



EE3123 Introduction to Electric Power Systems

Faults, Robustness, and Cascading Failure

Dr. CQ Jiang

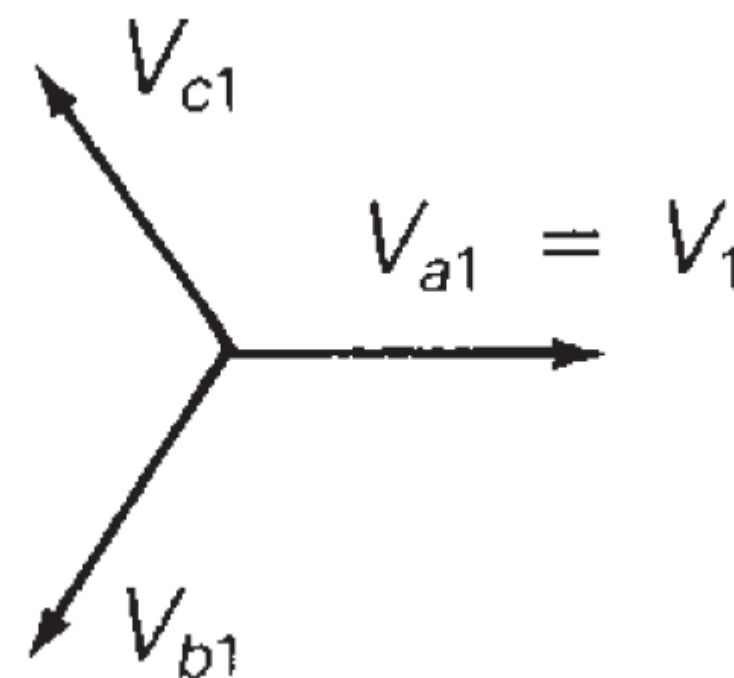
Many thanks to Prof. Michael Tse

Definition of symmetrical components

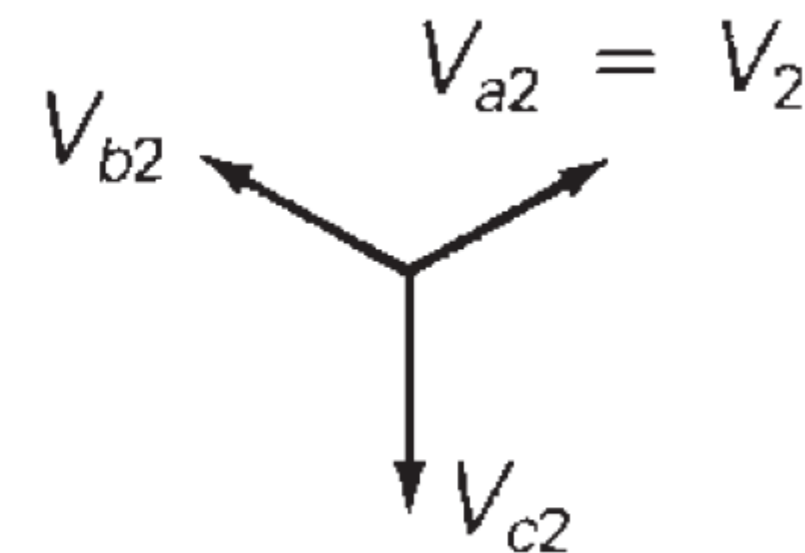
- **Zero-sequence** components, consisting of three phasors with equal magnitudes and with zero phase displacement.
- **Positive-sequence** components, consisting of three phasors with equal magnitudes, $+120^\circ$ phase displacement, and positive sequence.
- **Negative-sequence** components, consisting of three phasors with equal magnitudes, $+120^\circ$ phase displacement, and negative sequence.

$$V_{a0} \quad V_{b0} \quad V_{c0} = V_0$$


Zero-sequence



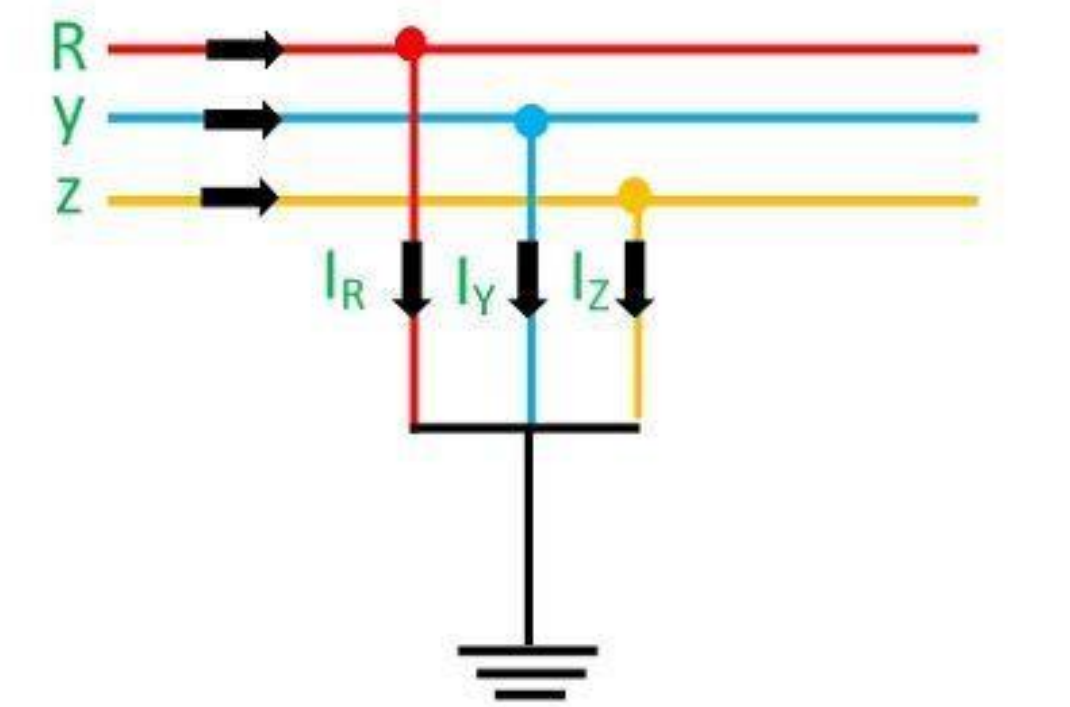
Positive-sequence



Negative-sequence

Symmetrical faults in power system

- ❑ In symmetrical faults, all phases are shorted to each other or to earth (L-L-L) or (L-L-L-G).
- ❑ The nature of this type of fault is balanced.
- ❑ In this type of fault, fault currents in all phases are symmetrical i.e. their magnitudes are equal and they are equally displaced by angle 120° as shown in right figure.
- ❑ Short circuits occur in power systems when equipment insulation fails due to system overvoltages caused by lightning or switching surges, to insulation contamination (salt spray or pollution), or to other mechanical causes. The resulting short circuit or “fault” current is determined by the internal voltages of the synchronous machines and by the system impedances between the machine voltages and the fault.



Symmetrical Fault

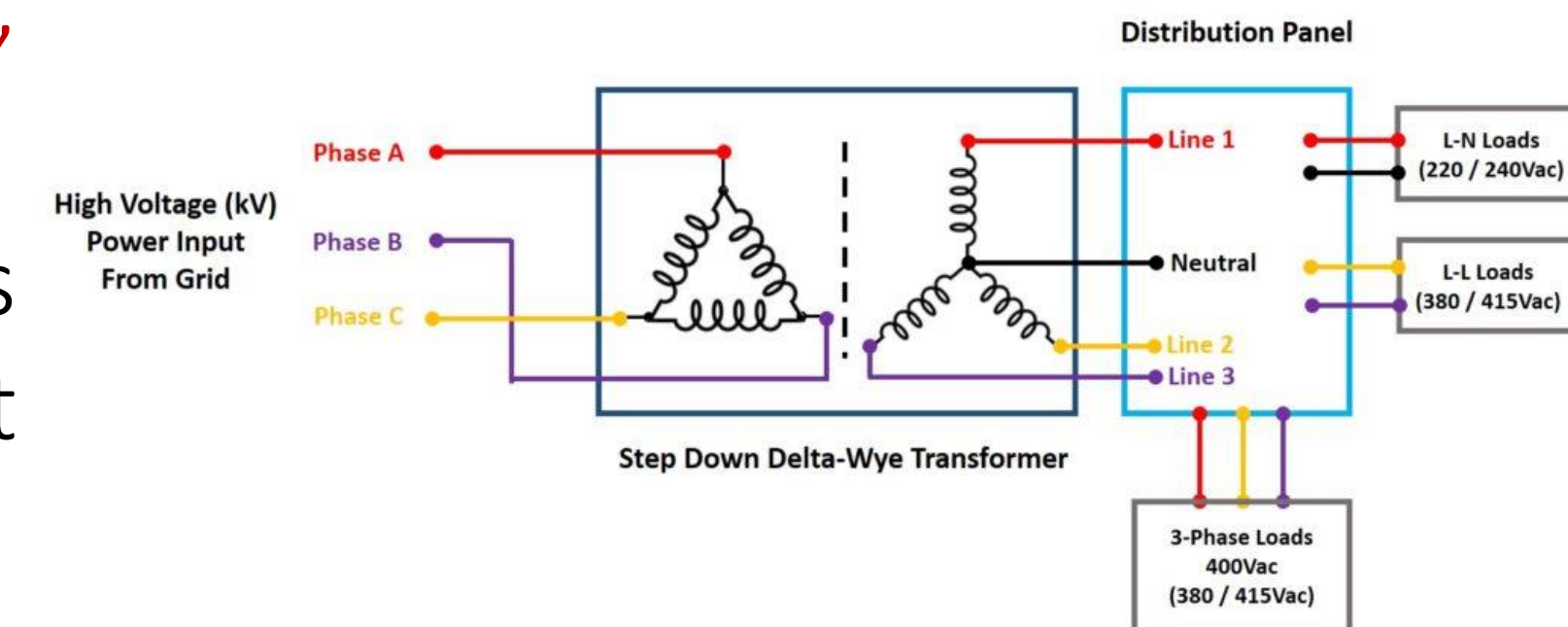
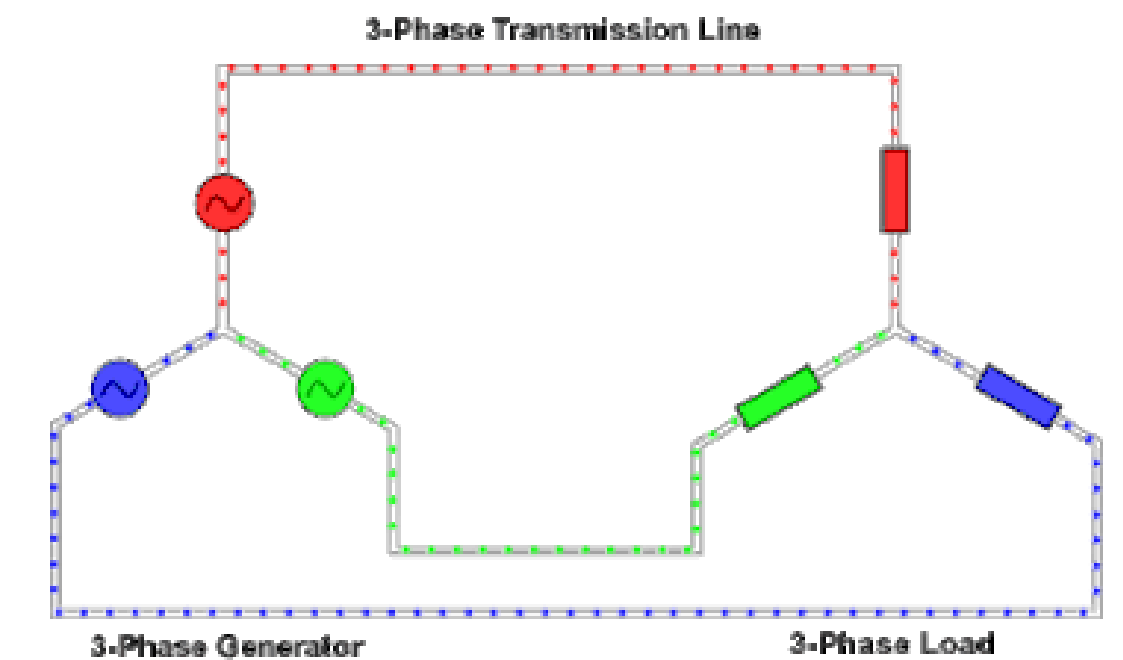
Circuit Globe

<https://circuitglobe.com/symmetrical-and-unsymmetrical-faults.html>

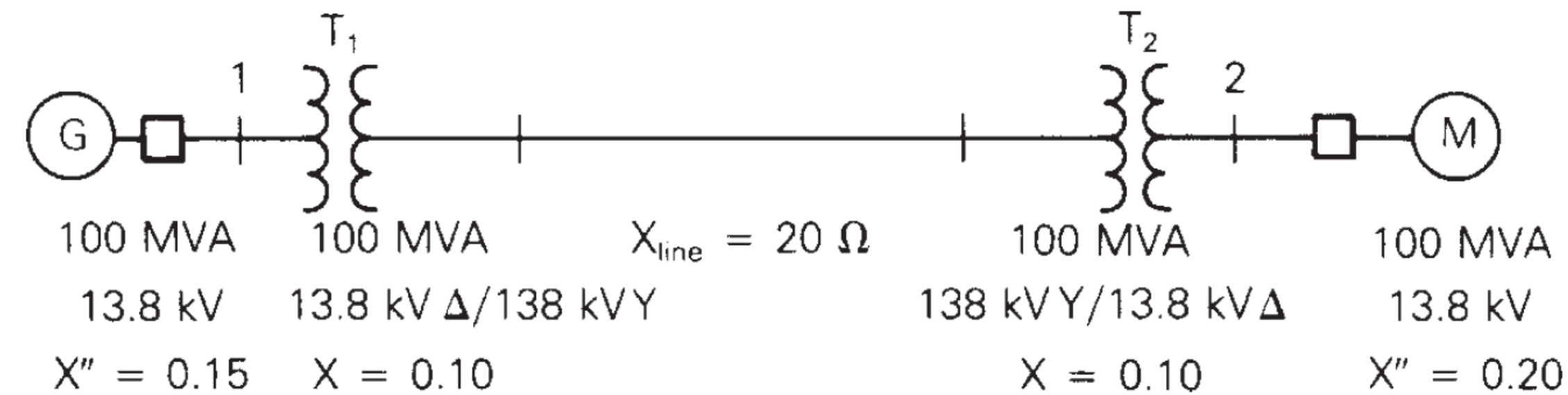
Symmetrical faults: three-phase short circuits

In order to **calculate the subtransient** fault current for a three-phase short circuit in a power system, make the following assumptions:

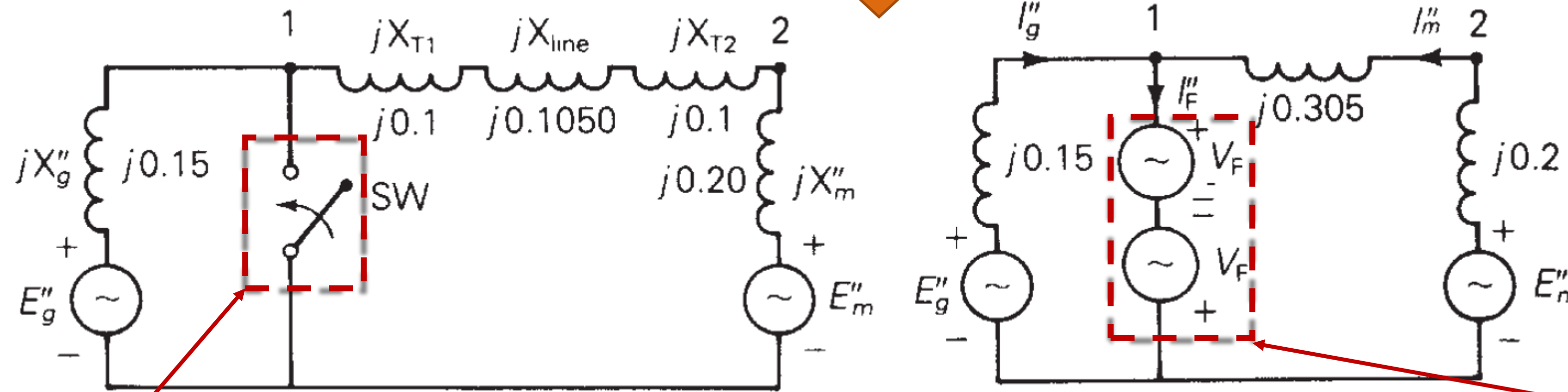
- Transformers are represented by their leakage reactances. **Winding resistances, shunt admittances, and Δ -Y phase shifts** are neglected.
- Transmission lines are represented by their equivalent series reactances. Neglect **series resistances and shunt admittances**.
- Synchronous machines are represented by constant-voltage sources behind subtransient reactances. Neglect **armature resistance, saliency, and saturation**.
- Neglect all **nonrotating impedance** loads. Especially for small motors rated less than 50 hp, either neglect induction motors or represent them in the same manner as synchronous machines.



Symmetrical faults: three-phase short circuits



- ❖ Consider a three-phase short circuit at bus 1. For purposes of calculating the subtransient fault current, E_g'' and E_m'' are assumed to be constant-voltage sources.



- ❖ Short circuit fault represented by SW

(a) Three-phase short circuit

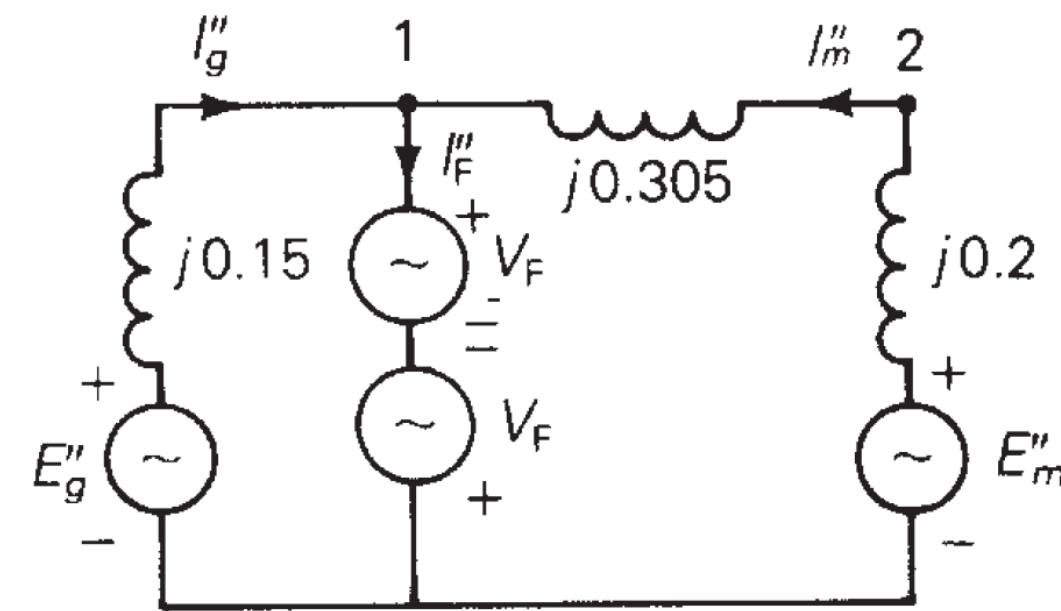
(b) Short circuit represented by two opposing voltage sources

- ❖ Two opposing voltage sources with equal phasor values V_F

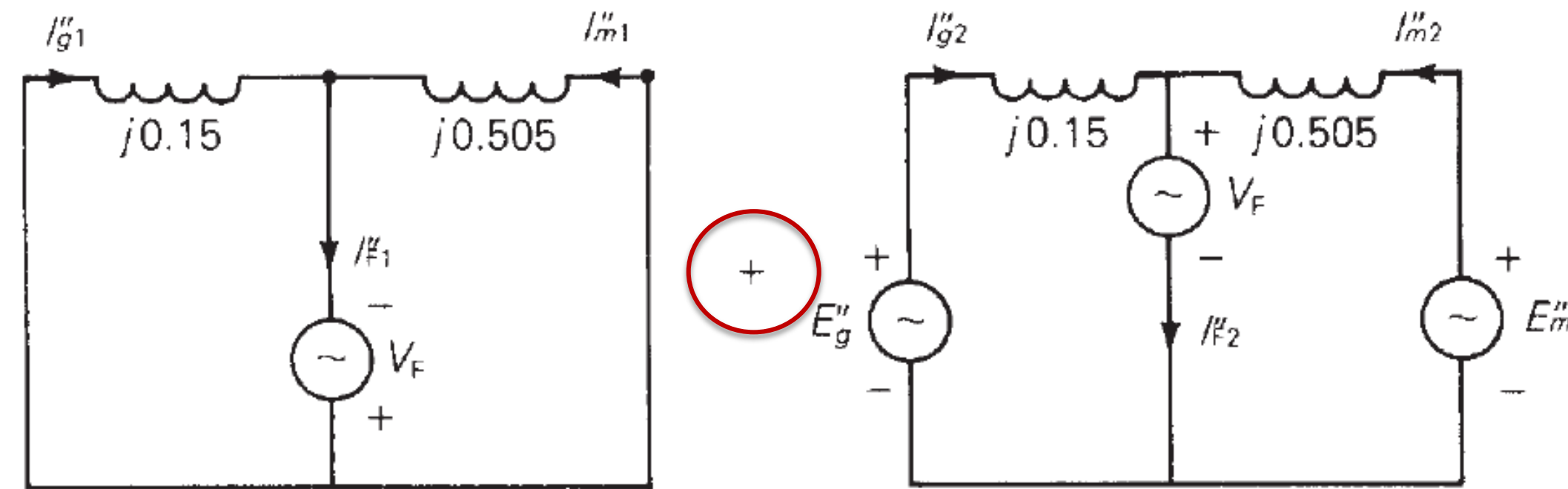
- ❖ When fault occurs, the motor is still spinning, and then having the back EMF (voltage).

Symmetrical faults: three-phase short circuits

Using superposition, the fault current then can be calculated from the below two circuits.

