00772 \\ 0.9734 \end{bmatrix}$$

Newton Raphson - Example

$$\bar{x}^{[3]} = \begin{bmatrix} -0.04706 \\ -0.008705 \\ 0.97168 \end{bmatrix} \quad \Delta c^{[2]} = \begin{bmatrix} P_2^{sch} \\ P_3^{sch} \\ Q_2^{sch} \end{bmatrix} - \begin{bmatrix} P_2^{[1]} \\ P_3^{[1]} \\ Q_2^{[1]} \end{bmatrix} = \begin{bmatrix} -4.0 \\ 2.0 \\ -2.5 \end{bmatrix} - \begin{bmatrix} -4.0 \\ 2.0 \\ -2.5 \end{bmatrix} = \begin{bmatrix} 0.0000 \\ 0.0000 \\ 0.0000 \end{bmatrix}$$

$$\varepsilon_{\max} = 2.5\times10^{-4}$$

$$P_1 = |V_1|^2|Y_{11}|\cos(\theta_{11}) + |V_1||V_2||Y_{12}|\cos(\theta_{12} - \delta_1 + \delta_2) + |V_1||V_3||Y_{13}|\cos(\theta_{13} - \delta_1 + \delta_3)$$

$$Q_1 = -|V_1|^2|Y_{11}|\sin(\theta_{11}) - |V_1||V_2||Y_{12}|\sin(\theta_{12} - \delta_1 + \delta_2) - |V_1||V_3||Y_{13}|\sin(\theta_{13} - \delta_1 + \delta_3)$$

$$Q_3 = -|V_3||V_1||Y_{31}|\sin(\theta_{31} - \delta_3 + \delta_1) - |V_3||V_2||Y_{32}|\sin(\theta_{32} - \delta_3 + \delta_2) - |V_3|^2|Y_{33}|\sin(\theta_{33})$$

$$P_1 = 2.1842\,pu$$

$$Q_1 = 1.4085\,pu$$

$$Q_3 = 1.4617\,pu$$

When Things Go Wrong. . .

Question

Is it possible for any set of power injections and voltage magnitudes to always yield a valid power flow solution?

- The answer is no!
- So what happens when there is no solution to the power flow problem?
  - Physically, this means that the system cannot sustain the flow of power, that is the *system collapses*
    - The system loading is so high, causing large voltage drops across the network due to reactive power losses mostly
    - It is synonym with extreme imbalances between network reactive power demand and what can be provided by the sources of reactive power

Decoupled
Fast Decoupled
DC

Faster Power Flow Options

Decoupled & Fast Decoupled Power Flow

Observation

The Jacobian matrix in the Newton-Raphson power flow solution has the following property

$$J = \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V} \end{bmatrix} \approx \begin{bmatrix} \frac{\partial P}{\partial \theta} & 0 \\ 0 & \frac{\partial Q}{\partial V} \end{bmatrix}$$

where $\frac{\partial P}{\partial \theta}$ and $\frac{\partial Q}{\partial V}$ are square matrices

- **P – V and Q – θ are weak, hence *decoupled***
- **This is a physical property of ac power networks**

Decoupled power flow => inverts two smaller-dimension matrices

Fast-decoupled power flow => inverts two smaller-dimension matrices only once

DC Power Flow

The DC power flow is well-suited for security analysis and planning problems

- Fast because it requires a single iteration and a single matrix inversion
- Line power flow calculations are straightforward
- Unlike full nonlinear and fast decoupled load flows, the DC load flow
  - Is only an approximation
  - Always converges
  - Calculates bus voltage angles only, not bus voltage magnitudes

$$\frac{\partial P}{\partial \theta}$$

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Power System Security

Power System Security

Power system security involves the practices designed **to keep the system operating when components fail**

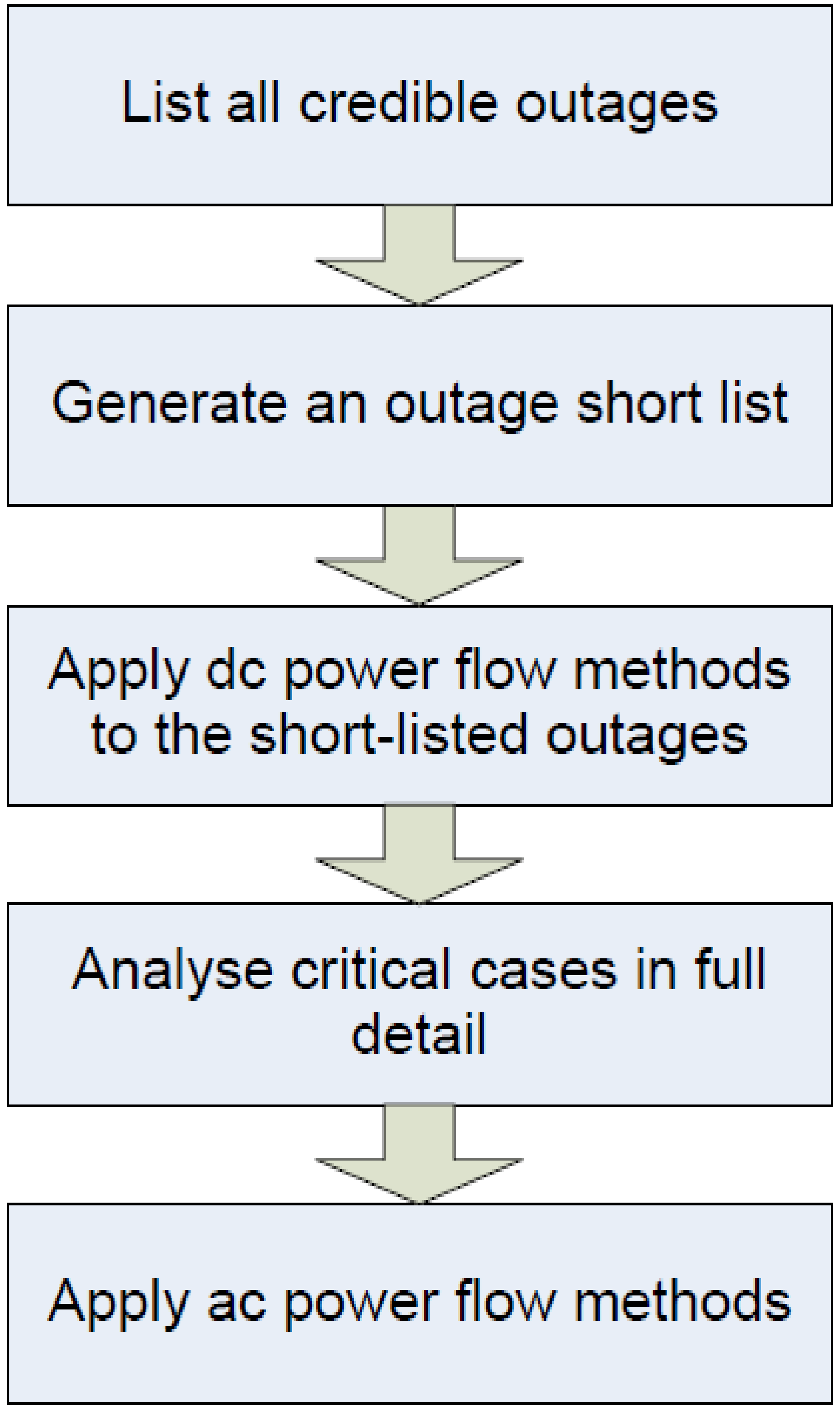
“N – 1 security” is a security standard that requires a power system to continue to work satisfactorily following the loss of any one of its N elements.

“N – M security” is a security standard that requires a power system to continue to work satisfactorily following the loss of any M = 1, 2, 3,… of its N elements.

Functions of System Security
Contingency analysis

Contingency analysis programs model possible system troubles before they arise

- Defensive approach to the operation of the system.
- Contingency analysis is challenged by the speed of the power flow analysis module used
  - Approximate power flow models are used
    - DC power flow
- Thorough analysis is performed for critical cases only
- Programs are based on a model of the power system and are used to study outage events


List all credible outages

Generate an outage short list

Apply dc power flow methods to the short-listed outages

Analyse critical cases in full detail

Apply ac power flow methods

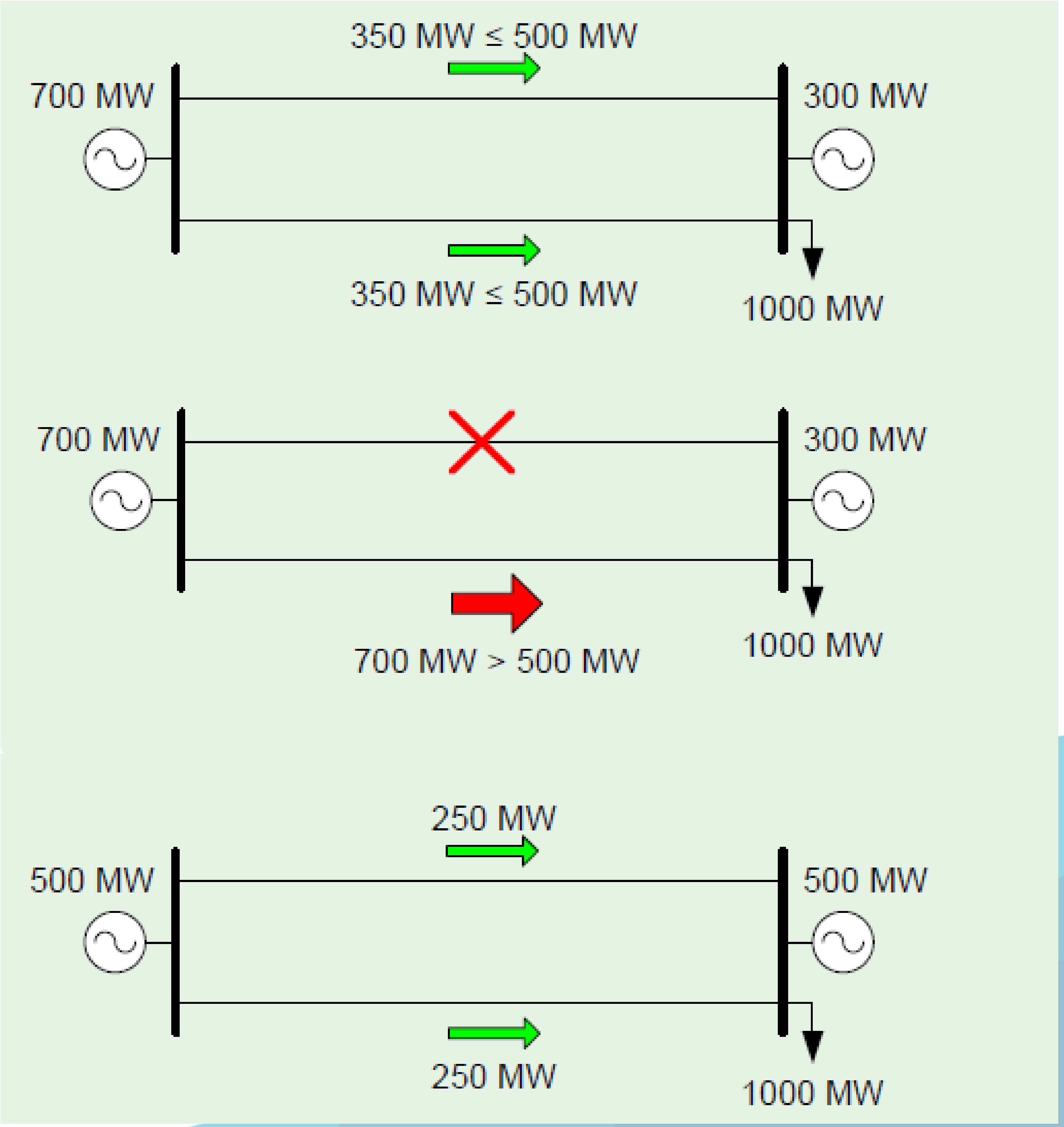
Power System Security - Principles

To plan ahead of contingencies by:

Implementing security enhancing actions *preventive control actions*

Post-contingency *corrective control actions* are also needed

The key idea to providing security is *redundancy.*



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Introduction to Transient Analysis

Power System Stability

- The property of a power system which enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance.