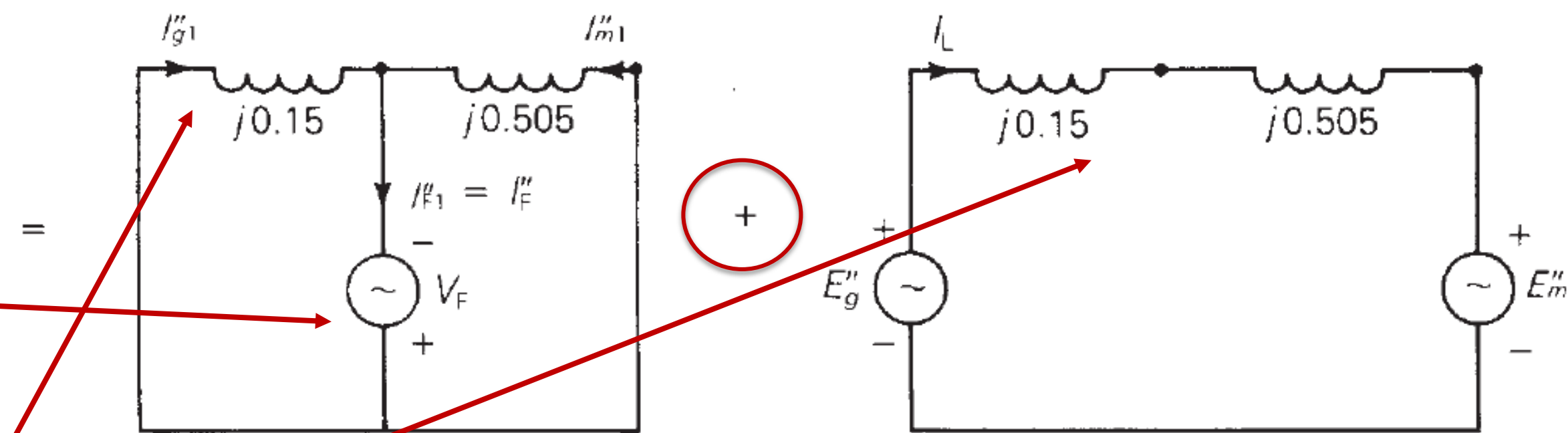


(b) Short circuit represented by two opposing voltage sources



(c) Application of superposition

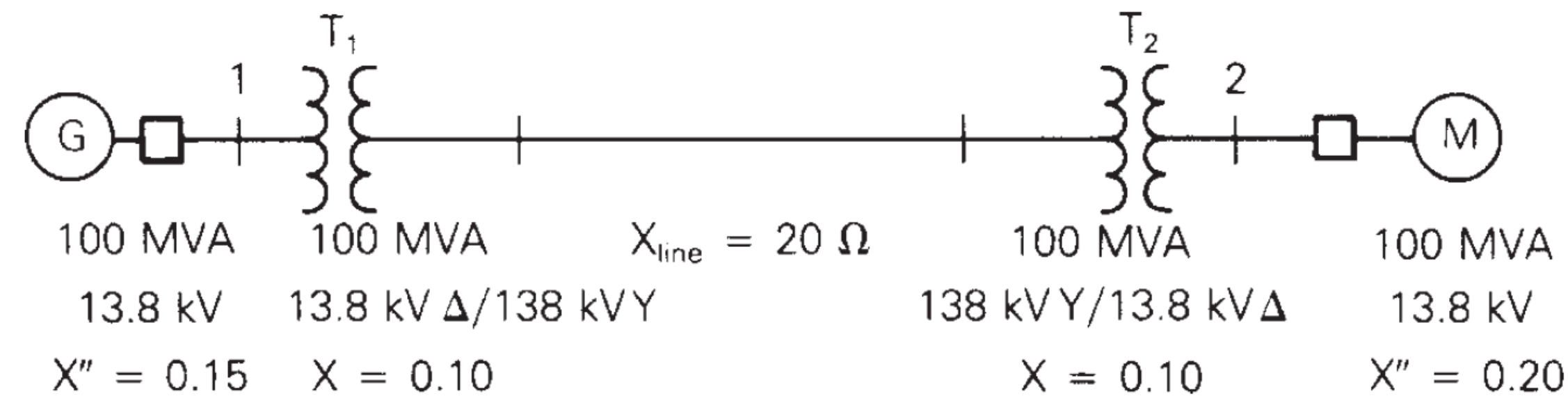
- if V_F equals the prefault voltage at the fault, then $I_{F2}'' = 0$.
- The subtransient fault current is then determined from the first circuit of d.
- The contribution to the fault from the generator is $I_g'' = I_{g1}'' + I_{g2}'' = I_{g1}'' + I_L$, where I_L is the prefault generator current.



(d) V_F set equal to prefault voltage at fault

Symmetrical faults: three-phase short circuits

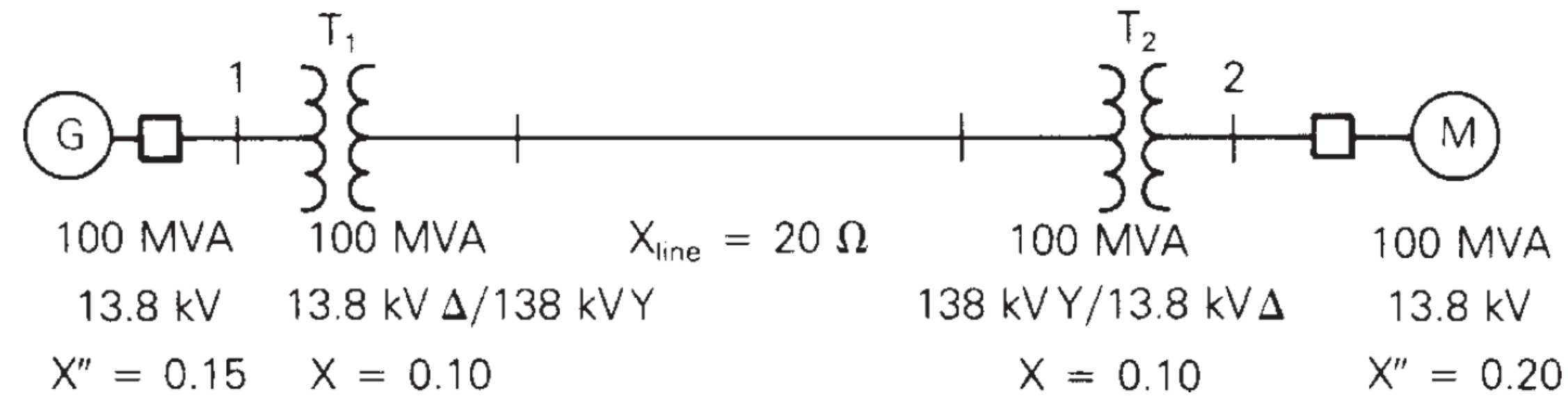
Example:



The synchronous generator is operating at rated MVA, 0.95 p.f. lagging and at 5% above rated voltage when a bolted three-phase short circuit occurs at bus 1. Calculate the per-unit values of

- (a) Subtransient fault current;
- (b) Subtransient generator and motor currents neglecting prefault current; and
- (c) Subtransient generator and motor currents including prefault current.

Symmetrical faults: three-phase short circuits



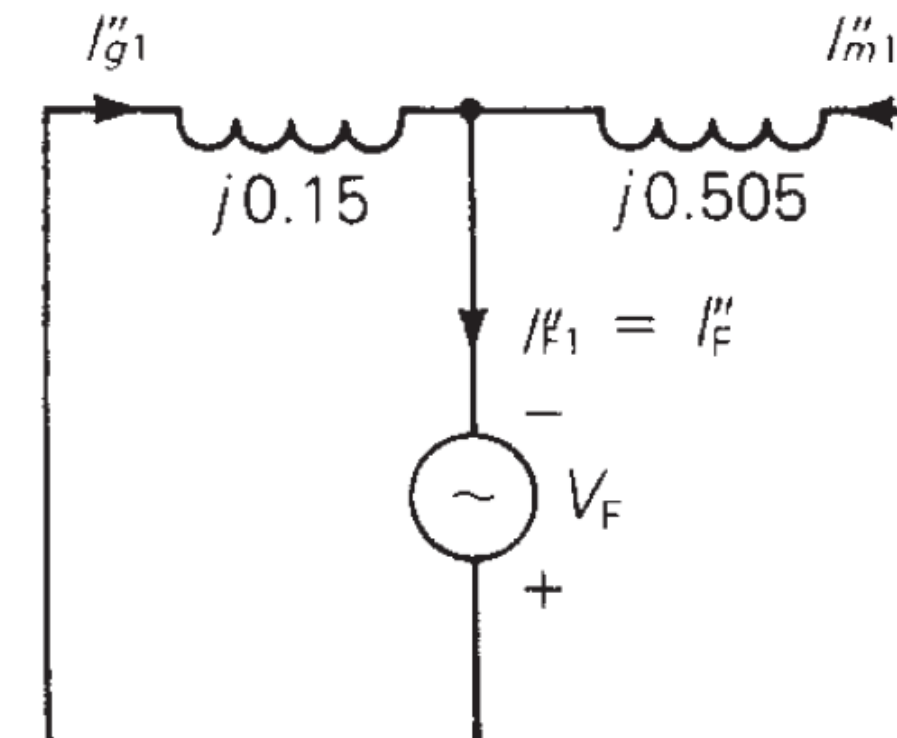
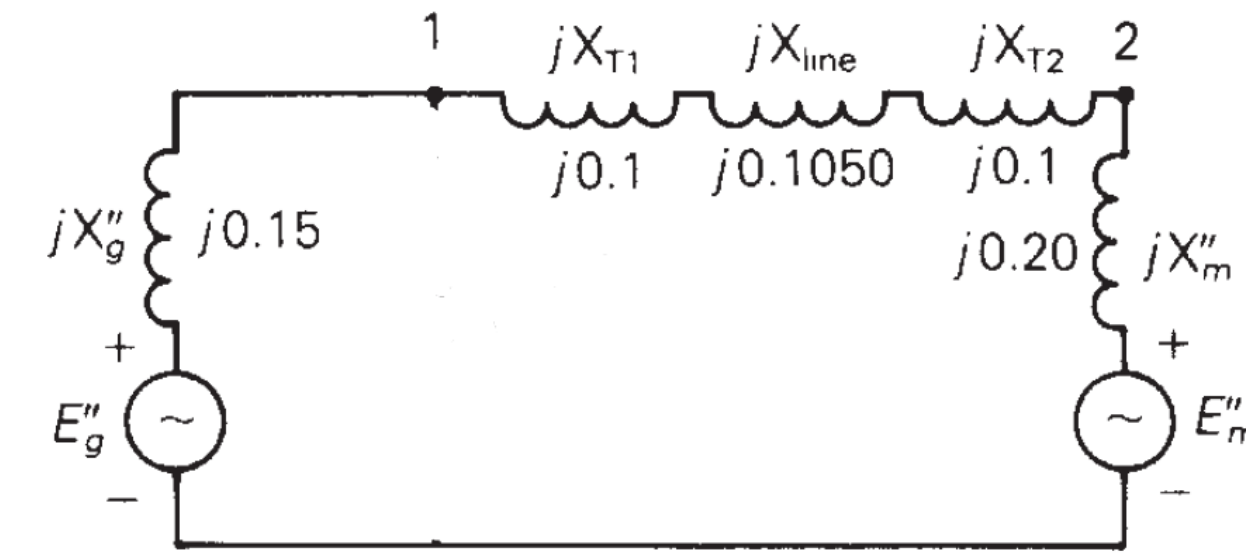
Solution:

a. Using a 100-MVA base, the base impedance in the zone of the transmission line is

$$Z_{\text{base, line}} = \frac{(138)^2}{100} = 190.44 \Omega$$

and

$$X_{\text{line}} = \frac{20}{190.44} = 0.1050 \text{ per unit}$$



$$Z_{\text{Th}} = jX_{\text{Th}} = j \frac{(0.15)(0.505)}{(0.15 + 0.505)} = j0.11565 \text{ per unit}$$

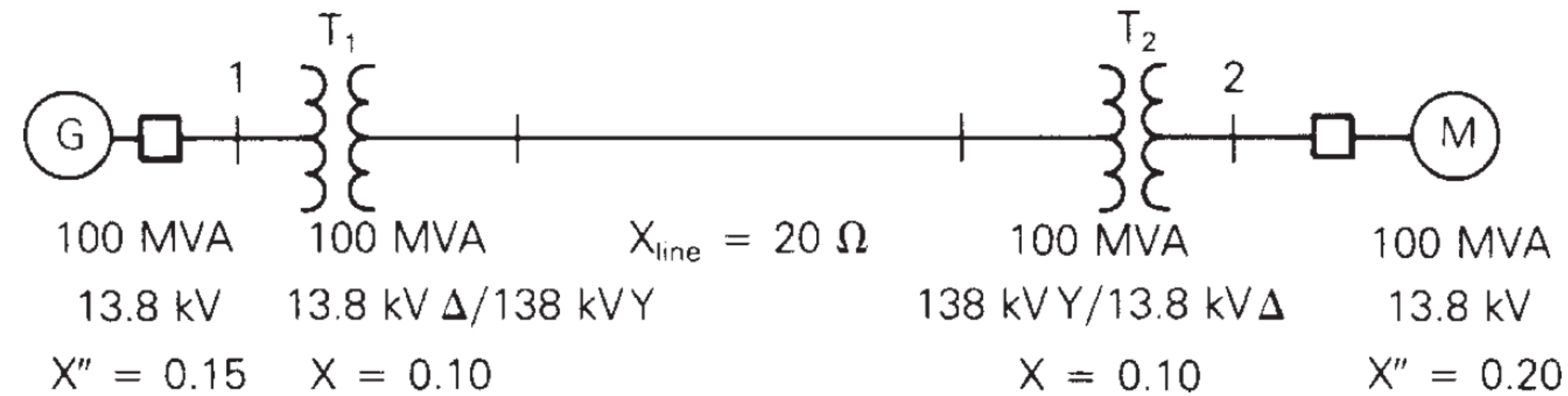
and the prefault voltage at the generator terminals is

$$V_F = 1.05 \angle 0^\circ \text{ per unit}$$

The subtransient fault current is then

$$I_F'' = \frac{V_F}{Z_{\text{Th}}} = \frac{1.05 \angle 0^\circ}{j0.11565} = -j9.079 \text{ per unit}$$

Symmetrical faults: three-phase short circuits



Solution:

b. Using current division in the first circuit

$$I''_{g1} = \left(\frac{0.505}{0.505 + 0.15} \right) I''_F = (0.7710)(-j9.079) = -j7.000 \text{ per unit}$$

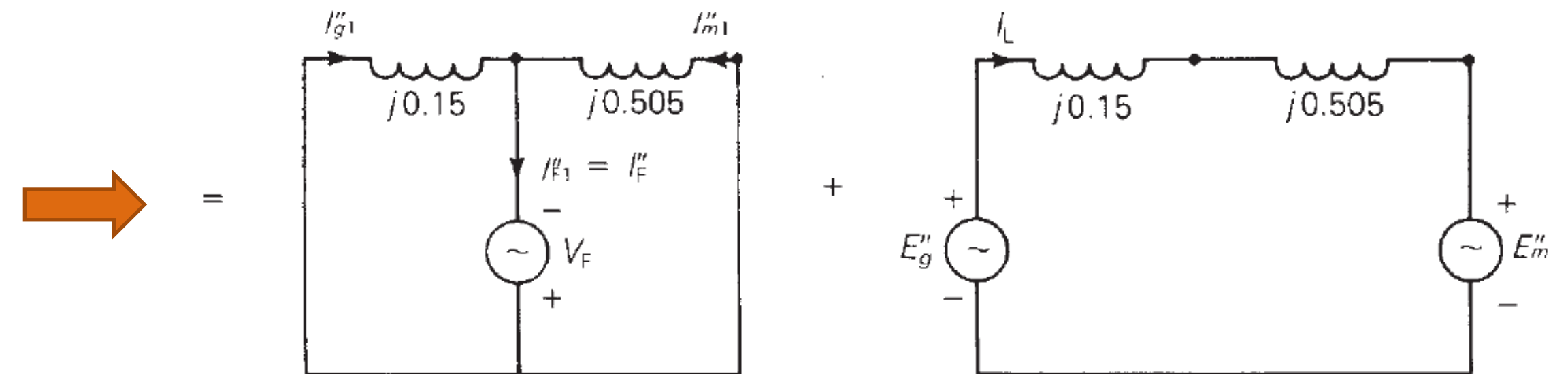
$$I''_{m1} = \left(\frac{0.15}{0.505 + 0.15} \right) I''_F = (0.2290)(-j9.079) = -j2.079 \text{ per unit}$$

c. The generator base current is

$$I_{\text{base,gen}} = \frac{100}{(\sqrt{3})(13.8)} = 4.1837 \text{ kA}$$

and the prefault generator current is

$$\begin{aligned} I_L &= \frac{100}{(\sqrt{3})(1.05 \times 13.8)} \angle -\cos^{-1} 0.95 = 3.9845 \angle -18.19^\circ \text{ kA} \\ &= \frac{3.9845 \angle -18.19^\circ}{4.1837} = 0.9524 \angle -18.19^\circ \\ &= 0.9048 - j0.2974 \text{ per unit} \end{aligned}$$



(d) V_F set equal to prefault voltage at fault

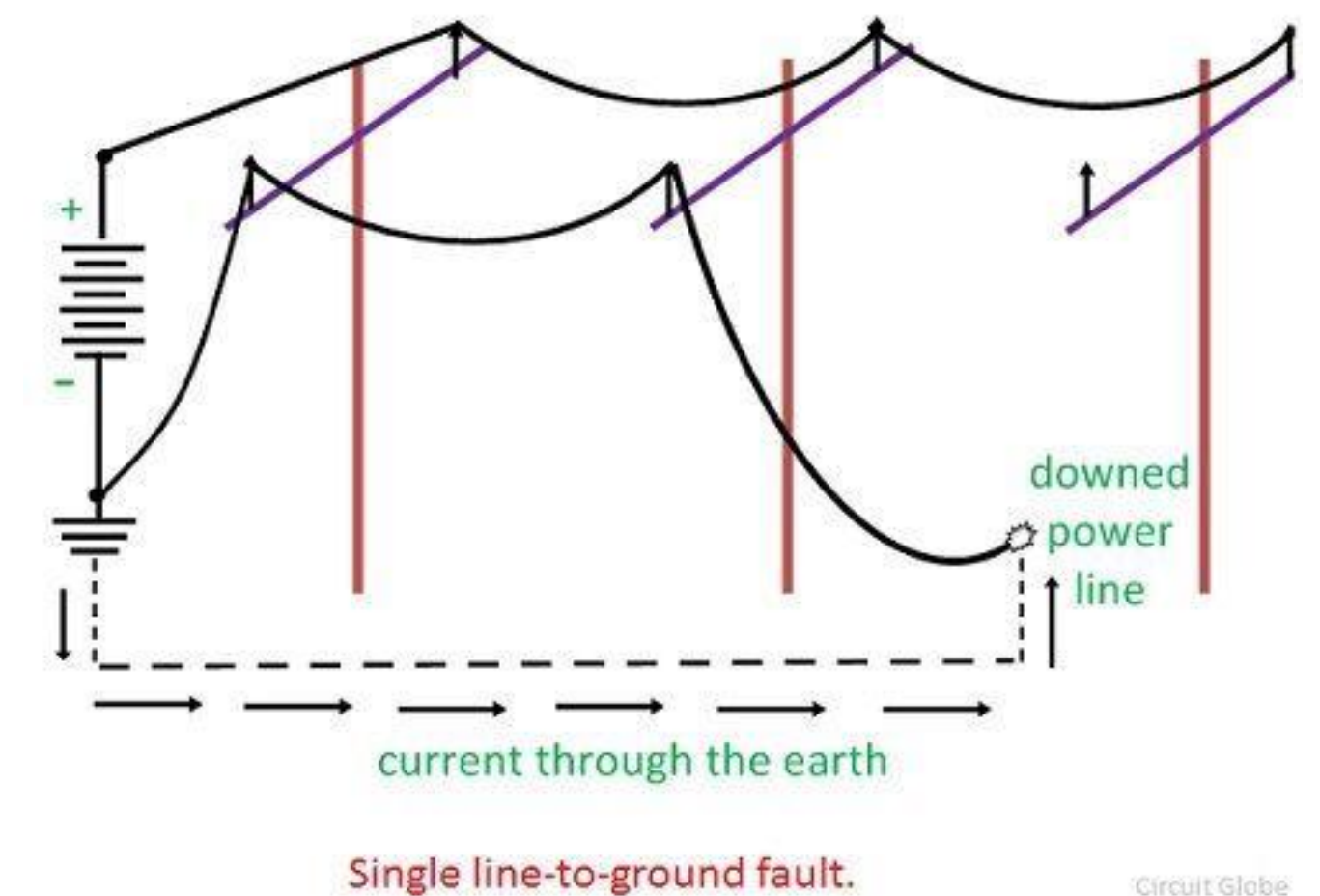
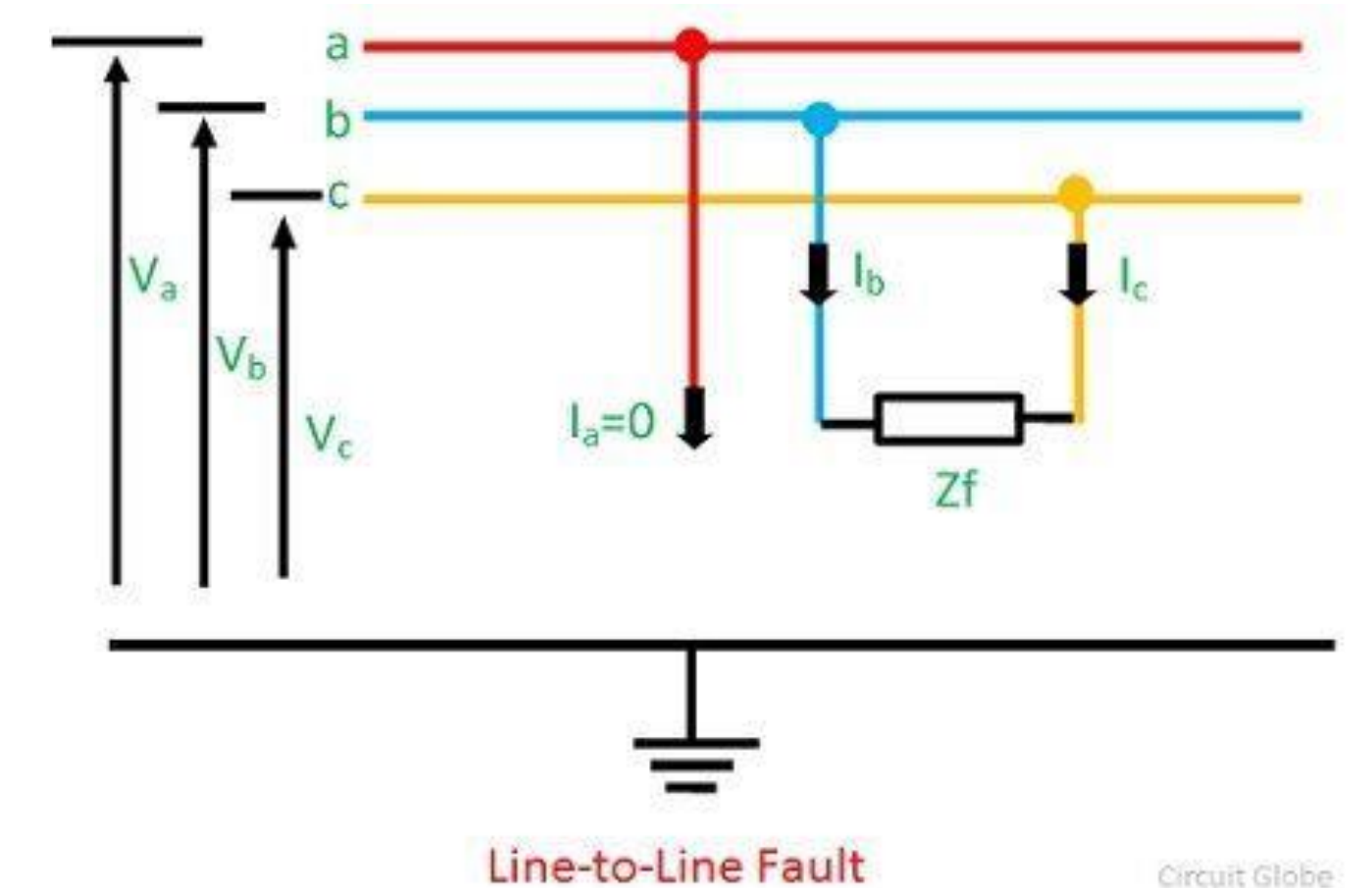
The subtransient generator and motor currents, including prefault current are then

$$\begin{aligned} I''_g &= I''_{g1} + I_L = -j7.000 + 0.9048 - j0.2974 \\ &= 0.9048 - j7.297 = 7.353 \angle -82.9^\circ \text{ per unit} \end{aligned}$$

$$\begin{aligned} I''_m &= I''_{m1} - I_L = -j2.079 - 0.9048 + j0.2974 \\ &= -0.9048 - j1.782 = 1.999 \angle 243.1^\circ \text{ per unit} \end{aligned}$$