- Instability may be manifested in many different ways depending on system configuration and operating mode.

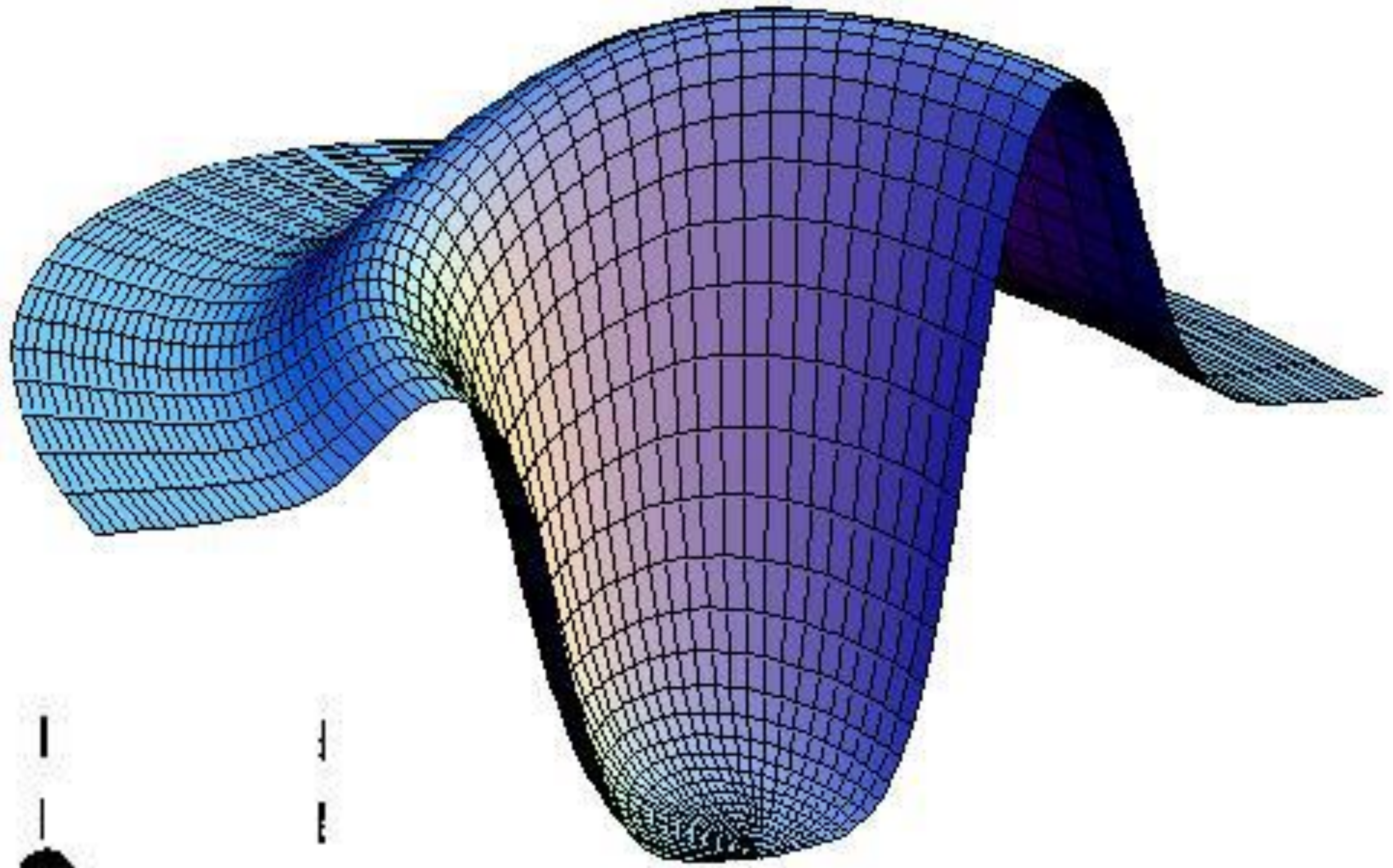
Steady State vs Dynamic

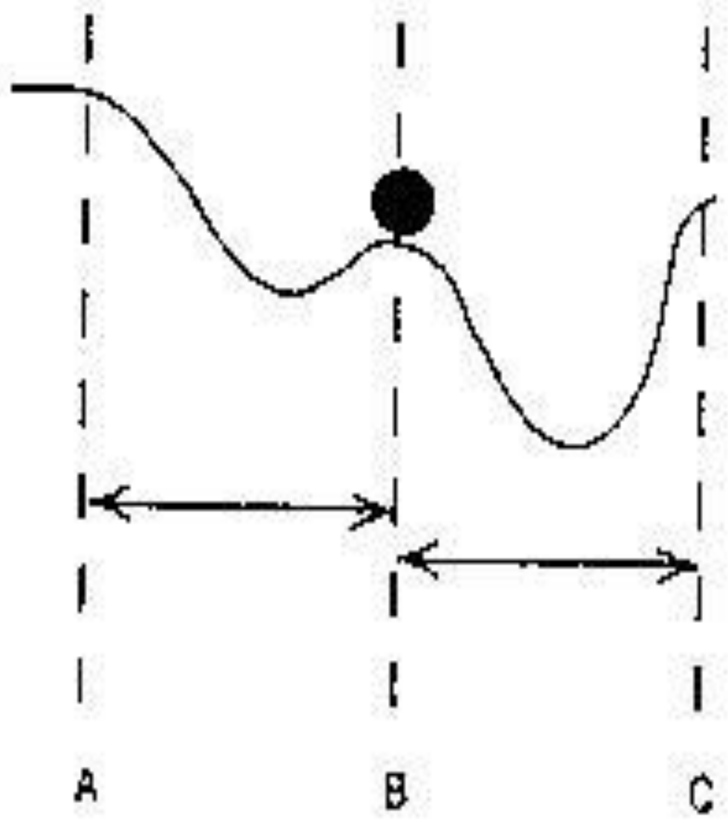
Steady state = stability = equilibrium point

- things are not changing (power systems pseudo)
- concerned with whether the system variables are within the correct limits.

Transient stability

- “transient” means changing and temporal.
- The state of the system is changing.
- We are concerned with the transition from one equilibrium to another.
- The change is a result of a “large” disturbance.

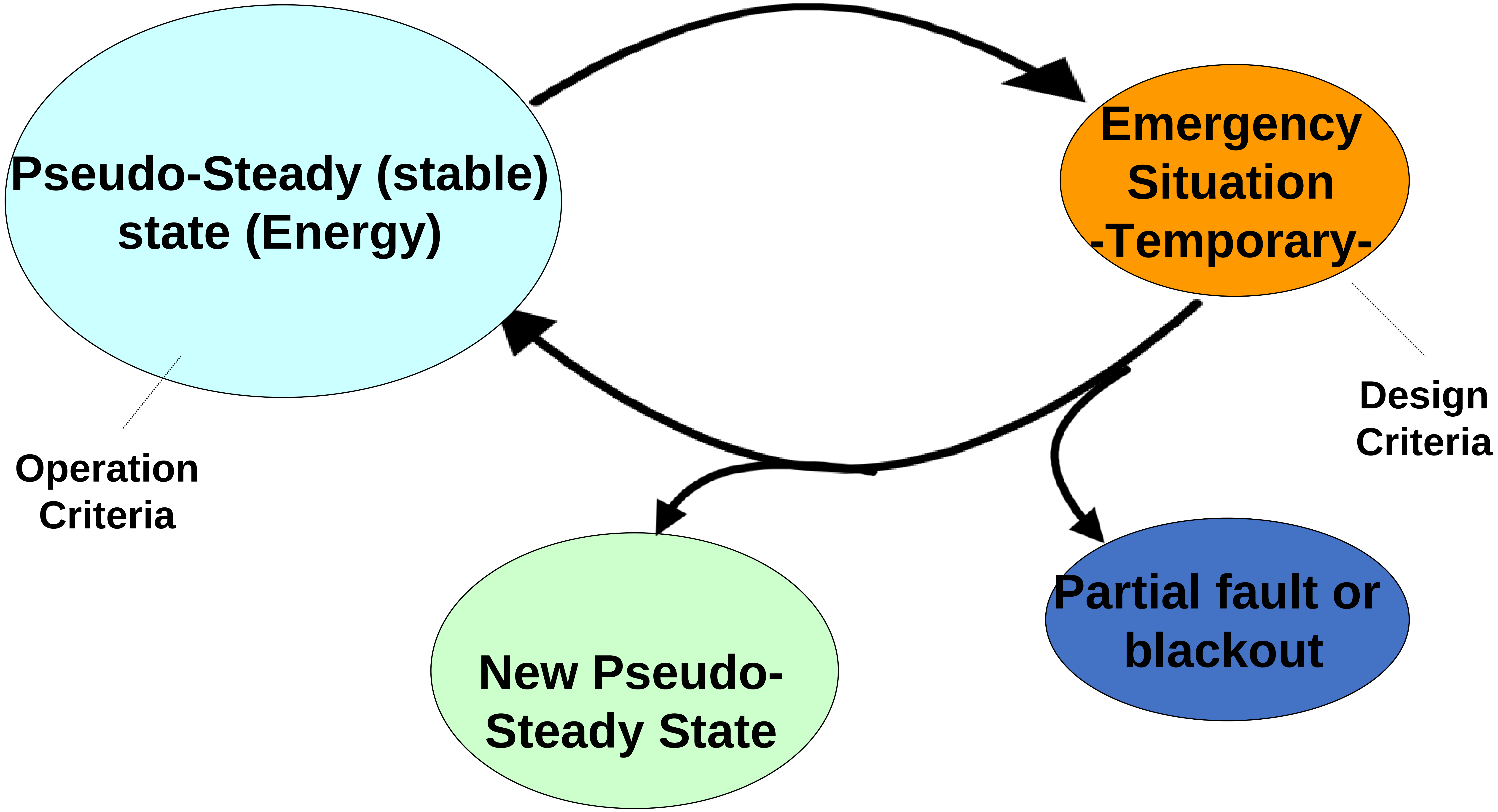




Transient Stability

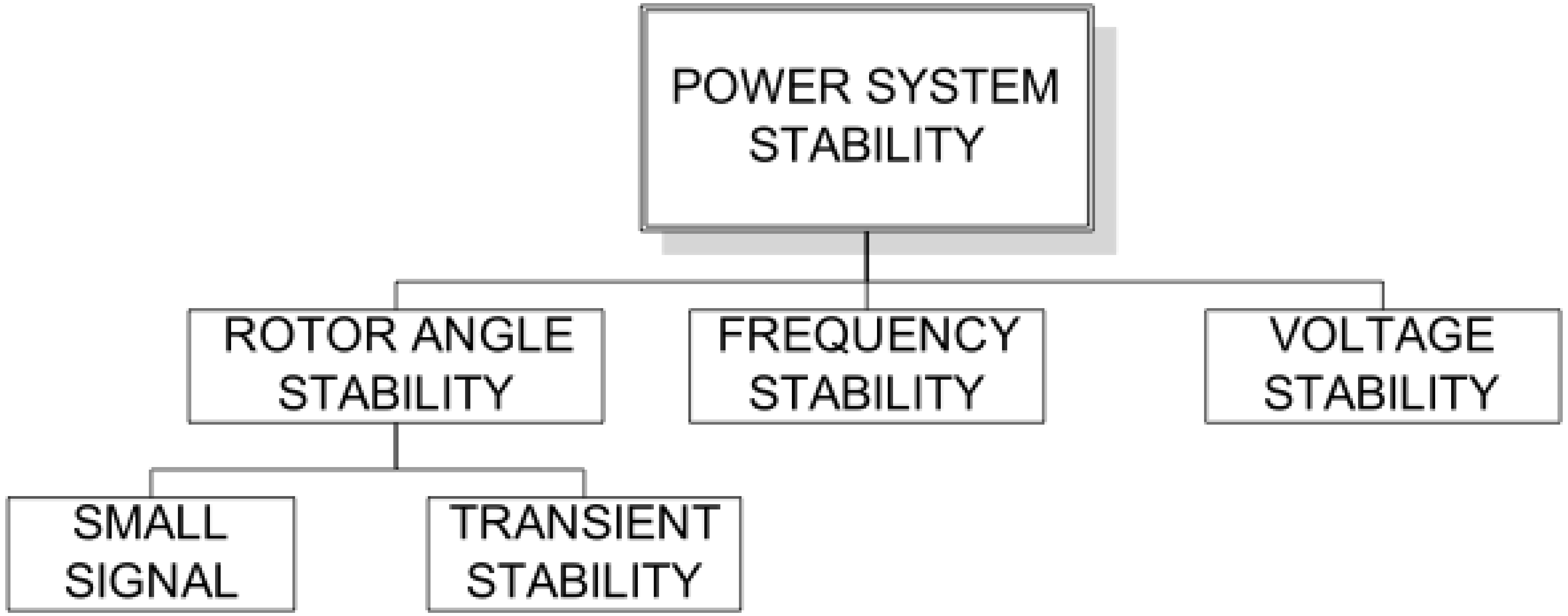
- Transient stability is the ability of a power system to maintain synchronism when subjected to a severe transient disturbance.
- Ability of synchronous machines to move from one steady-state operating point following a disturbance to another steady-state operating point, without losing synchronism.

Dynamic State of Power Systems