Unsymmetrical faults in power system

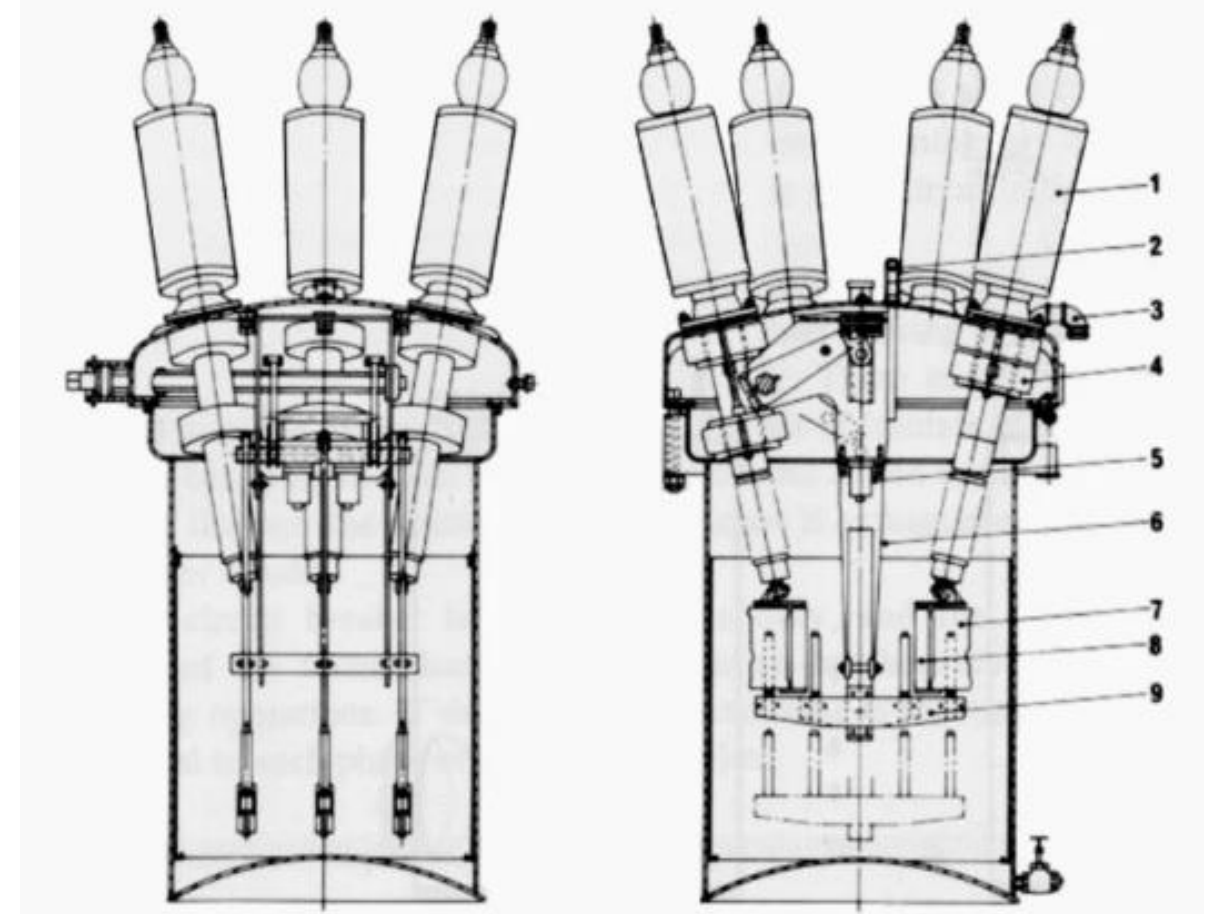
- ❑ Unsymmetrical faults involve only one or two phases. In unsymmetrical faults the three phase lines become unbalanced.
- ❑ Such types of faults occur between line-to-ground or between lines. An unsymmetrical series fault is between phases or between phase-to-ground, whereas unsymmetrical shunt fault is an unbalanced in the line impedances.
- ❑ Shunt fault in the three phase system can be classified as:
 - Single line-to-ground fault (LG).
 - Line-to-line fault (LL).
 - Double Line-to-ground fault (LLG).
 - Three-phase short circuit fault (LLL).
 - Three-phase-to-ground fault (LLLG).



<https://circuitglobe.com/symmetrical-and-unsymmetrical-faults.html>

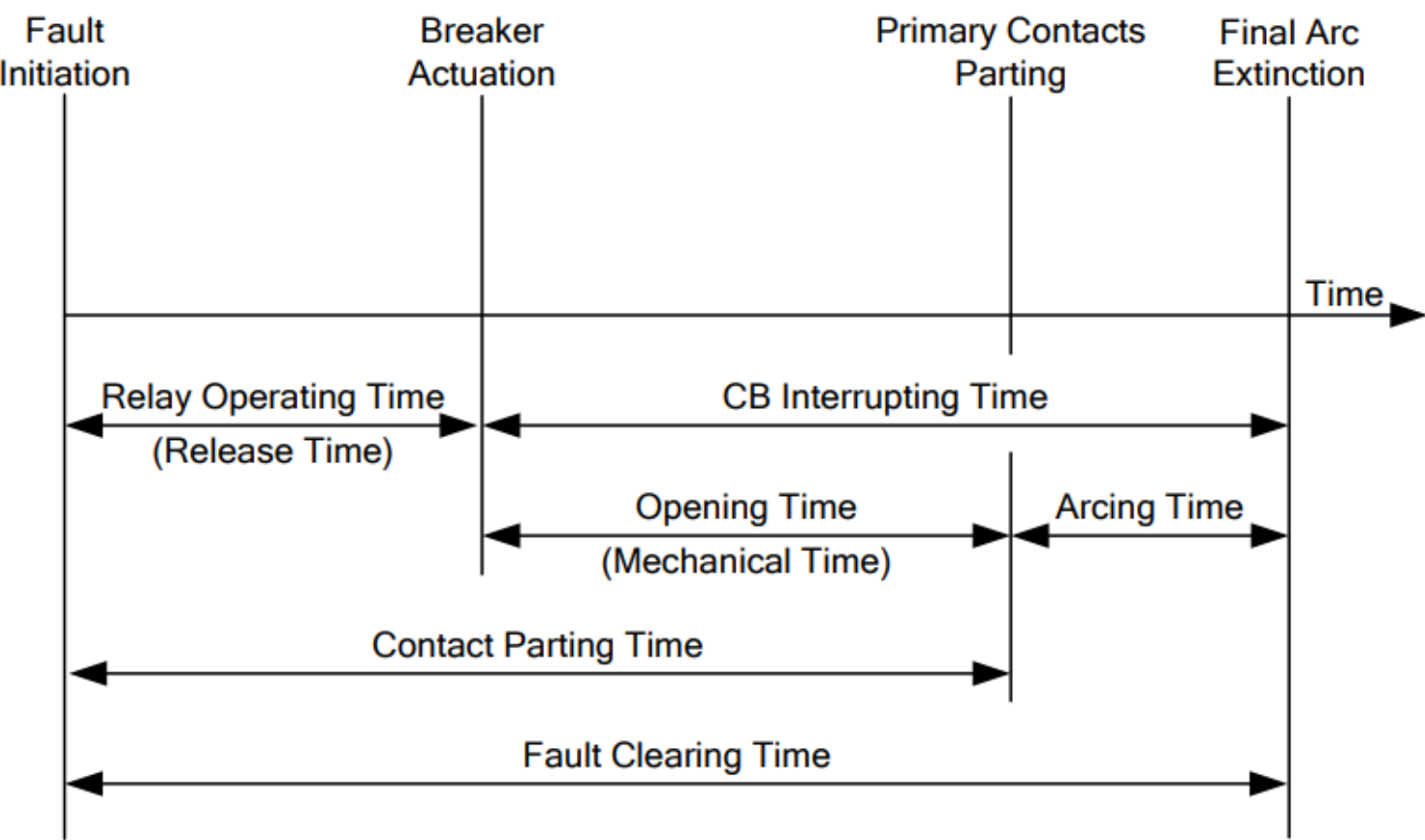
Circuit breaker

- A *circuit breaker* is a mechanical switch capable of interrupting fault currents and of reclosing.
- When circuit-breaker contacts separate while carrying current, an arc forms. The breaker is designed to extinguish the arc by elongating and cooling it.
- The fact that ac arc current naturally passes through zero twice during its 60 Hz cycle aids the arc extinction process.
- There are different types of circuit breakers depending on the medium—air, oil, SF₆ gas, or vacuum—in which the arc is elongated.
- Standard practice is to reclose only once, approximately 15 to 50 cycles (depending on operating voltage) after the breaker interrupts the fault.

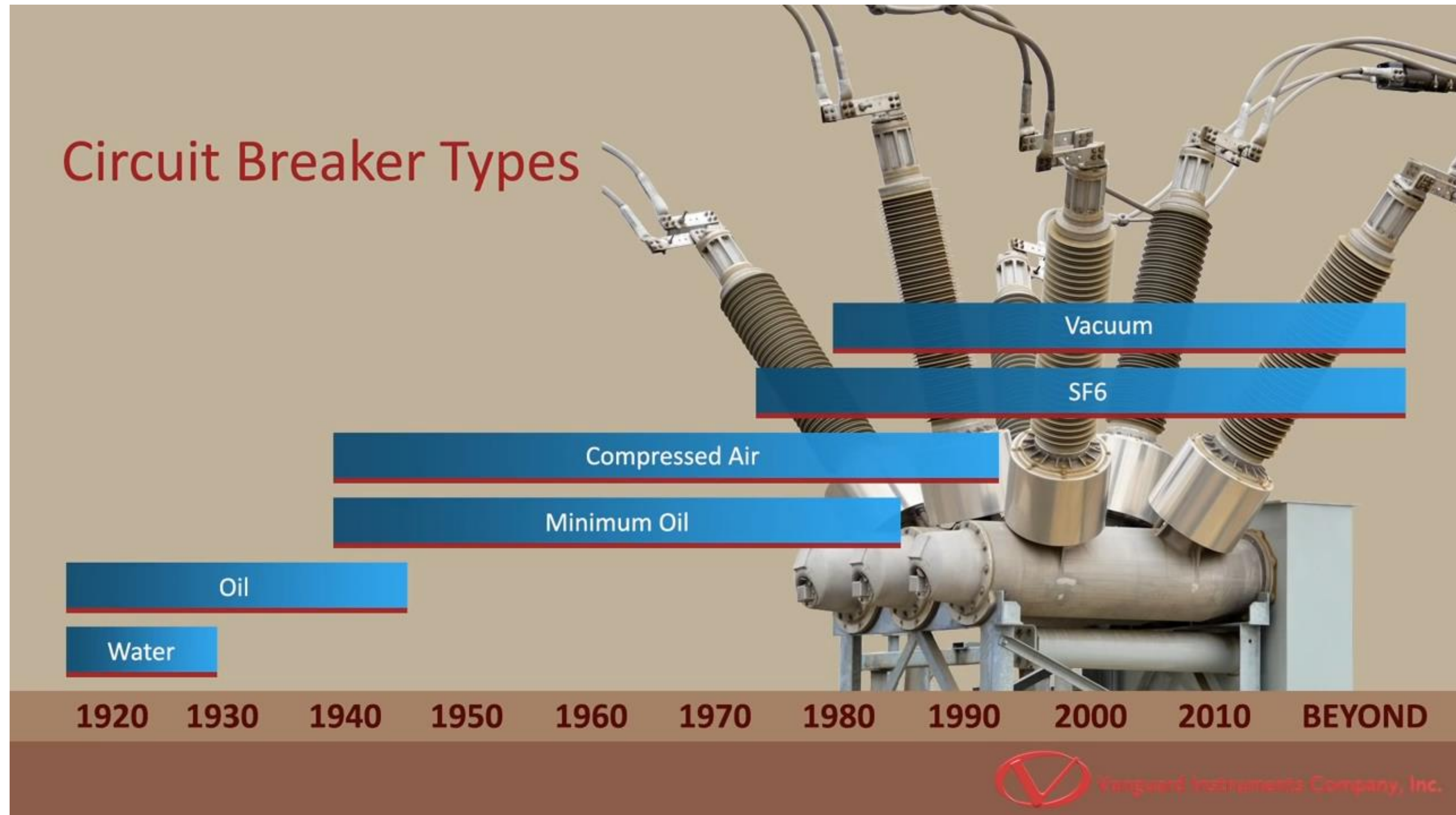


Circuit breaker

Rated Values								Related Required Capabilities					
								Current Values					
								Max Symmetrical Interrupting Capability	3-Second Short-Time Current Carrying Capability	Closing and Latching Capability 1.6K Times Rated Short-Circuit Current			
Identification		Voltage		Insulation Level		Current		Rated Values		Rated Max Voltage Divided by K (kV, rms)	Col 12	Col 13	Col 14
Nominal Voltage Class (kV, rms)	Nominal 3-Phase MVA Class	Rated Max Voltage (kV, rms)	Rated Voltage Range Factor (K)	Rated Withstand Test Voltage	Low Frequency (kV, rms)	Impulse (kV, Crest)	Rated Continuous Current at 60 Hz (Amperes, rms)	Rated Short-Circuit Current at Rated Max kV (kA, rms)	Rated Interrupting Time (Cycles)				
Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10	Col 11	Col 12	Col 13	Col 14
14.4	250	15.5	2.67			600	8.9	5	2	5.8	24	24	38
14.4	500	15.5	1.29			1200	18	5	2	12	23	23	37
23	500	25.8	2.15			1200	11	5	2	12	24	24	38
34.5	1500	38	1.65			1200	22	5	2	23	36	36	58
46	1500	48.3	1.21			1200	17	5	2	40	21	21	33
69	2500	72.5	1.21			1200	19	5	2	60	23	23	37
115		121	1.0			1200	20	3	1	121	20	20	32
115		121	1.0			1600	40	3	1	121	40	40	64
115		121	1.0			2000	40	3	1	121	40	40	64
115		121	1.0			2000	63	3	1	121	63	63	101
115		121	1.0			3000	40	3	1	121	40	40	64
115		121	1.0			3000	63	3	1	121	63	63	101
138		145	1.0			1200	20	3	1	145	20	20	32
138	Not	145	1.0			1600	40	3	1	145	40	40	64
138		145	1.0			2000	40	3	1	145	40	40	64
138		145	1.0			2000	63	3	1	145	63	63	101
138		145	1.0			2000	80	3	1	145	80	80	128
138	Applicable	145	1.0			3000	40	3	1	145	40	40	64
138		145	1.0			3000	63	3	1	145	63	63	101
138		145	1.0			3000	80	3	1	145	80	80	128
161		169	1.0			1200	16	3	1	169	16	16	26
161		169	1.0			1600	31.5	3	1	169	31.5	31.5	50
161		169	1.0			2000	40	3	1	169	40	40	64
161		169	1.0			2000	50	3	1	169	50	50	80
230		242	1.0			1600	31.5	3	1	242	31.5	31.5	50
230		242	1.0			2000	31.5	3	1	242	31.5	31.5	50
230		242	1.0			3000	31.5	3	1	242	31.5	31.5	50
230		242	1.0			2000	40	3	1	242	40	40	64
230		242	1.0			3000	40	3	1	242	40	40	64
230		242	1.0			3000	63	3	1	242	63	63	101
345		362	1.0			2000	40	3	1	362	40	40	64
345		362	1.0			3000	40	3	1	362	40	40	64
500		550	1.0			2000	40	2	1	550	40	40	64
500		550	1.0			3000	40	2	1	550	40	40	64
700		765	1.0			2000	40	2	1	765	40	40	64
700		765	1.0			3000	40	2	1	765	40	40	64



Circuit breaker



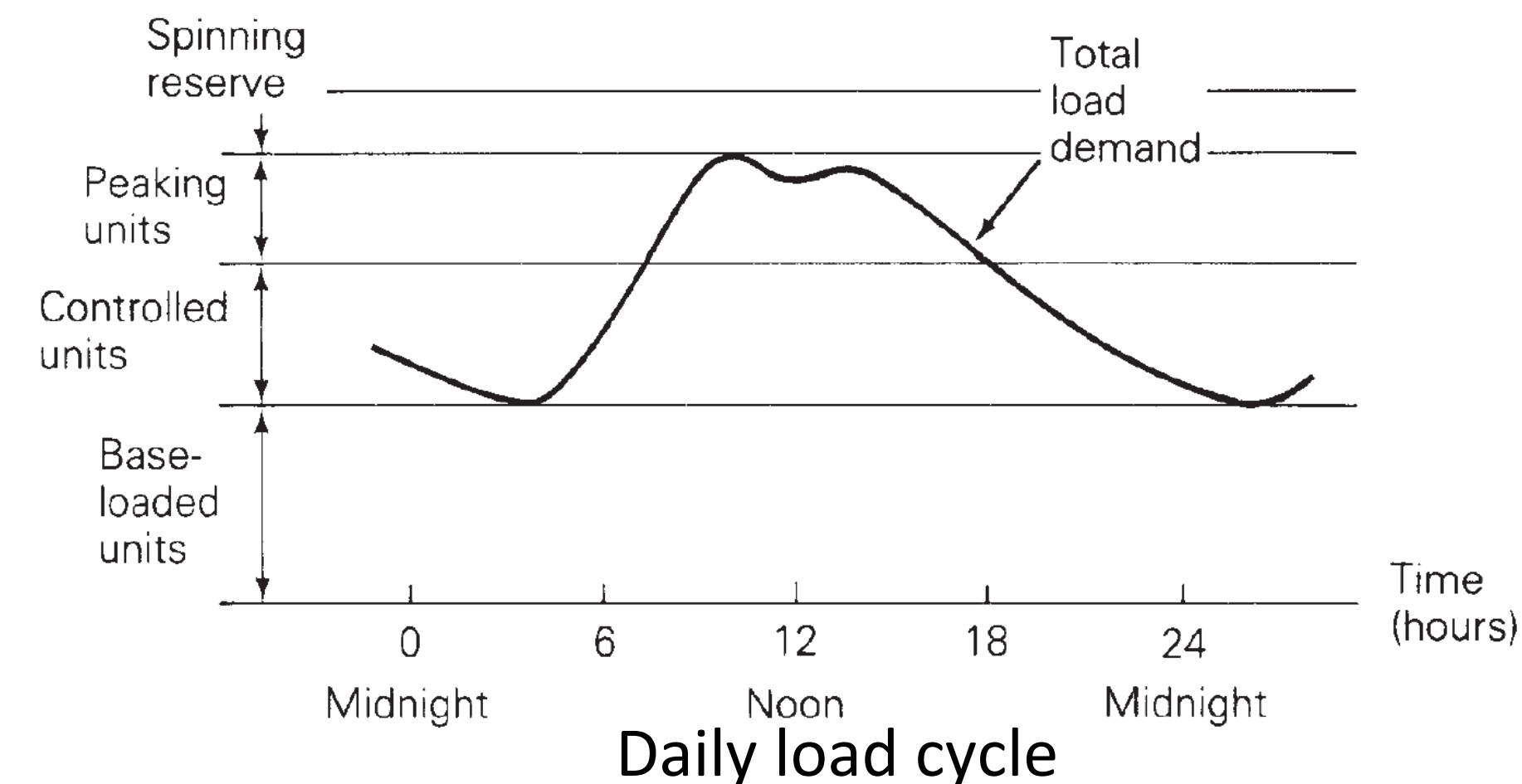
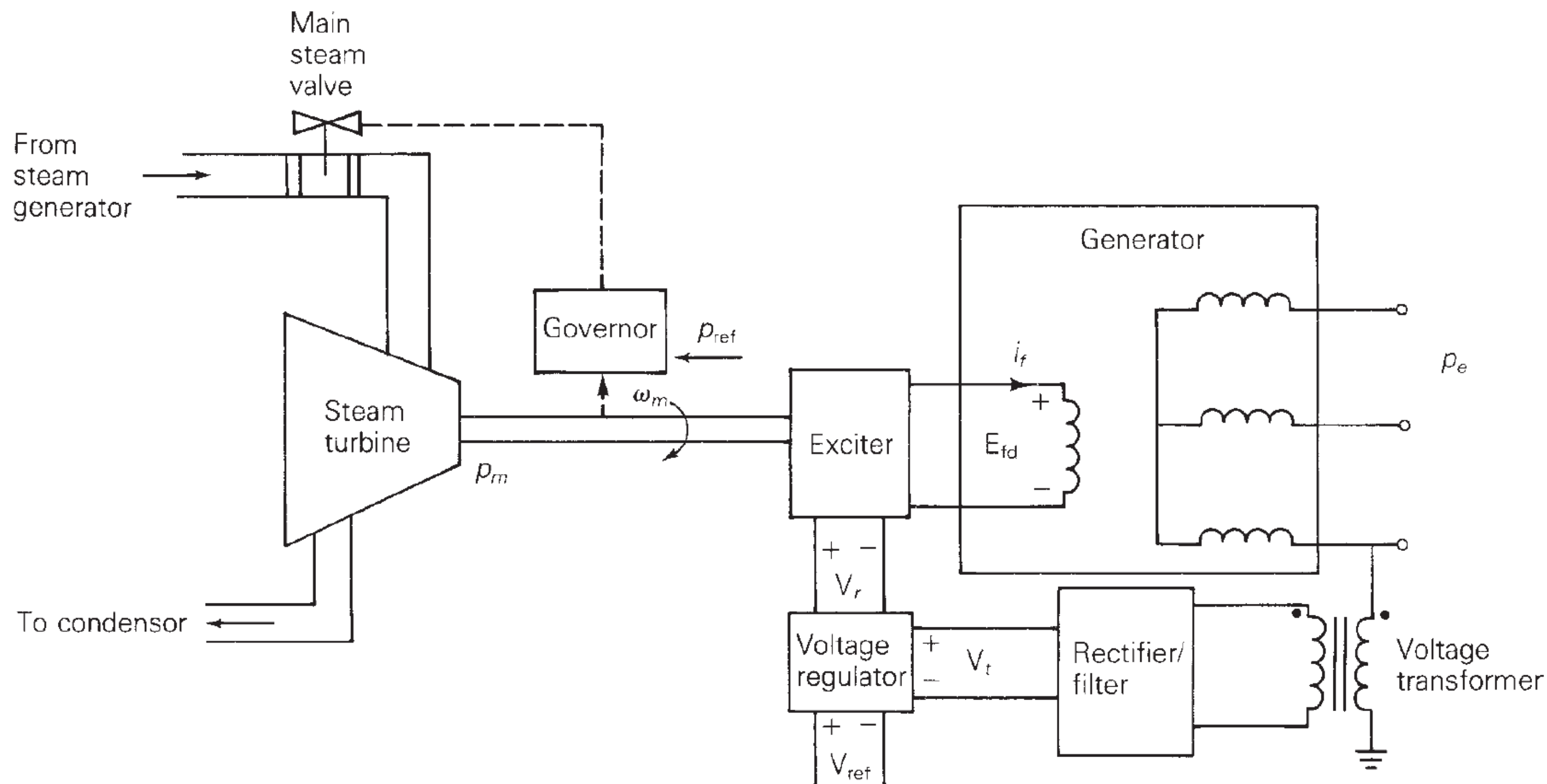
Power system controls

- Automatic control systems are used extensively in power systems. Local controls are employed at turbine-generator units and at selected voltage-controlled buses. Central controls are employed at area control centers.
- The central control center monitors information including area frequency, generating unit outputs, and tie-line power flows to interconnected areas.
- This information is used by automatic load-frequency control (LFC) in order to maintain area frequency at its scheduled value (60 Hz) and net tie-line power flow out of the area at its scheduled value.
- Raise and lower reference power signals are dispatched to the turbine-governors of controlled units.