Classification Power System Stability

Power system stability is a single problem. However, it is impractical to study and deal with it as such (too complex).


POWER SYSTEM STABILITY

ROTOR ANGLE STABILITY

FREQUENCY STABILITY

VOLTAGE STABILITY

SMALL SIGNAL

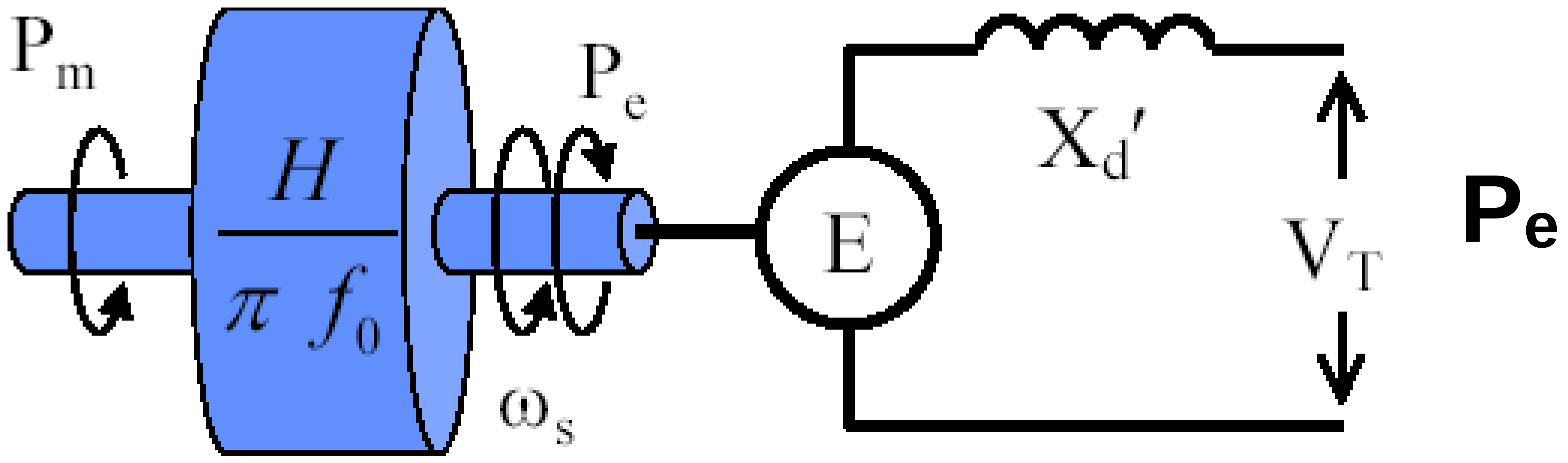
TRANSIENT STABILITY

Transient stability is the ability of a power system to maintain synchronism when subjected to a severe transient disturbance.