Grid Control Room - photo from State Grid

Power system controls

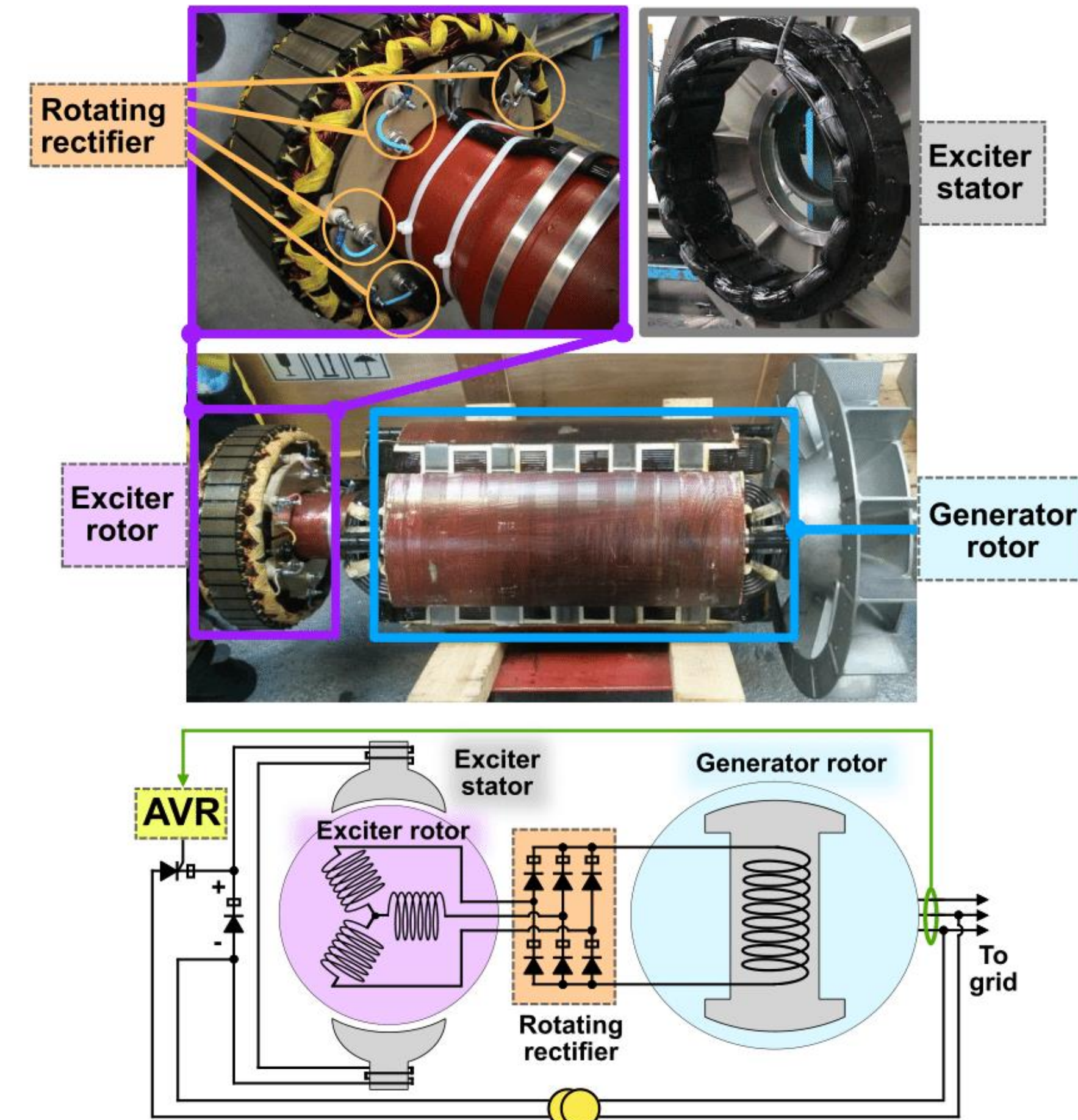


Voltage regulator and turbine-governor controls for a steam-turbine generator

- Two basic controls of a steam turbine-generator: the voltage regulator and turbine-governor.
- The voltage regulator adjusts the power output of the generator exciter in order to control the magnitude of generator terminal voltage V_t .
- The turbine-governor adjusts the steam valve position to control the mechanical power output p_m of the turbine.

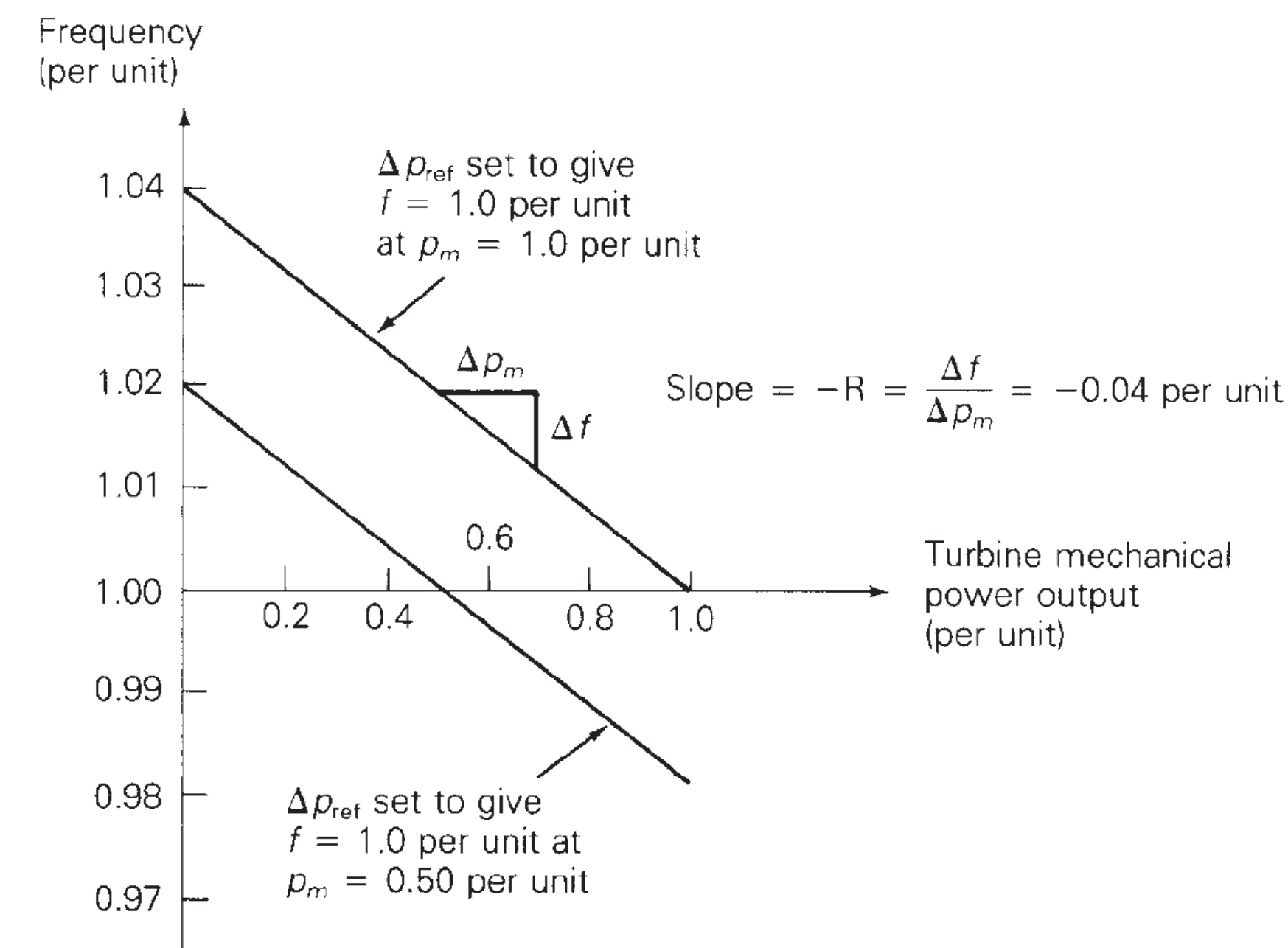
Power system controls - generator-voltage control

- The exciter delivers dc power to the field winding on the rotor of a synchronous generator.
- For older generators, the exciter consists of a dc generator driven by the rotor. The dc power is transferred to the rotor via slip rings and brushes.
- For newer generators, static or brushless exciters are often employed.
- While generators (for some wind turbines) do not have direct voltage control, the external resistance control system is usually modeled as a type of exciter.



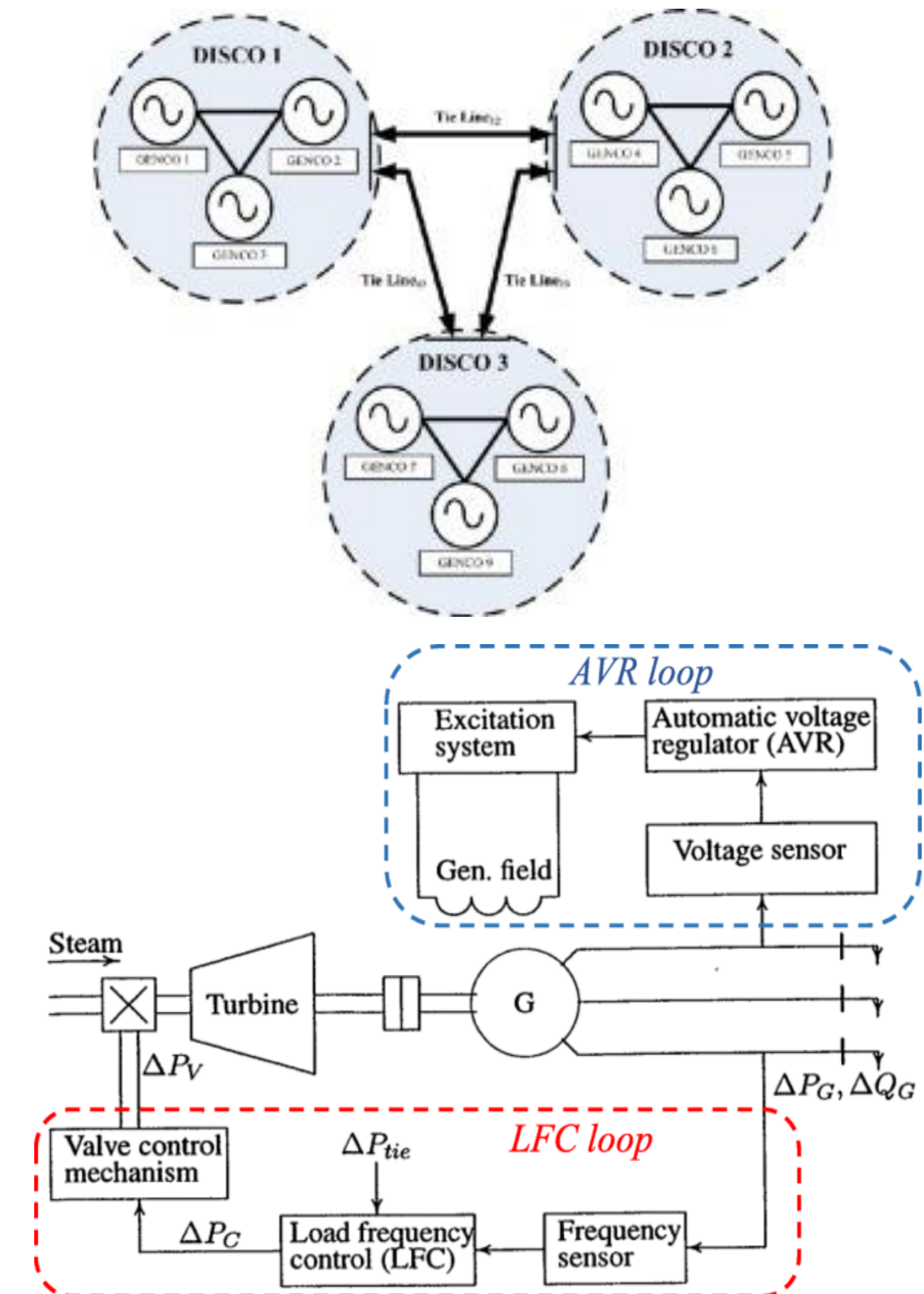
Power system controls - turbine-governor control

- Turbine-generator units operating in a power system contain stored kinetic energy due to their rotating masses.
- If the system load suddenly increases, stored kinetic energy is released to initially supply the load increase.
- Also, the electrical torque T_e of each turbine-generating unit increases to supply the load increase, while the mechanical torque T_m of the turbine initially remains constant.
- That is, each turbine-generator decelerates and the rotor speed drops as kinetic energy is released to supply the load increase.
- The electrical frequency of each generator, which is proportional to rotor speed for synchronous machines, also drops.

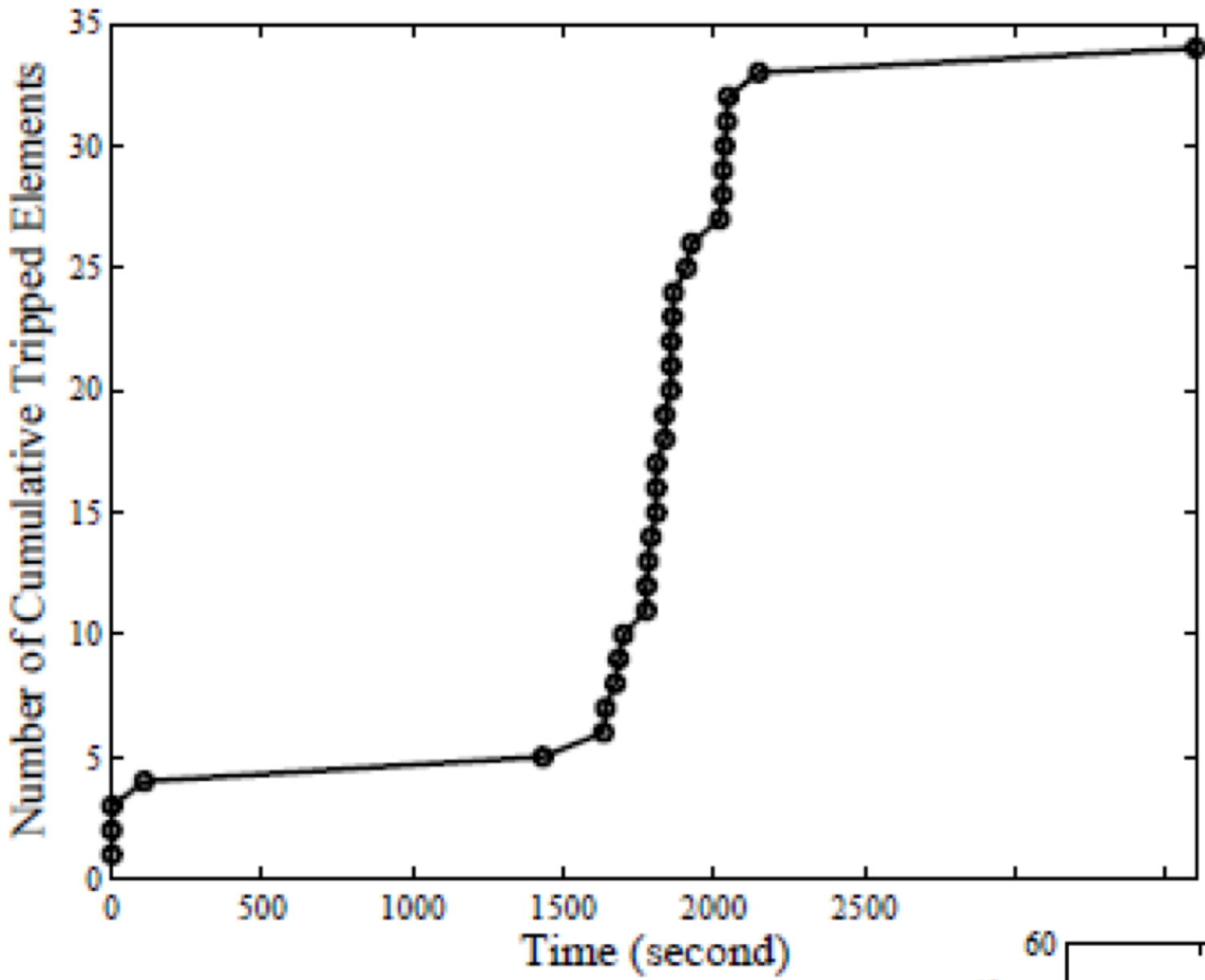
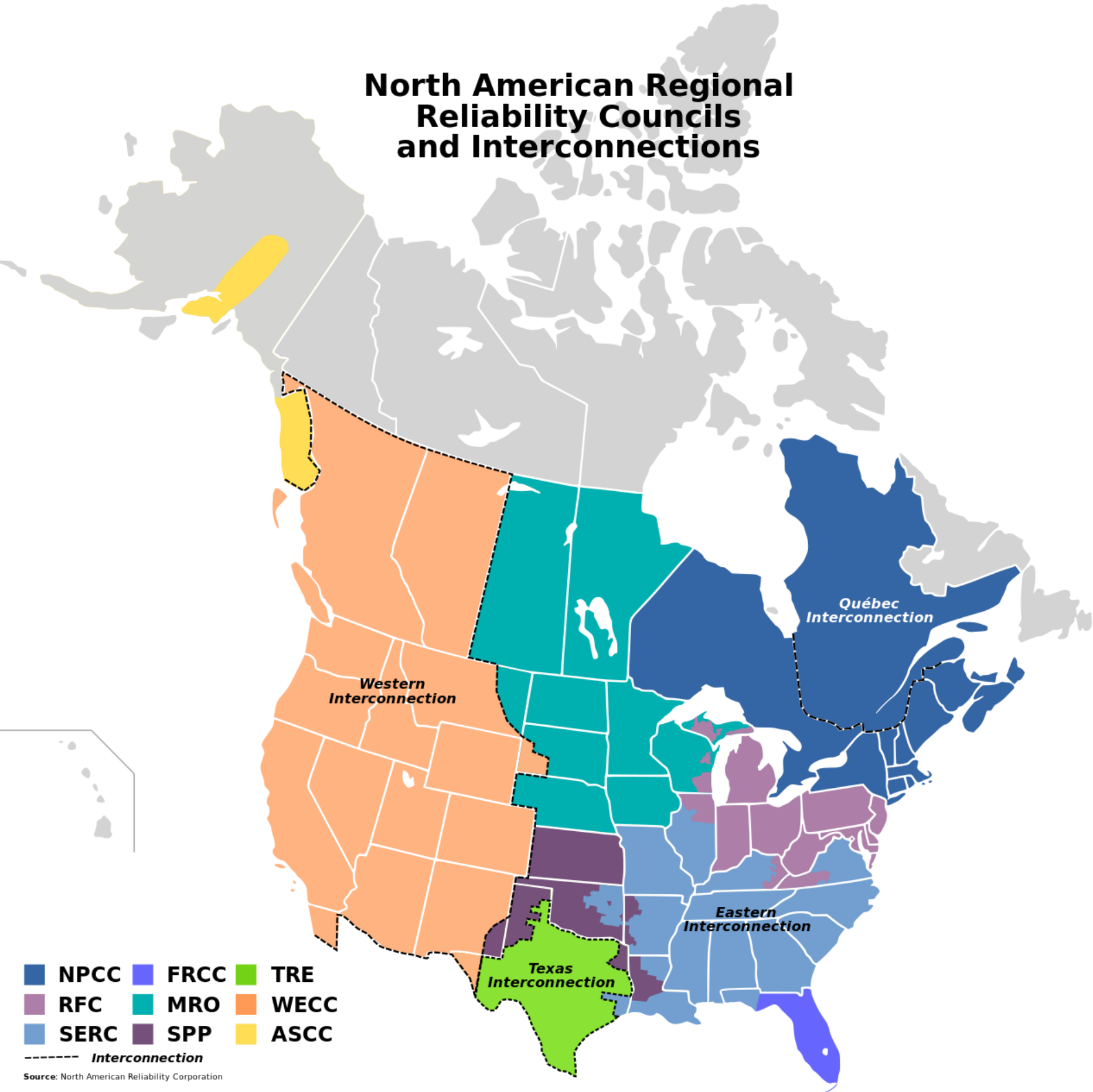


Power system controls- load-frequency control (LFC)

- In a power system consisting of interconnected areas, each area agrees to export or import a scheduled amount of power through transmission-line interconnections, or tie-lines, to its neighboring areas.
- The following summarizes the two basic load frequency control objectives for an interconnected power system:
 1. Following a load change, each area should assist in returning the steady state frequency error Δf to zero.
 2. Each area should maintain the net tie-line power flow out of the area at its scheduled value, in order for the area to absorb its own load changes.
- Note that LFC maintains control during normal changes in load and frequency—that is, changes that are not too large. During emergencies, when large imbalances between generation and load occur, LFC is bypassed and other, emergency controls are applied.