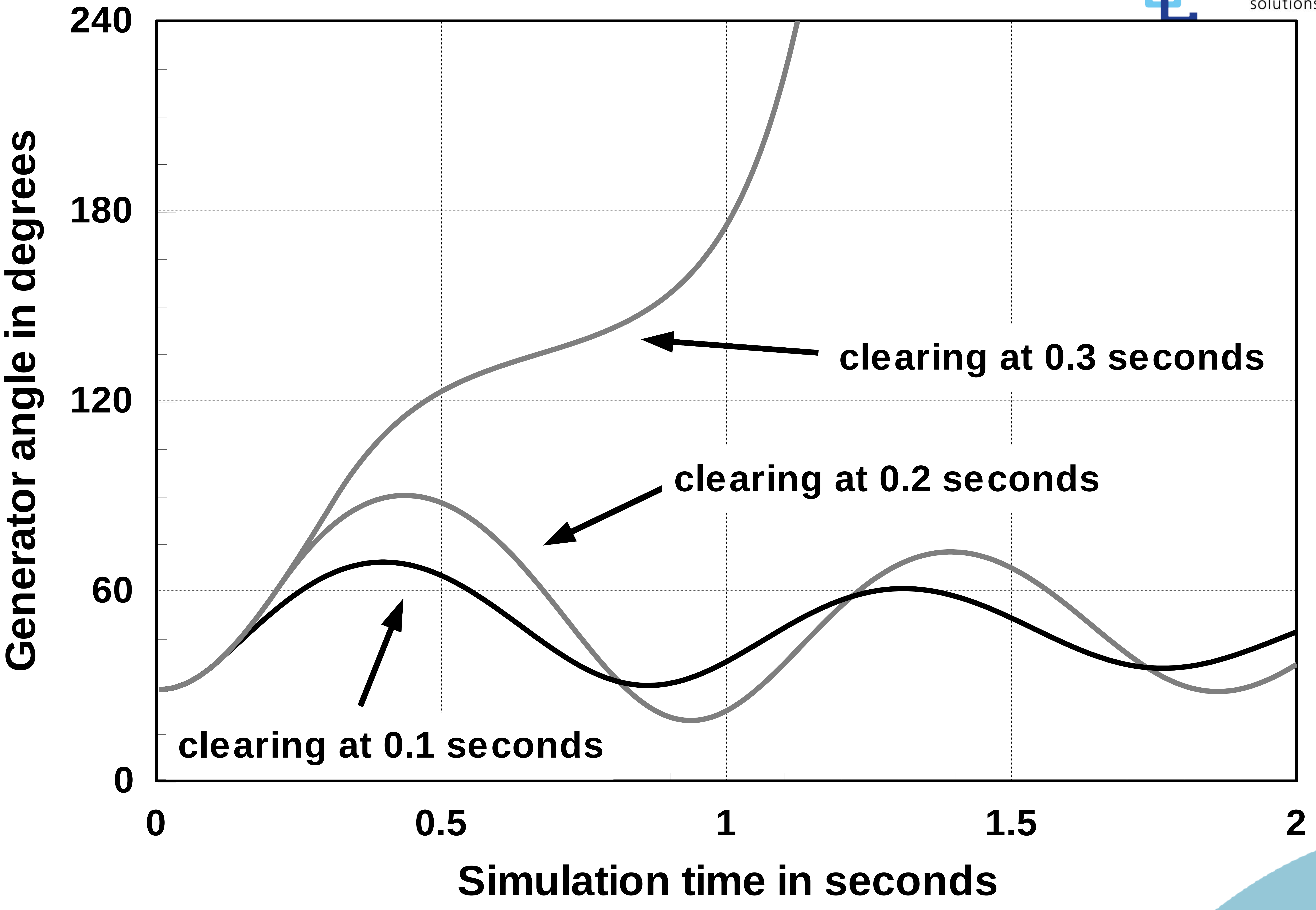
Power Angle Characteristics

Mechanical energy → **Rotational Kinetic energy** → **Electrical energy**

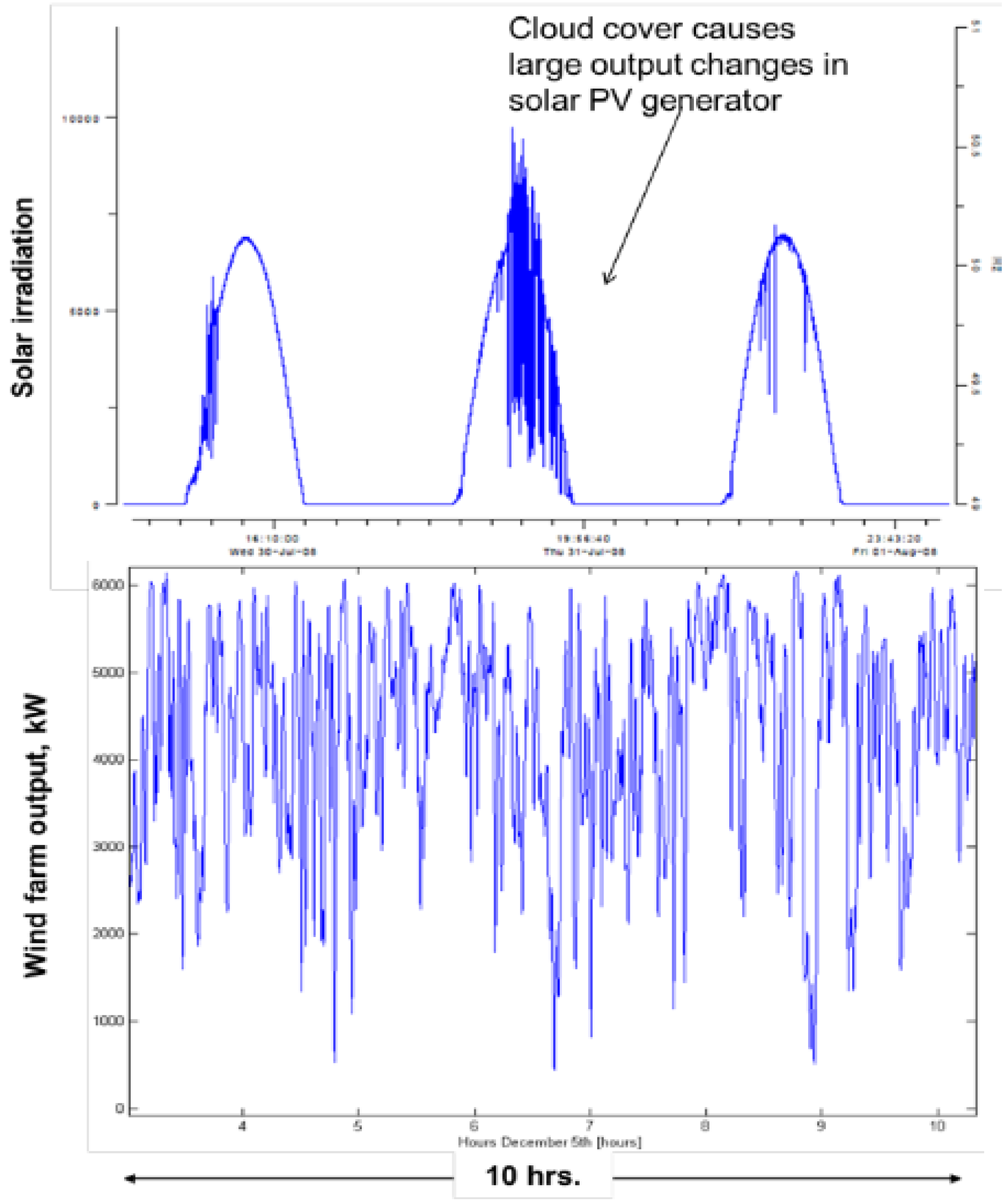
$$Kinetic\ energy = \frac{1}{2} J\omega^2$$