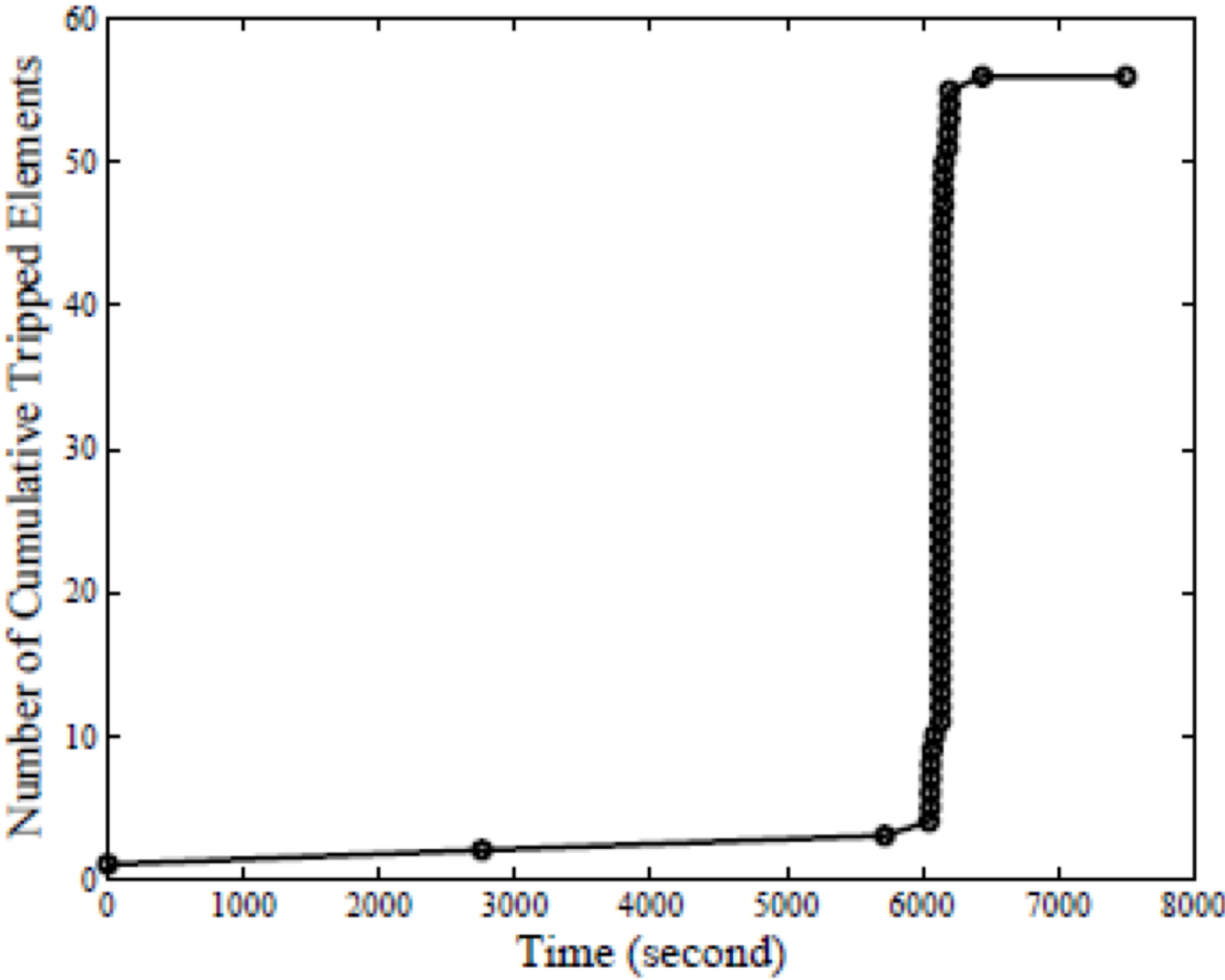


WSCC System Blackout in 1996



July 1996

August 1996



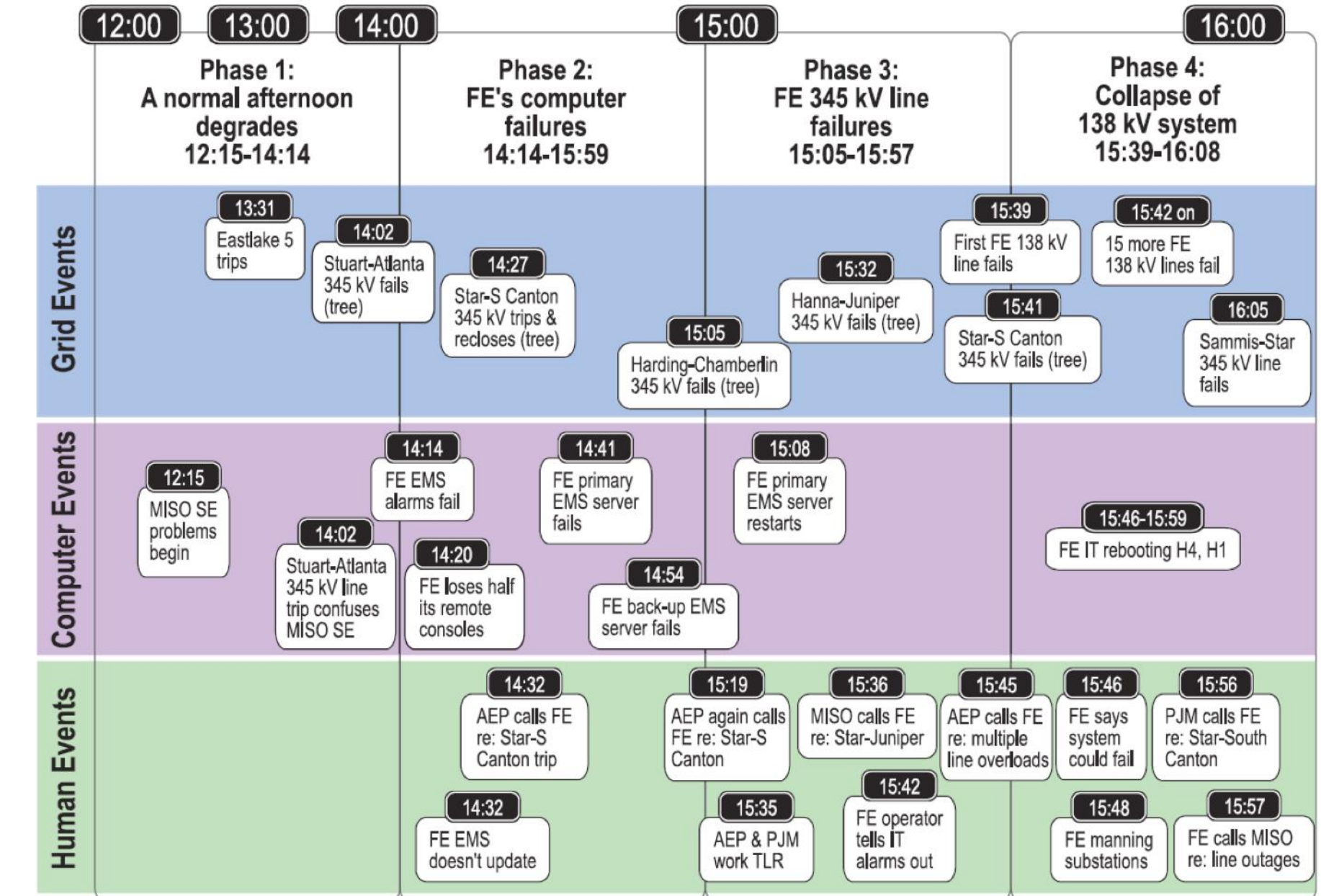
WSCC: Western System Coordinating Council, now called WESC, which is the largest electricity coordinating system across US, Canada and Mexico.

US Northeast blackout in 2003

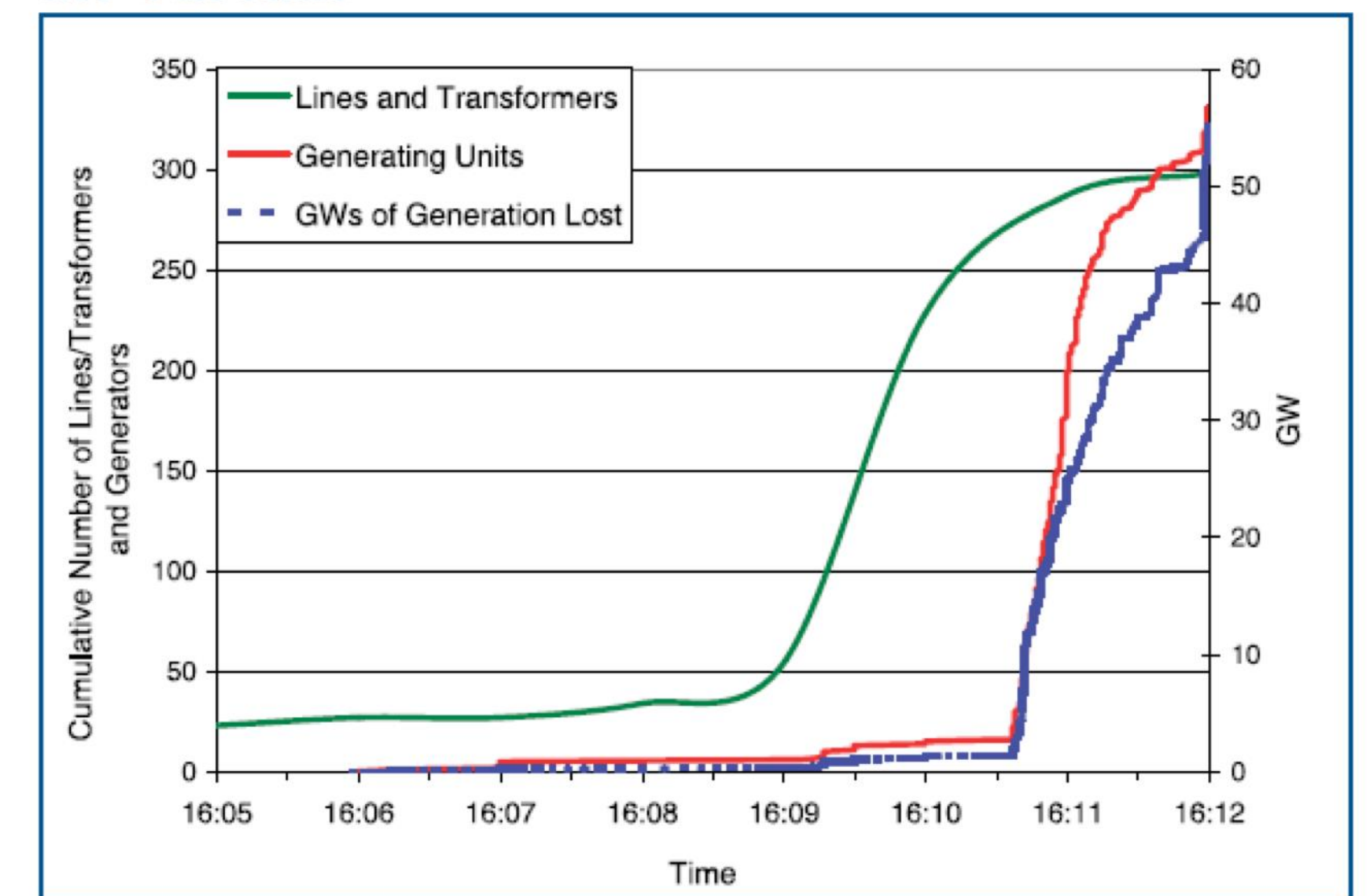
- The blackout's primary cause was a software bug in the alarm system at a control room of the FirstEnergy Corporation, located in Ohio.
- A lack of alarm left operators unaware of the need to re-distribute power after overloaded transmission lines hit unpruned foliage, which triggered a race condition in the control software.
- What would have been a manageable local blackout cascaded into massive widespread distress on the electric grid.



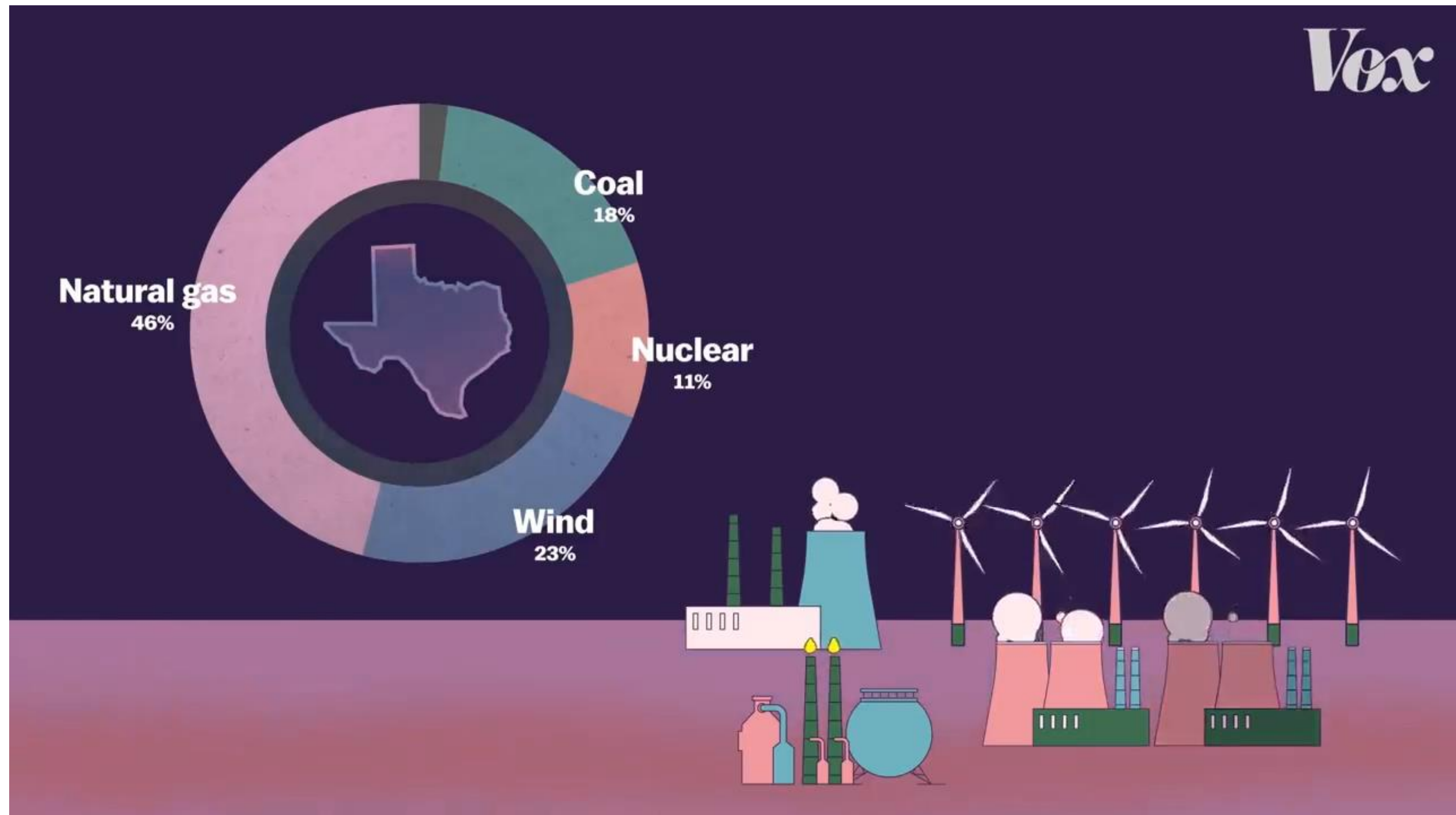
Figure 5.1. Timeline: Start of the Blackout in Ohio



the Cascade

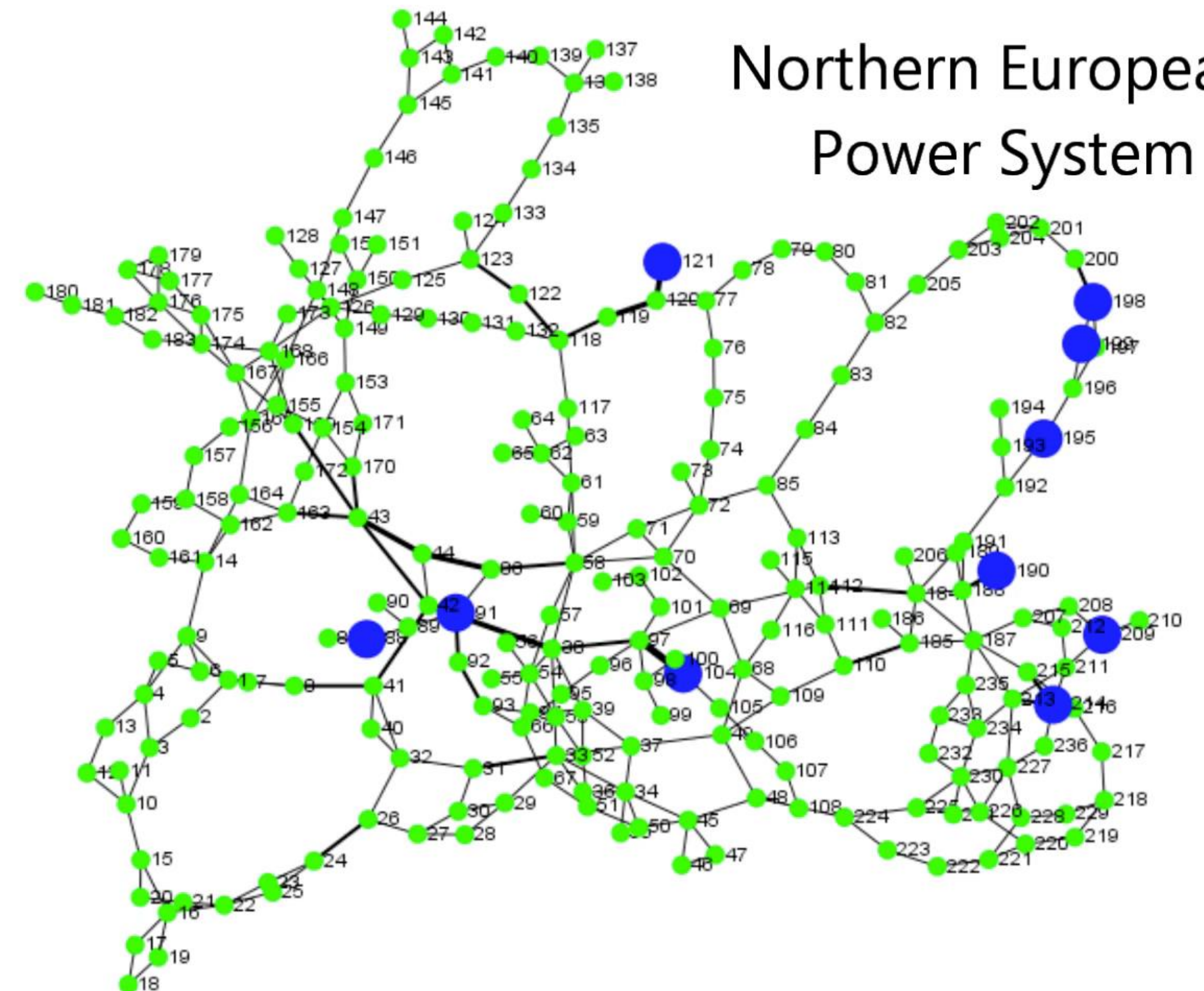


US blackout in 2021- Texas's power disaster



Cascading failure

- One component fails
- Another fails subsequently
- More fail like a domino effect
- Eventually components covering a large area fail
- Large scale blackout
- Many people has no asccess to electricity supply



Failure propagation profiles

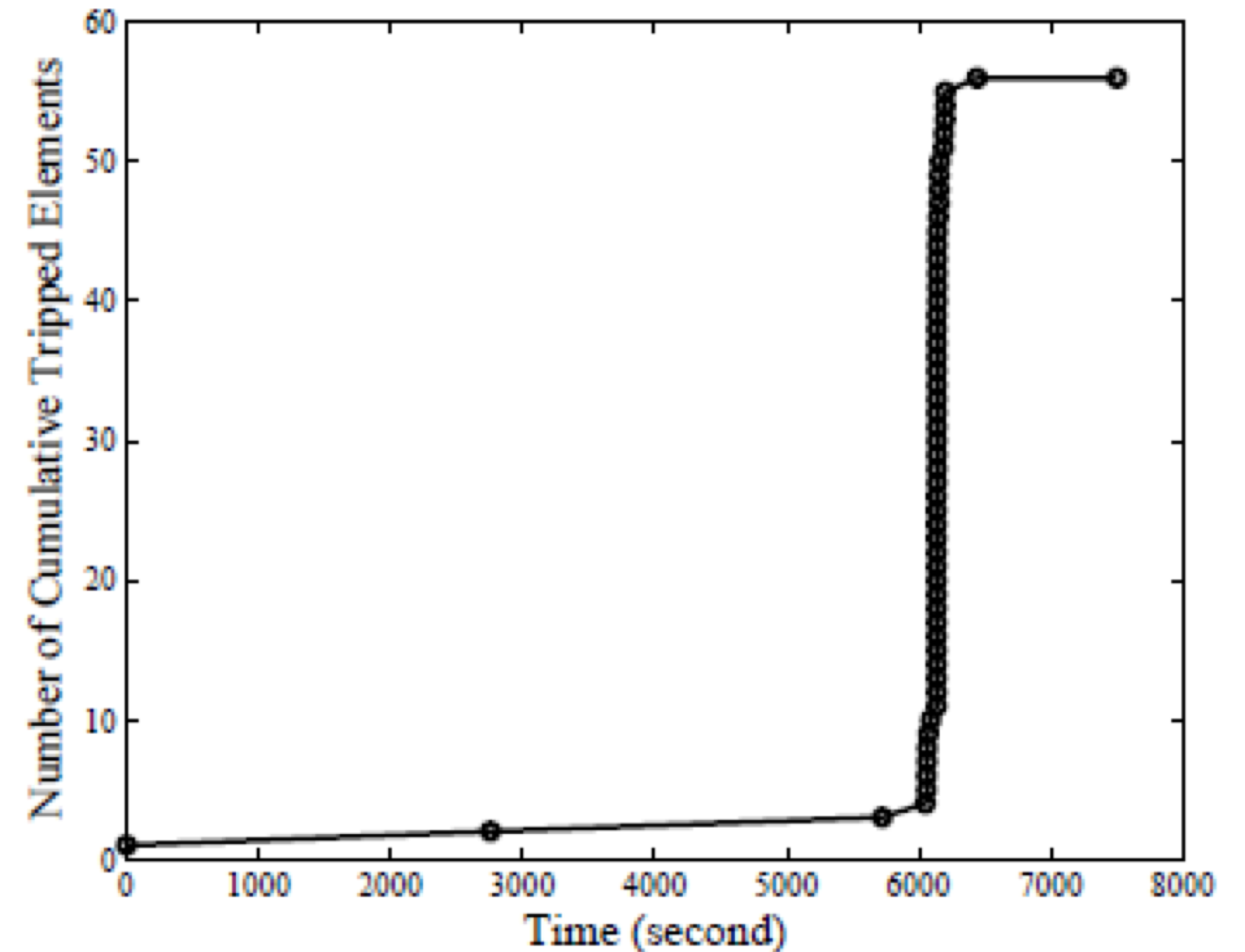
1

Track the cascading failure sequence in electric networks

- Power flow analysis
- Assess overloading iteratively

2

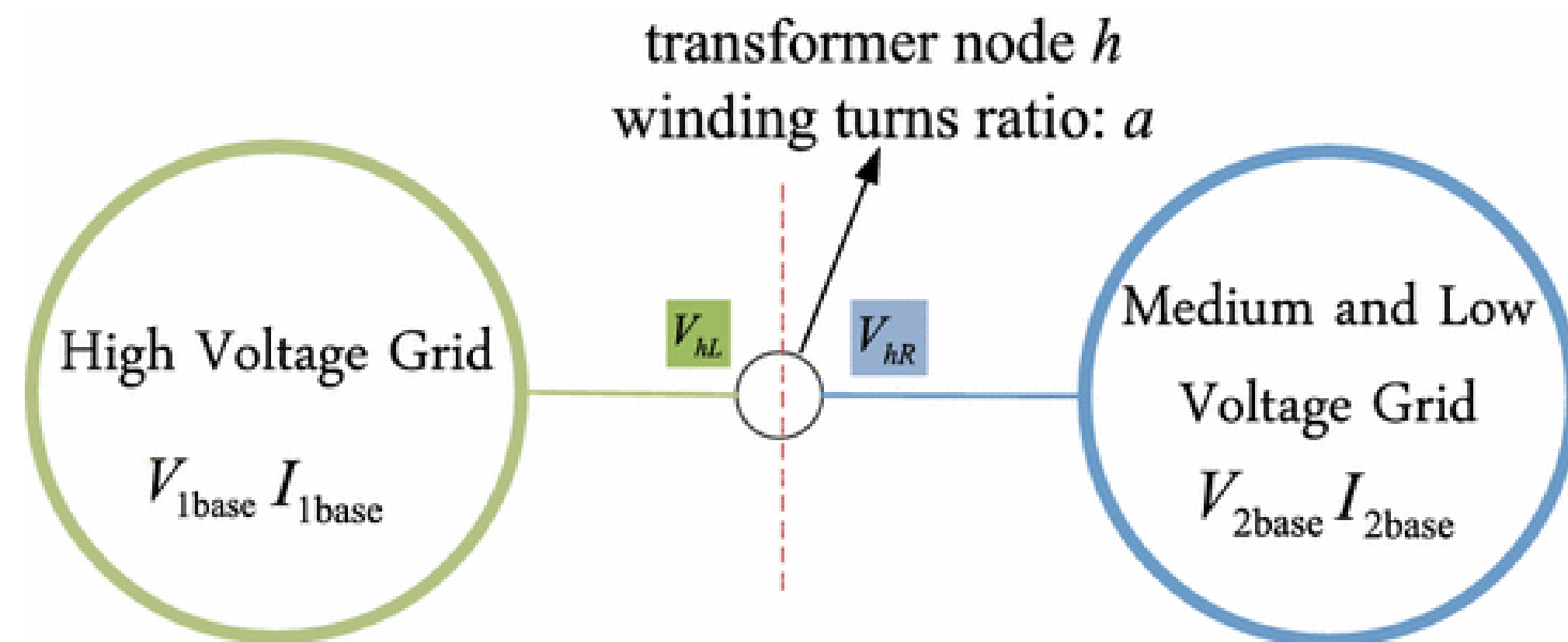
Times between successive failures are not necessarily identical. Statistical distribution becomes useful.



Simulation method

POWER FLOW ANALYSIS

- Physical variables
 - current / voltage / power
- solutions of PFA



$$\begin{bmatrix} Y_{11} & -Y_{12} & \cdots & -Y_{1n} \\ -Y_{21} & Y_{22} & \cdots & -Y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ -Y_{n1} & -Y_{n2} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix}$$

$$S = VI^*$$

P equations
Q equations

Voltage and power information
obtained for all nodes

Cascading failure mechanism

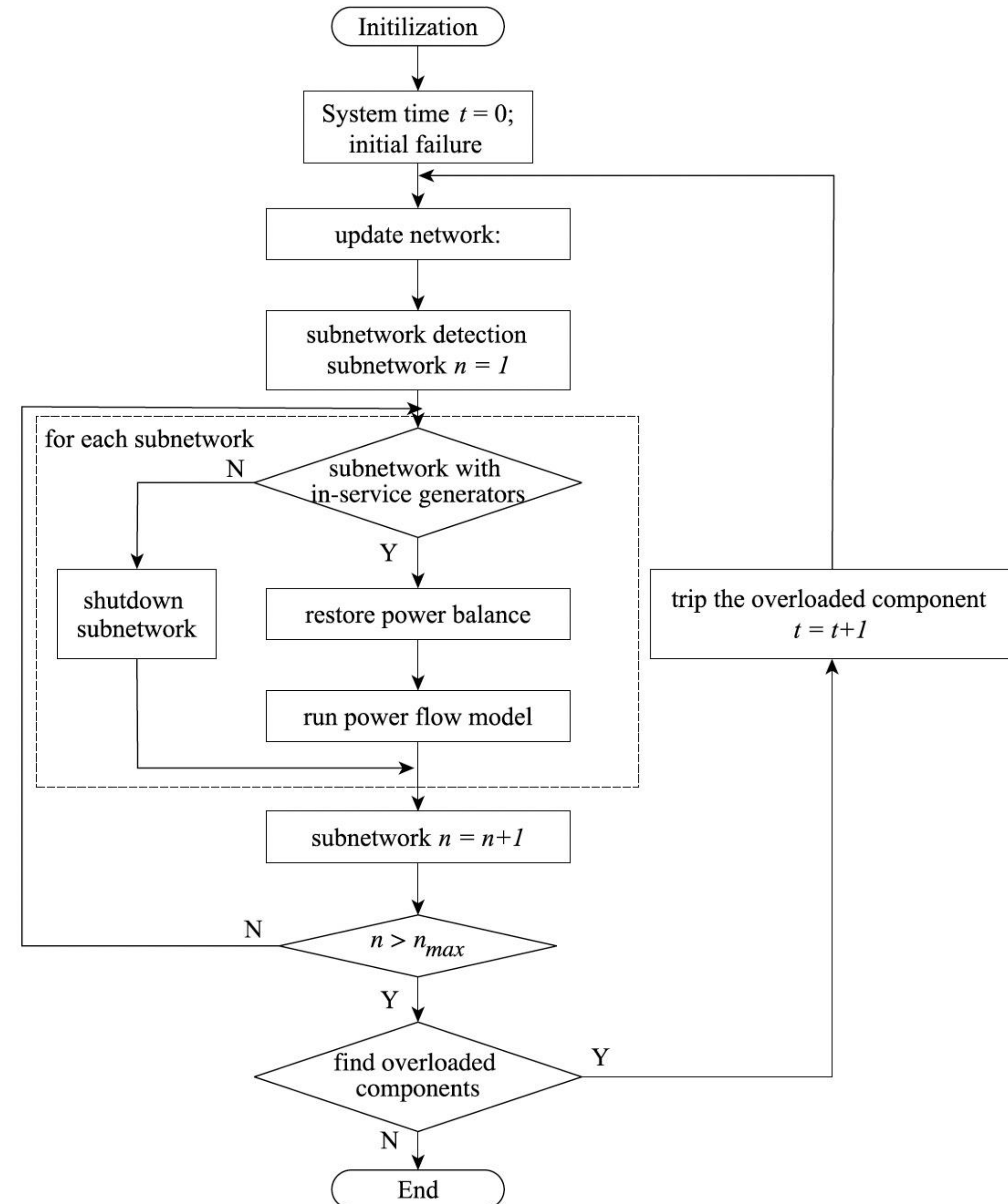
Process to identify area(s) (sub-networks) that have no power sources (blackout), as a dynamic sequence of failures of nodes and links.

Links and nodes fail if:

$$C_{ij} = (1 + \alpha)I_{ij}(0) + a$$

$$C_{oi} = (1 + \beta)v_i(0)I_{oi}(0) + b$$

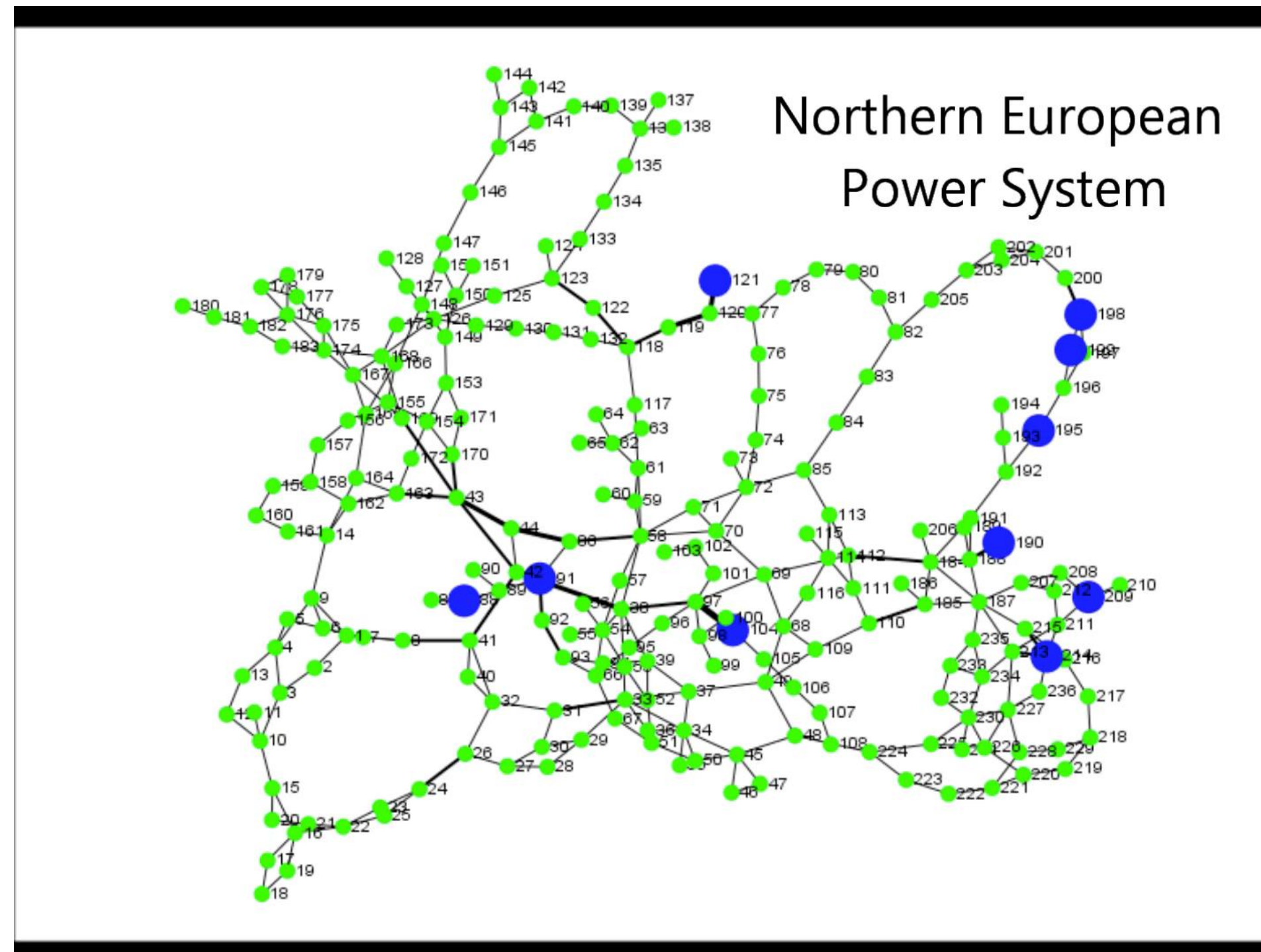
P. Crucitti, V. Latora, M. Marchiori, A topological analysis of the Italian electric power grid, Physica A, 2004

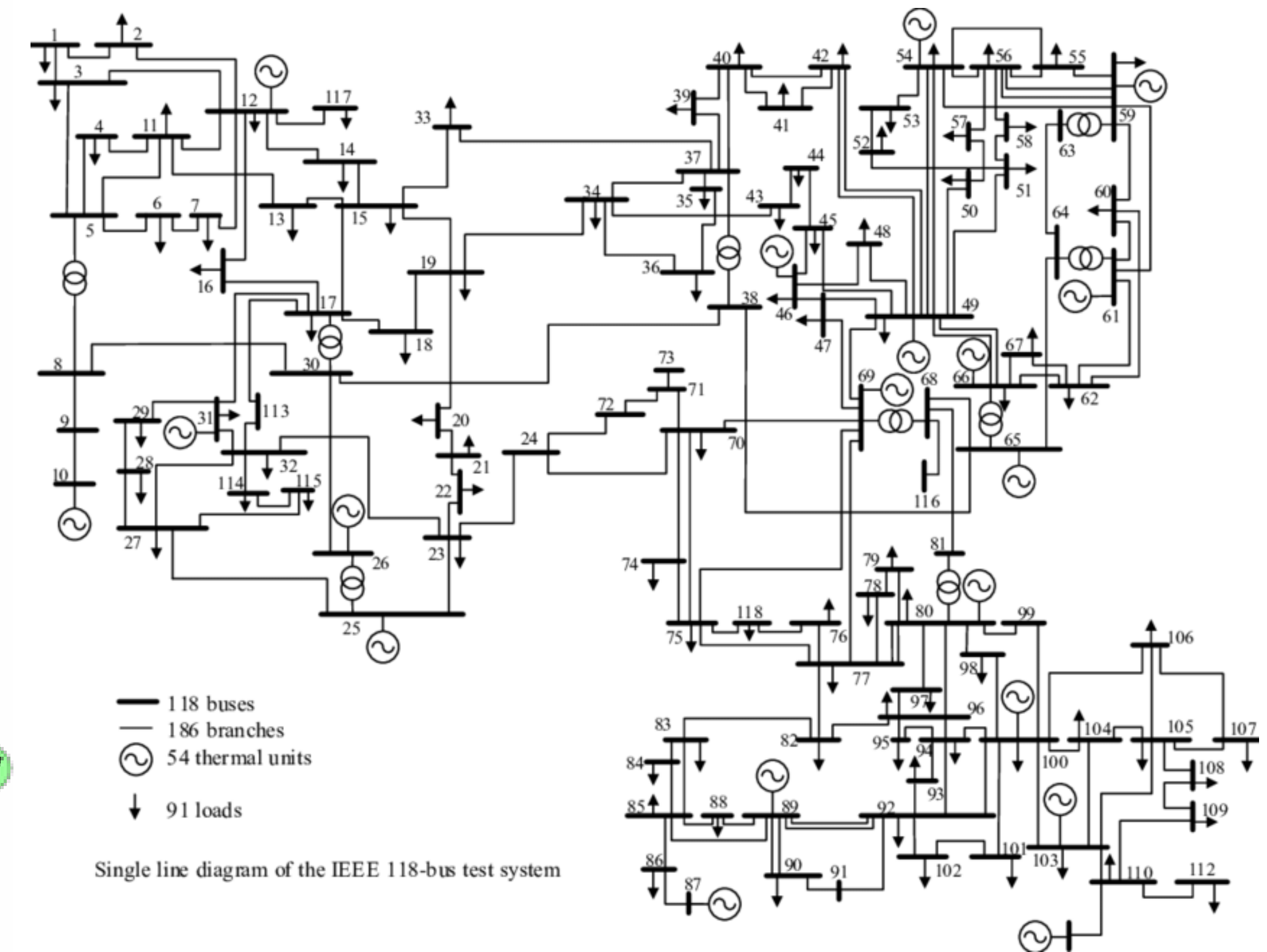
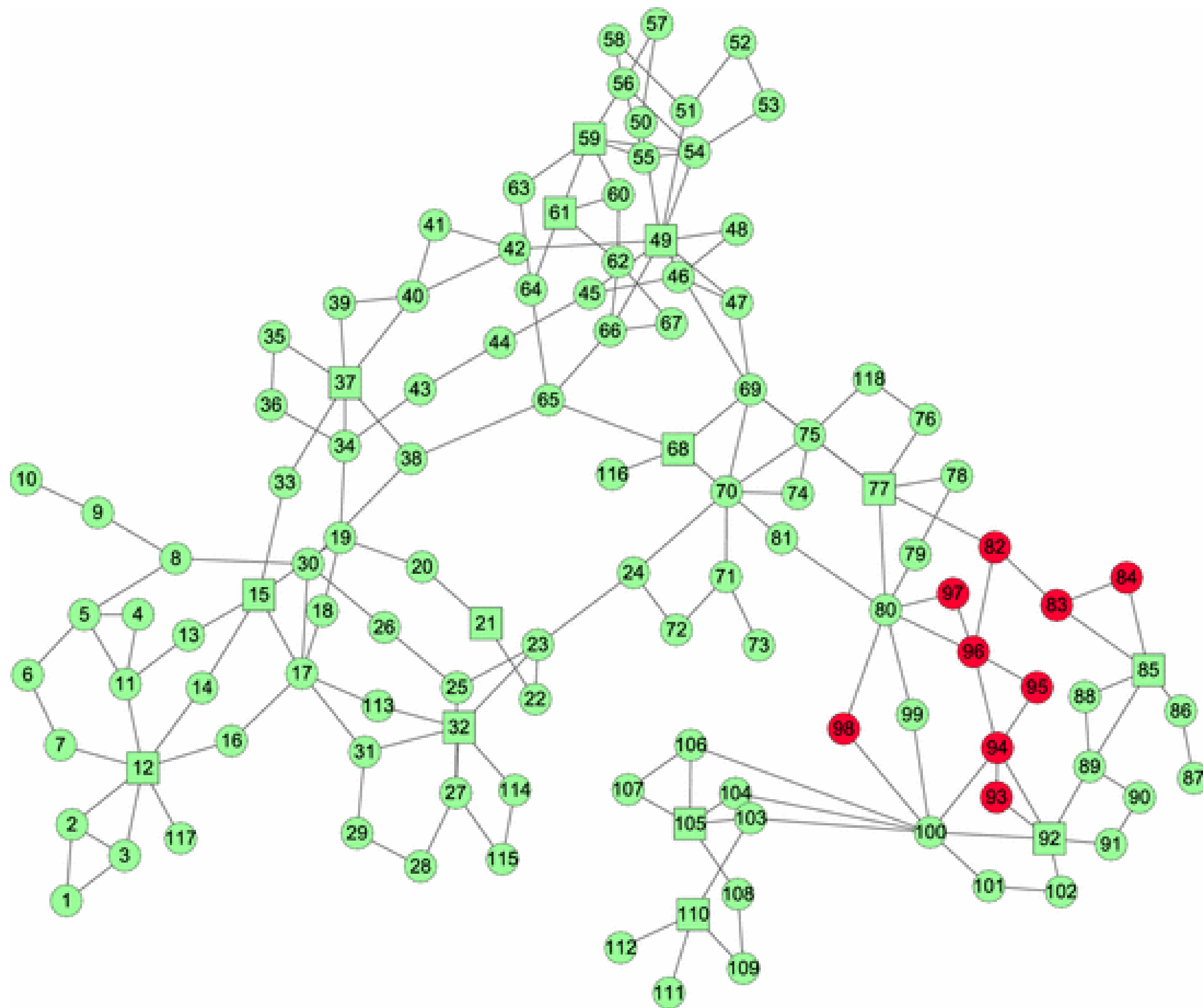


Cascading failure

Failed links and nodes are colored **red**. Blue circles are generators and green circles are loads. The voltages of the generators nodes are 1 p.u., the currents sinking at the loads are 1 p.u. Components' capacities are:

$$C_{ij} = (1 + \alpha)I_{ij}(0); C_{oi} = (1 + \beta)v_i I_{oi}(0)$$





Single line diagram of the IEEE 118-bus test system

Simulation of cascading failure triggered by breakdown of transmission line (77, 82) of IEEE 118 bus. Squares are generators. Red nodes are unserved nodes.

Robustness assessment

Robustness is taken to imply tolerance to damage from extreme loads or accidental loads, although the framework here is applicable to other adverse effects such as sensitivity to human error and deterioration.

- COMBINE physical model with network statistics
 - New *assessment metrics* (Zhang and Tse, IEEE JETCAS 2015)
 - PUN (percentage of unserved nodes)
 - PNL (percentage of non-critical links)
- **Critical loads** directly affect an organisation's ability to maintain key operations and must be kept running during a mains power supply failure, for example, a data centre's servers or life support equipment in a hospital.
- **Non-critical (or non-essential)** loads can be dropped during a power cut as they aren't fundamental to the organisation's operations. Printers, office lighting, and desk fans are good examples of non-essential loads.

Robustness Metric (Static)

Robustness refers to the ability of a power system to tolerate faults.

Two parameters:

Percentage of Unserved Nodes (PUN) caused by failed **component i**

Percentage of Non-critical Links (PNL)

PUN(i) for **component i** indicates its importance:

$$\text{PUN}(i) = \frac{n_{\text{unserved}}(i)}{n}$$

where n is the number of nodes, $n_{\text{unserved}}(i)$ is the number of unserved nodes caused by failure of **component i** .

Robustness Metric (Static)

If $PUN(i)$ is large, then component i is relatively more critical.

If the network has many components that have large PUN, the network is more vulnerable.