Typical Results



Renewable Energy Integration



Cloud cover causes large output changes in solar PV generator

10 hrs.

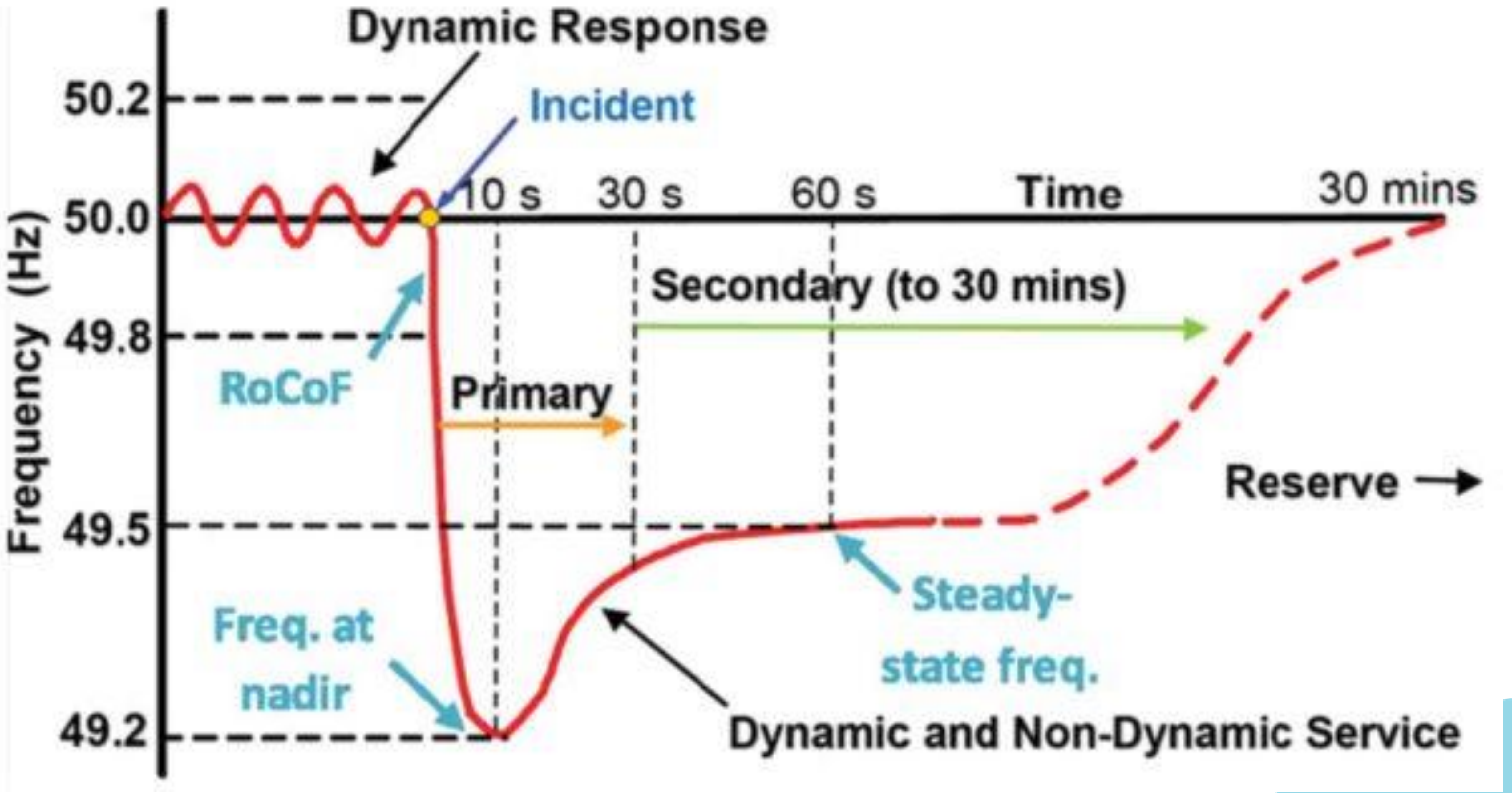
- Inherent volatility of renewable energy can compromise grid stability
- The renewable energy integration solution must address requirements traditionally fulfilled by diesel generation (base load)
    - Frequency and voltage control
    - Sufficient spinning reserve
    - Sufficient active and reactive power supply
    - Peak shaving and load levelling
    - Load sharing between generators
    - Fault current provision
- Renewable energy generation capacity should be sized to maximize ROI and fuel savings

Prioritising Technical Requirements

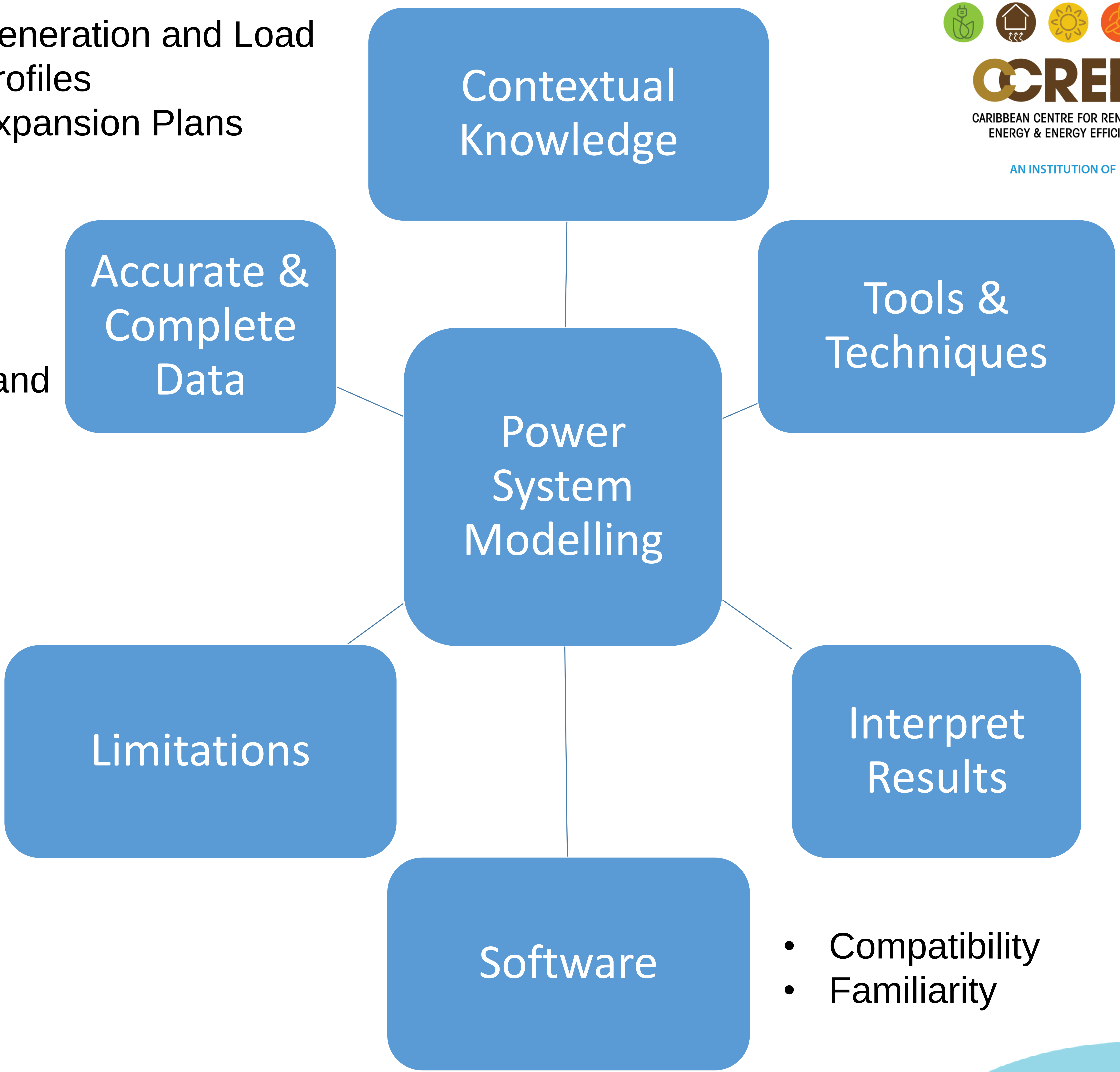
Power System Context	Technical Requirements
Always needed	• protection, load flows, short circuit analysis • static and transient stability • power quality • power reduction during over-frequency
Low VRE share	• communication • ramping rate study • adjustable reactive power • constraining active power (active power management)
Higher VRE share	• LVRT, protection scheme including current contribution • simulation models
Very high VRE share	• active power gradient limitation • reduced output operation mode for reserve provision • synthetic inertia
Exclusive use of VRE	• stand-alone frequency control • full integration into general frequency control scheme • stand-alone voltage control • full integration into general voltage control scheme

Synthetic Inertia

- Battery energy storage systems (BESS)
- Short-duration storage technologies for primary frequency control.
- Grid-scale batteries, respond at a much faster rate than the mechanical actions of traditional governor controls and blade pitch or wind turbine speed control mechanisms.
- Economic$.



http://www.ee.co.za/article/synthetic-inertia-grids-high-renewable-energy-content.html



Power System Modelling

Contextual Knowledge

- Generation and Load Profiles
- Expansion Plans

Accurate & Complete Data

- Availability
- Legacy Equipment
- Frequency and Accuracy of Collection

Tools & Techniques

- Power Flow
- Contingency Analysis
- Fault Analysis

Limitations

- Power System Security
- Operational
- Regulatory

Interpret Results

- Response as good as the data used to produced the model.

Software

- Compatibility
- Familiarity

Thank You