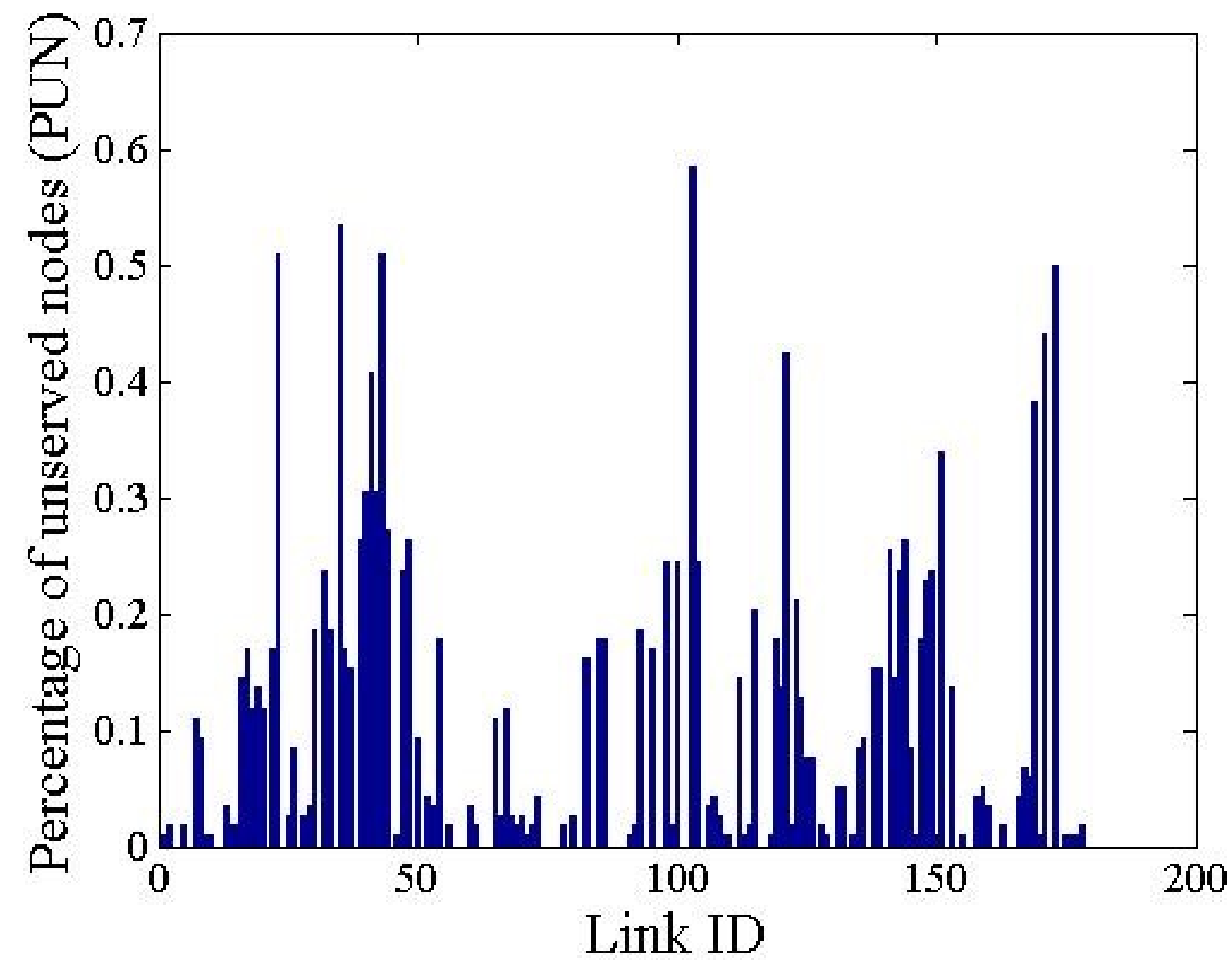
Percentage of Non-critical Links (PNL) whose PUNs are smaller than a *threshold* to indicate the ability of a network in tolerating faults.

$$PNL(\text{threshold}) = \frac{1}{m} \sum_{i \in M} \delta(i)$$

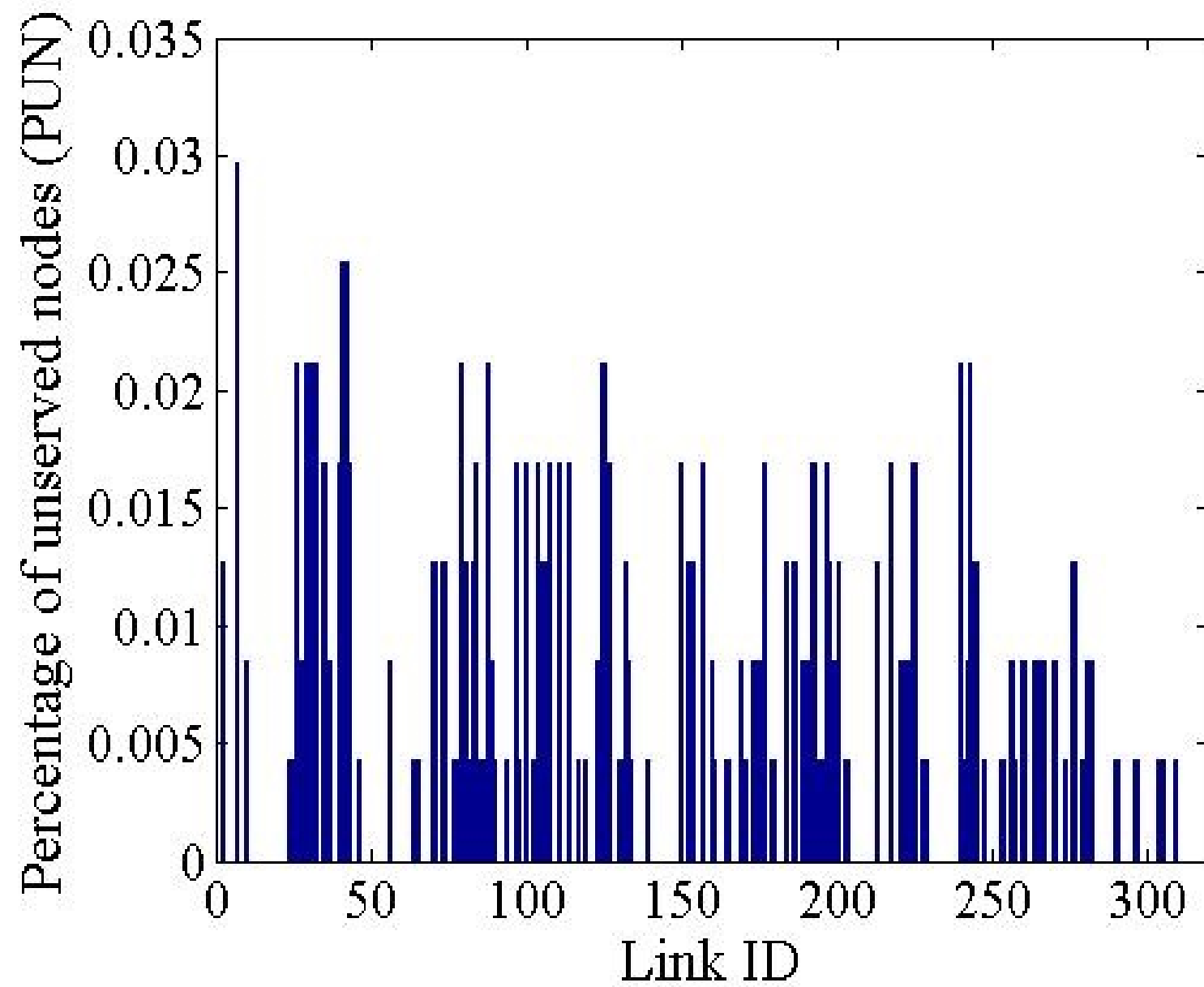
where M is the set of all links, m is number of links and

$$\delta(i) = \begin{cases} 1, & PUN(i) < \text{threshold} \\ 0, & \text{otherwise} \end{cases}$$

IEEE 118 Bus and Northern European Grid

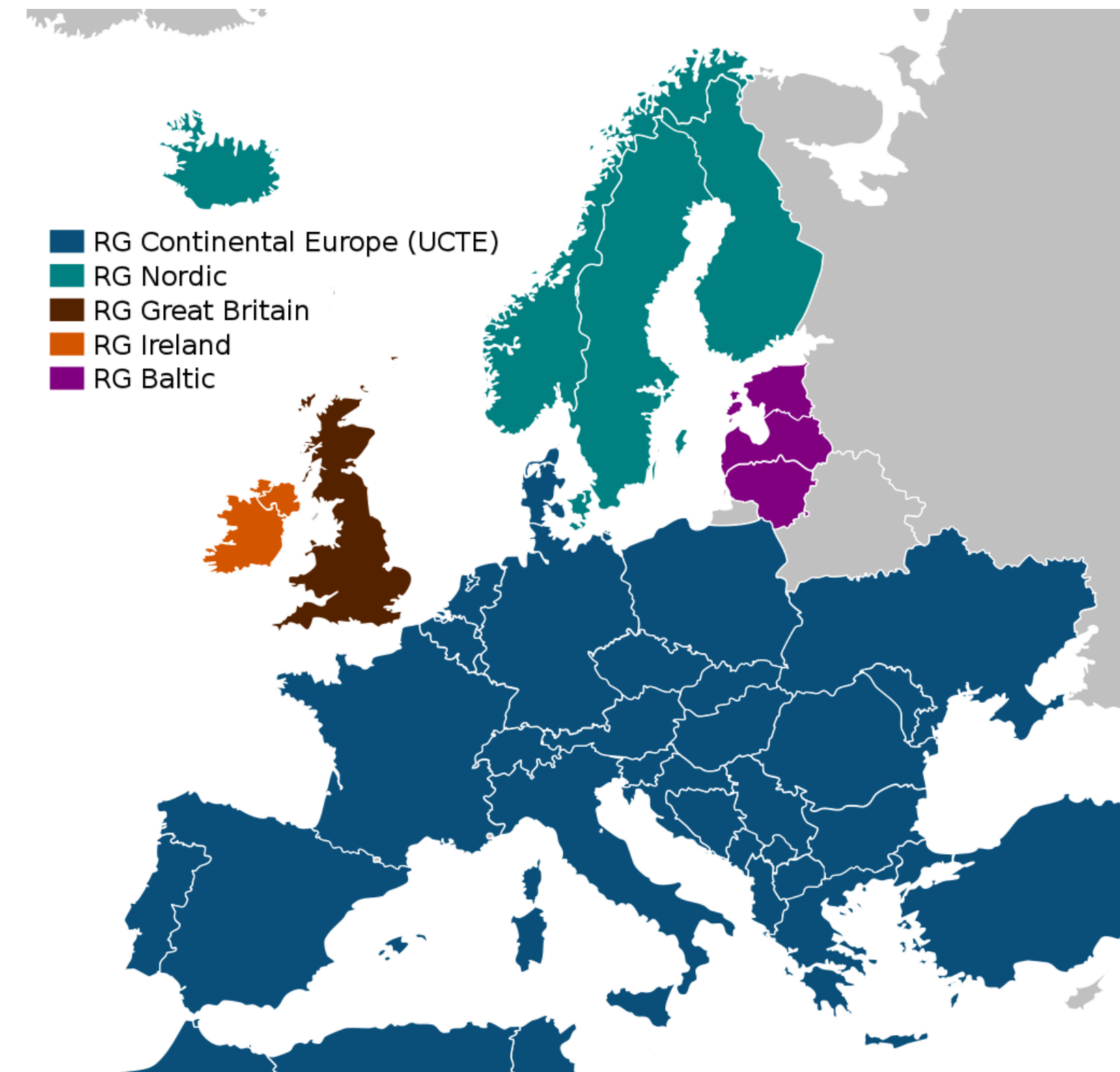


(a)



(b)

Simulation results of cascading failure and robustness assessment. (a) PUN of each link in IEEE 118 Bus; (b) PUN of each link in Northern European Grid.



<https://www.entsoe.eu/data/map/>

How network structural properties affect robustness

Effect of consumer's accessibility to generators

- Application 1: Effective generator allocation scheme to enhance the robustness of power grid

Effect of network structure

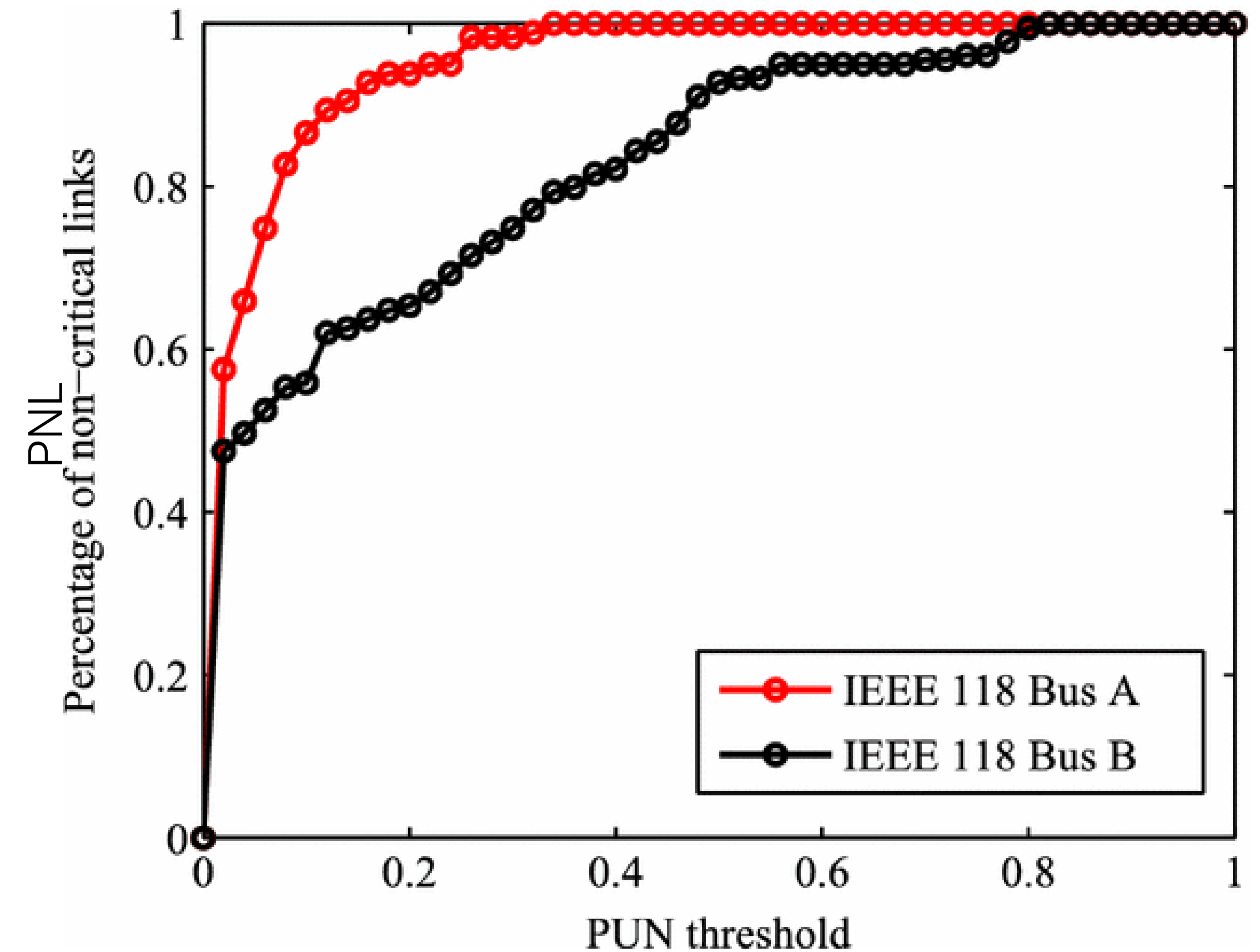
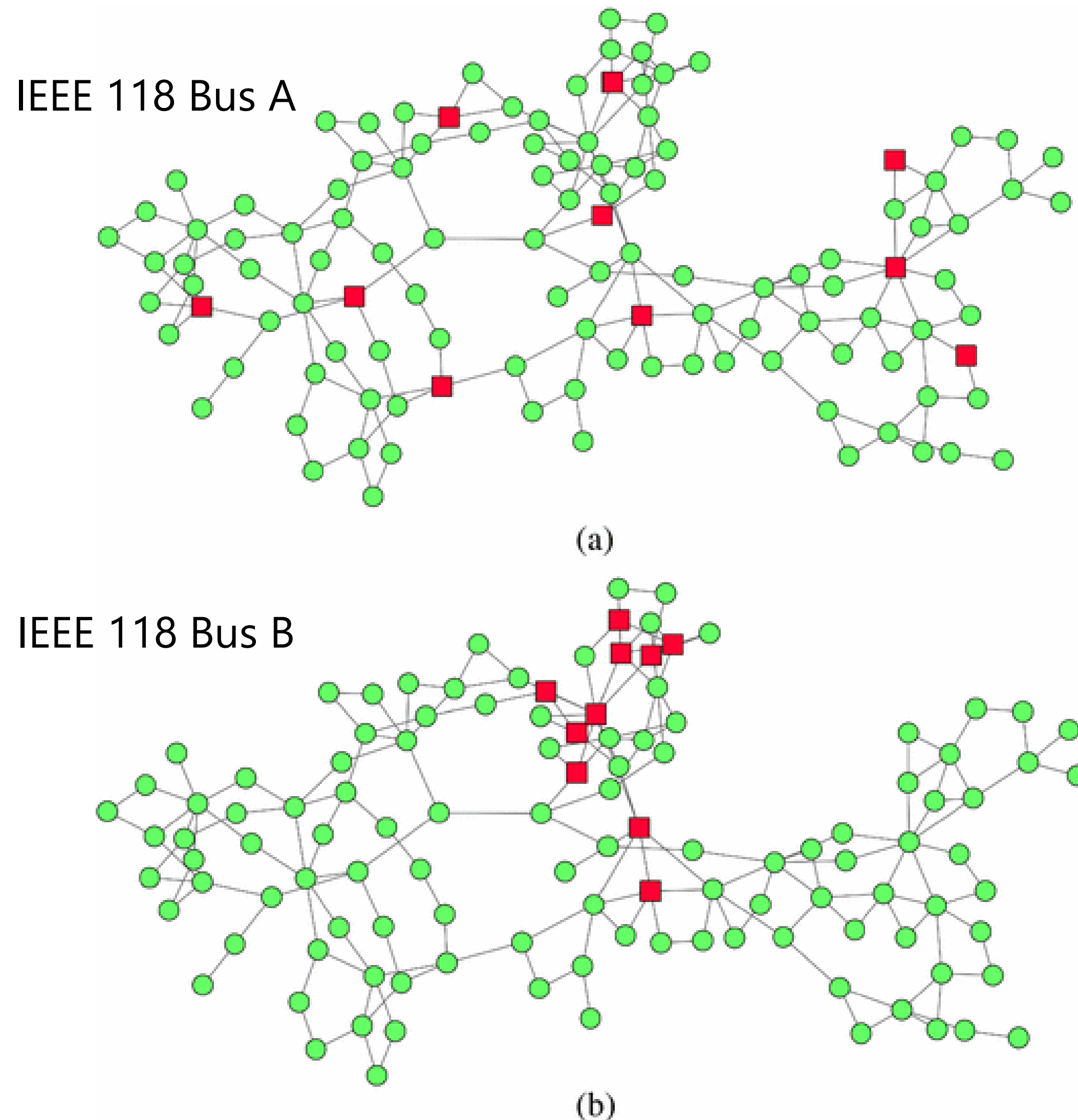
- Application 2: Optimization of structure, capacity and function of power networks



Lama island power plant, Hong Kong

Application Example:
How decentralisation of power
accessibility affects robustness

Effect of changing location of generators

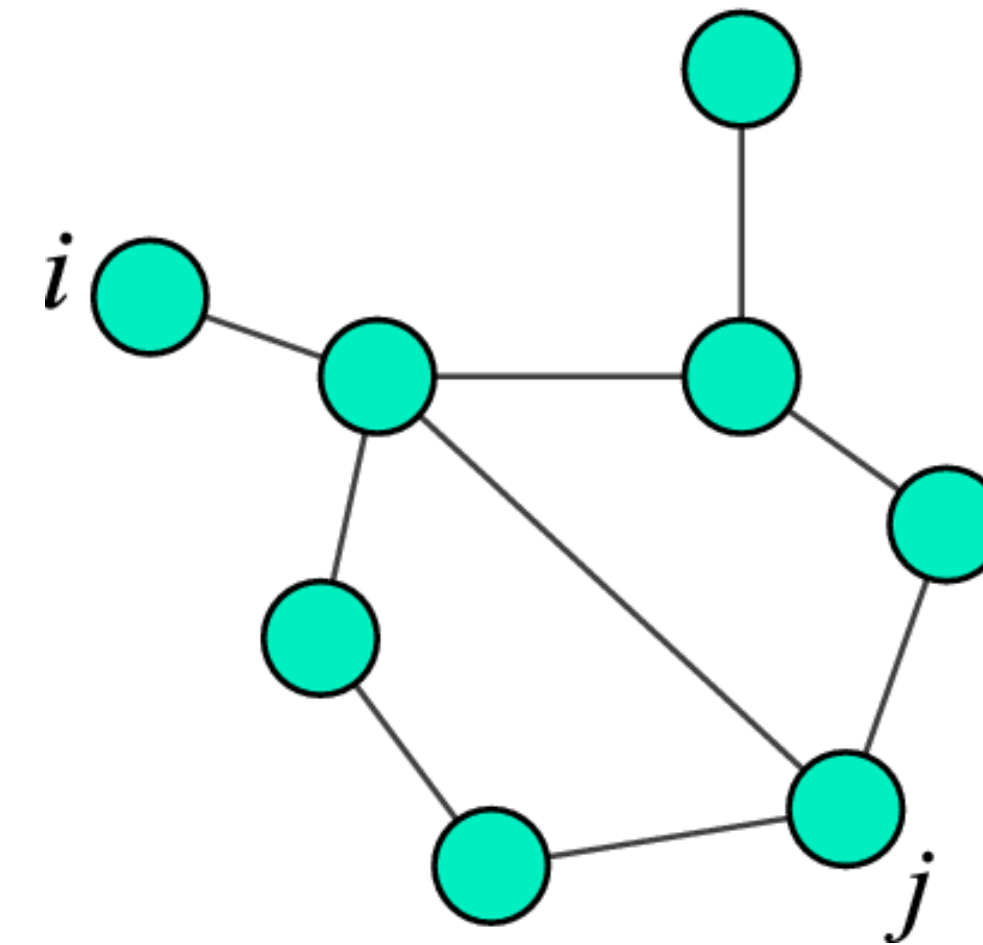


Robustness assessment of IEEE 118 Bus A and B. Buses A and B only differ in the location of generators, with Bus A has more decentralized distribution of generators.

How far are two nodes separated?

Concept of *resistance distance* of a power system proposed by Klein and Randić.

$$R_{ij} = \frac{V_i - V_j}{I_j}$$



When calculating the effective resistance between nodes *i* and *j*, we set node *i* as a voltage source with v_i , node *j* as a current sink with current of I_j and all other nodes as distribution nodes with sink currents of I_o . Using the circuit formulation, v_i can be readily derived.

How far is a node from a generator?

Resistance distance of node i to its nearest generator, $d(i)$:

$$d(i) = \min\{R_{is}, s \in G\}$$

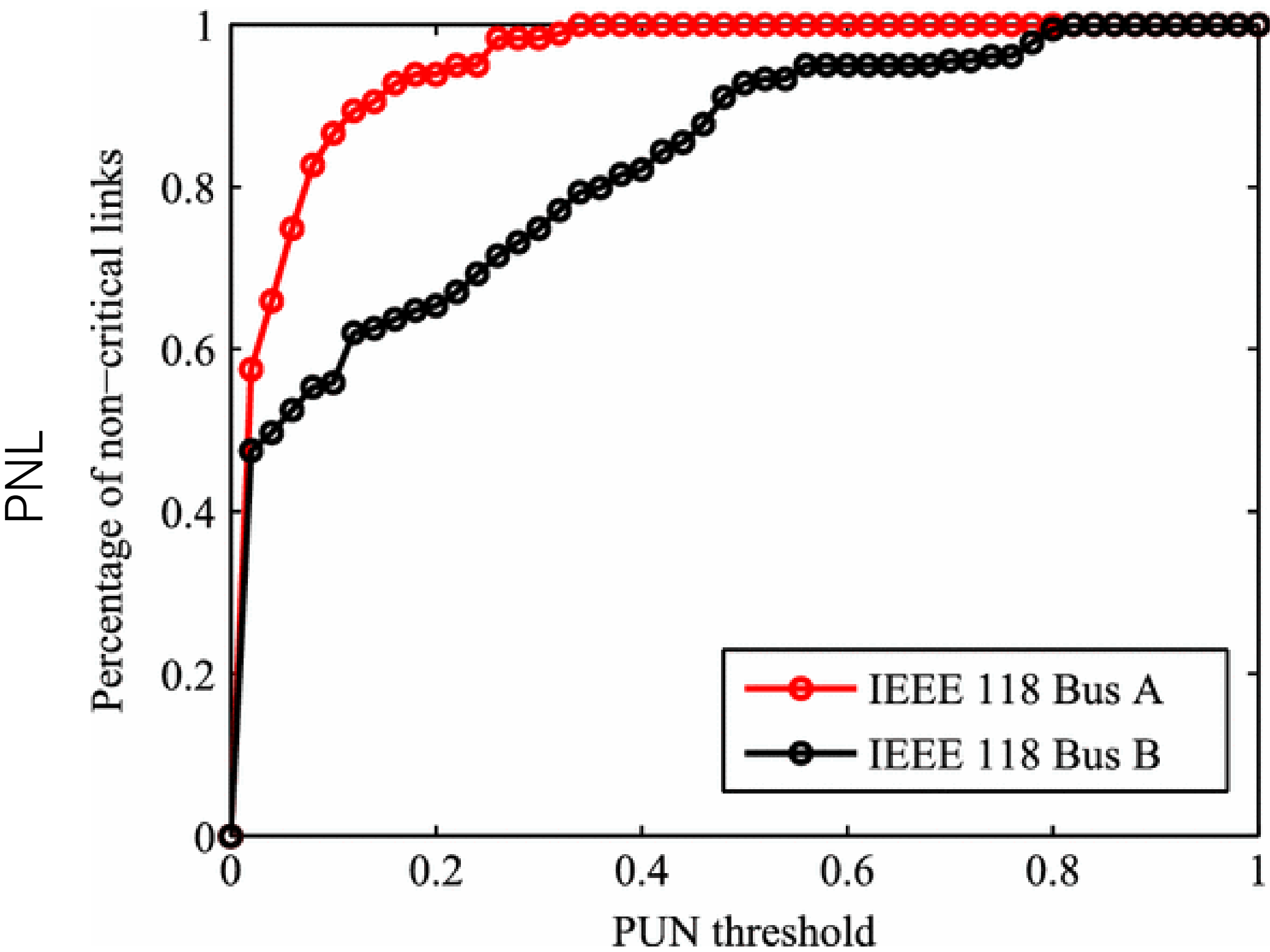
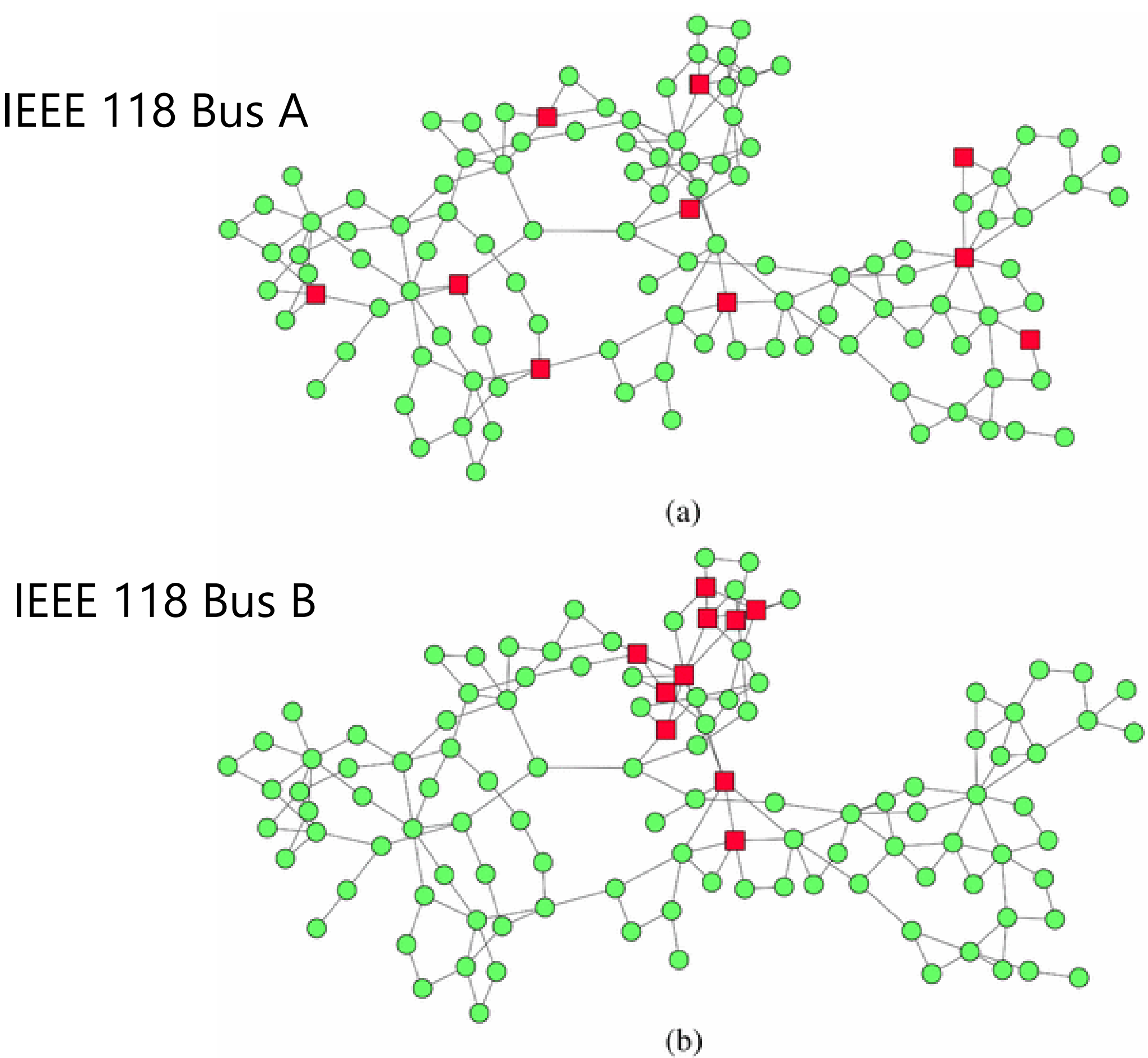
where G is the set of generators in the grid.

The averaged $d(i)$ of all loads is a measure of their *accessibility to generators*.

$$DG = \frac{1}{(n - g)} \sum_{i \in N \setminus G} d(i)$$

where $(n-g)$ is the number of loads, N and G are the sets of nodes and generators.

Why IEEE 118 Bus A is better?



	IEEE 118 Bus A	IEEE 118 Bus B
DG (p.u.)	0.9977	1.5334

Modelling dynamic profile of cascading failure

TIME

Which is the next element to trip?

How long does it take for the next element to trip?

Can we reconstruct the failure propagation profile?

Historical Data—WSCC 1996 Blackout in July and August
WECC - Western Systems Coordinating Council

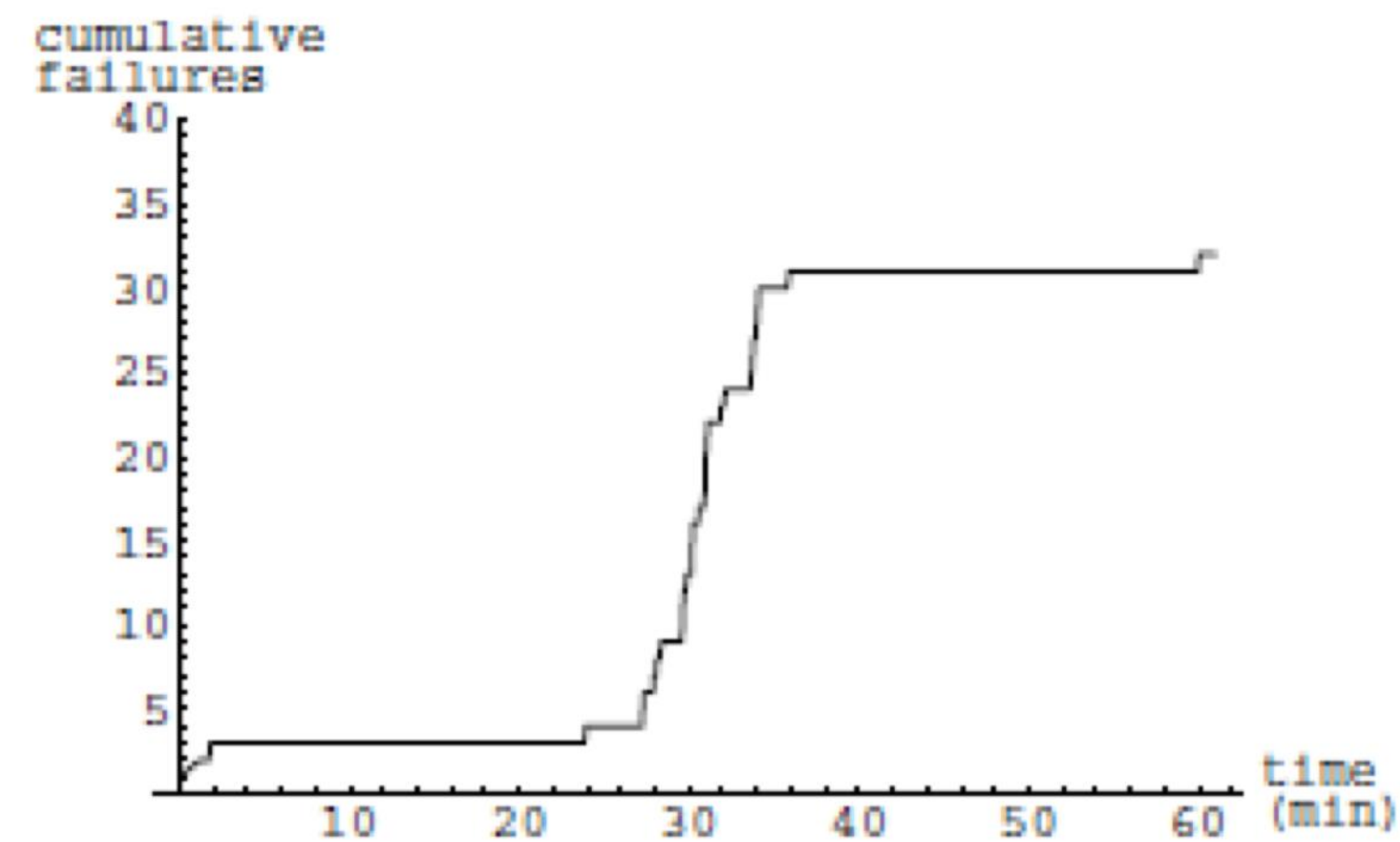


Figure 1. Cumulative line trips in WSCC July 1996 blackout. Time scale is minutes after 14:00 MDT.

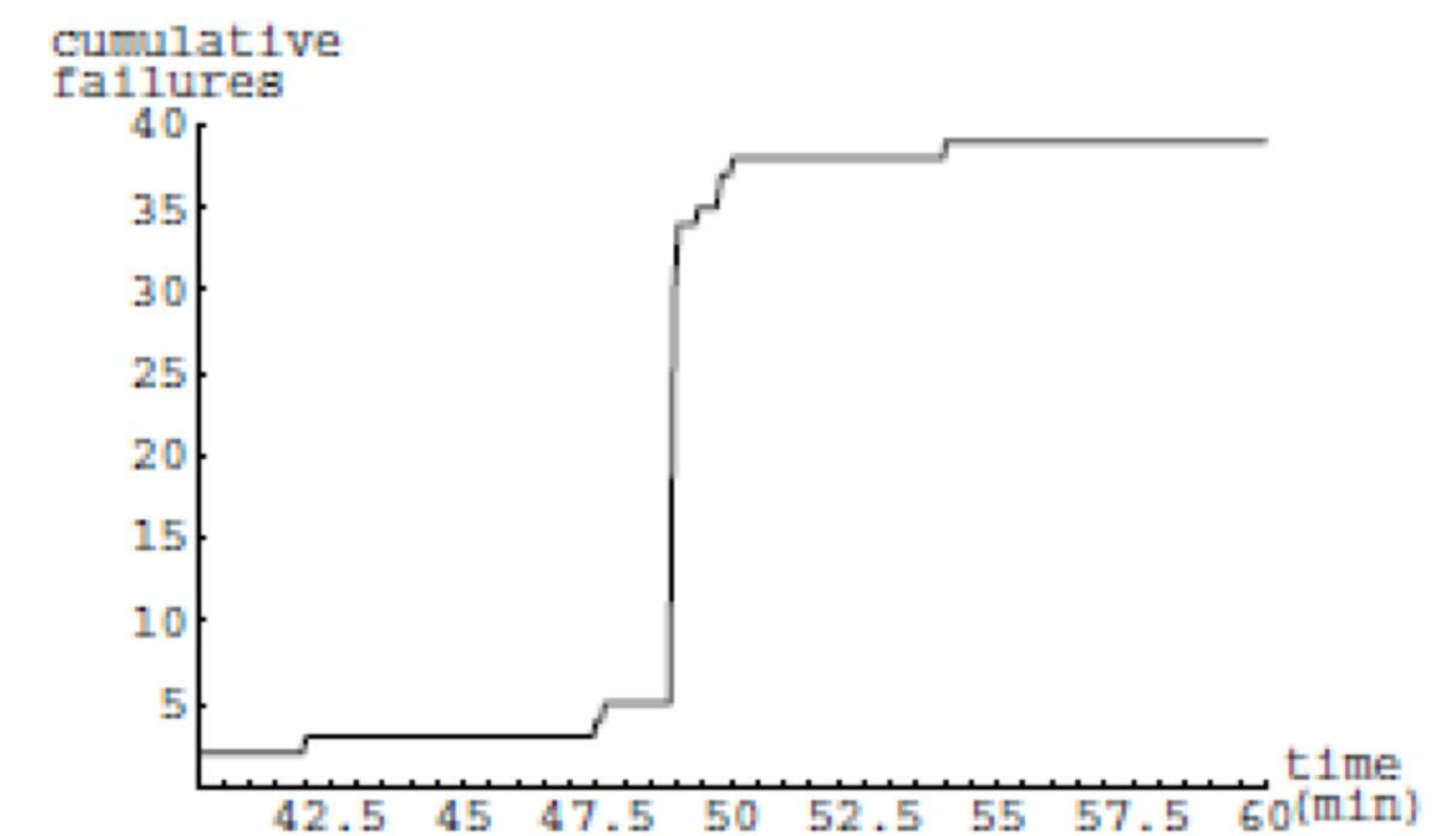
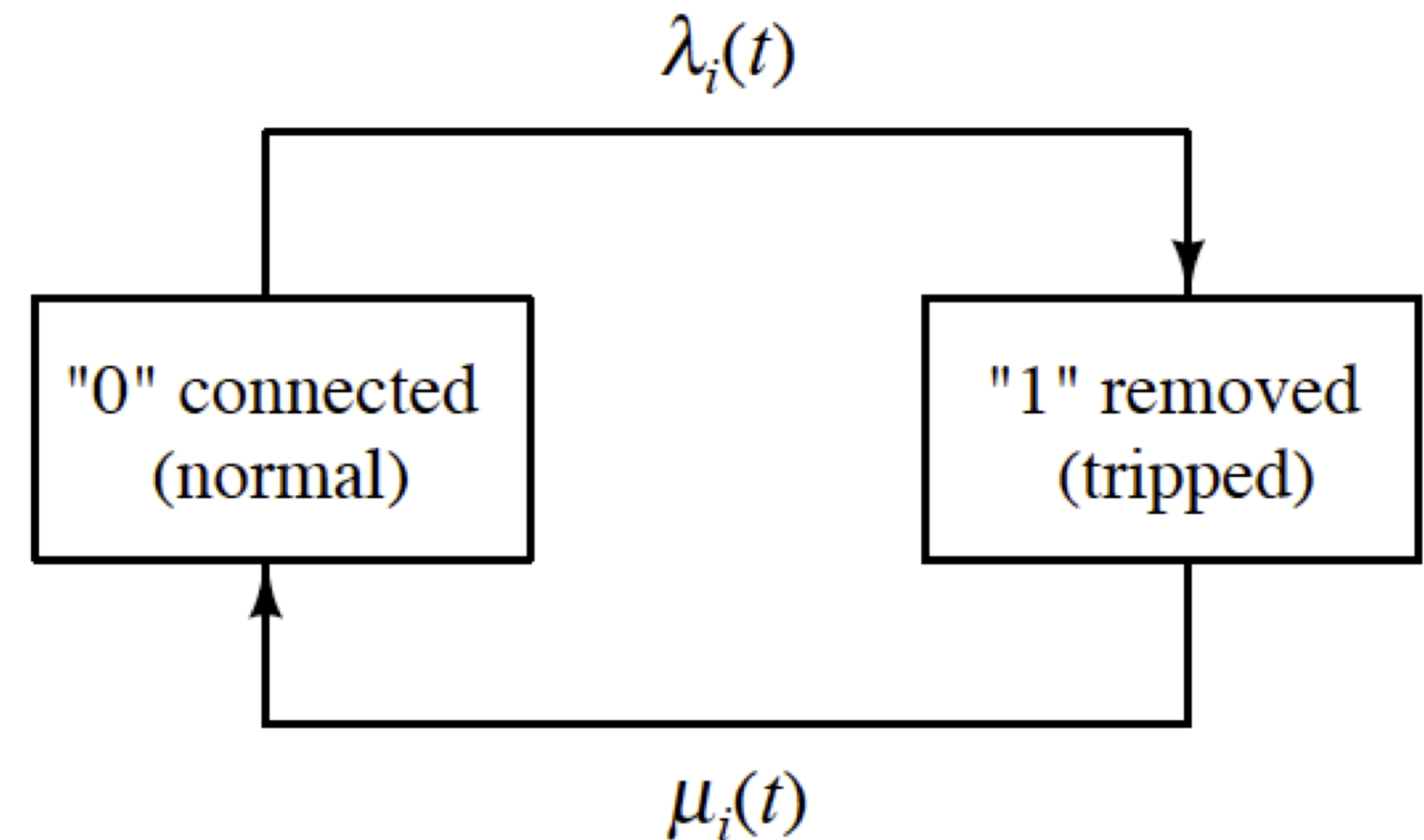


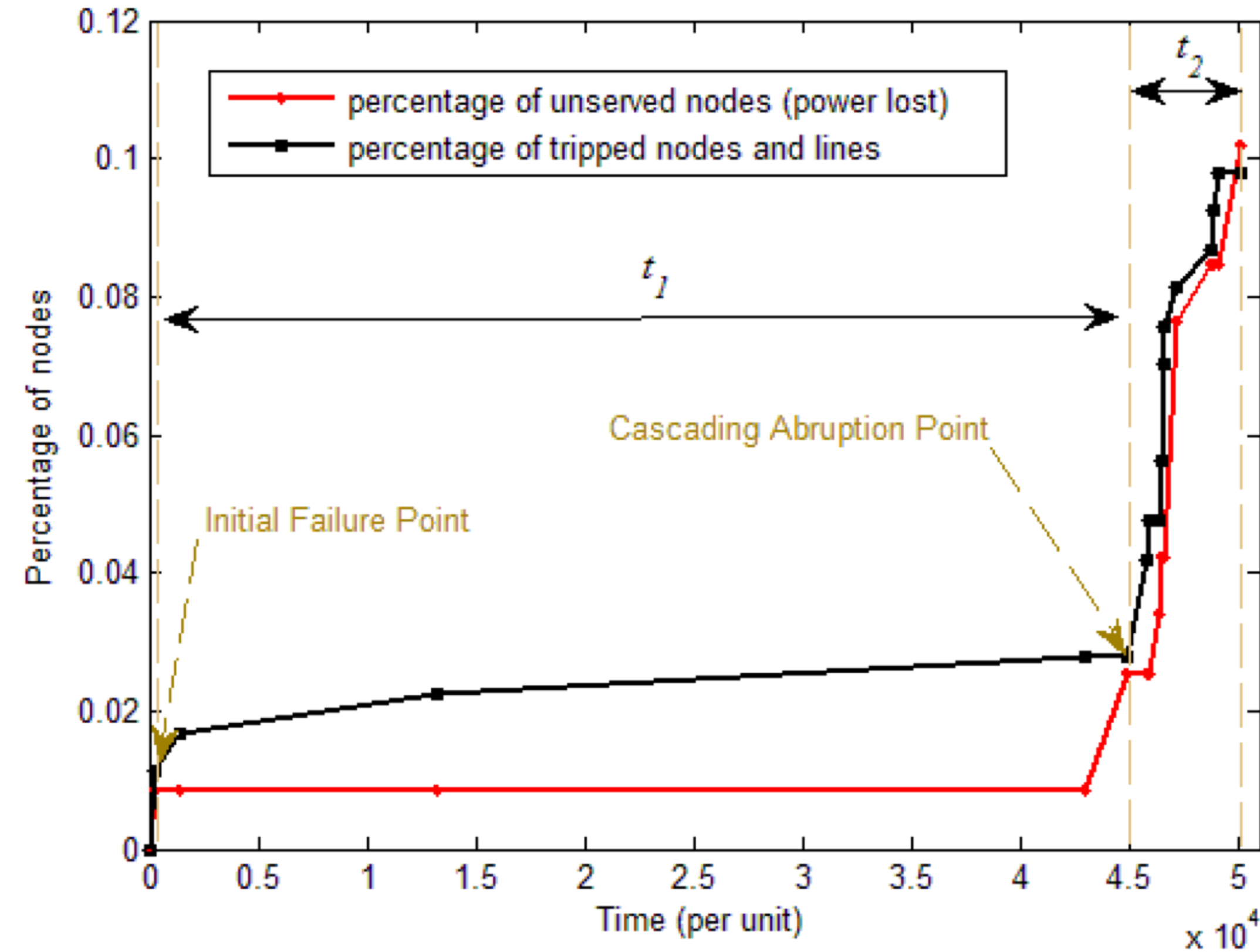
Figure 3. Cumulative line trips in WSCC August 1996 blackout. Time scale is minutes after 15:00 PDT.

Combined deterministic and stochastic model

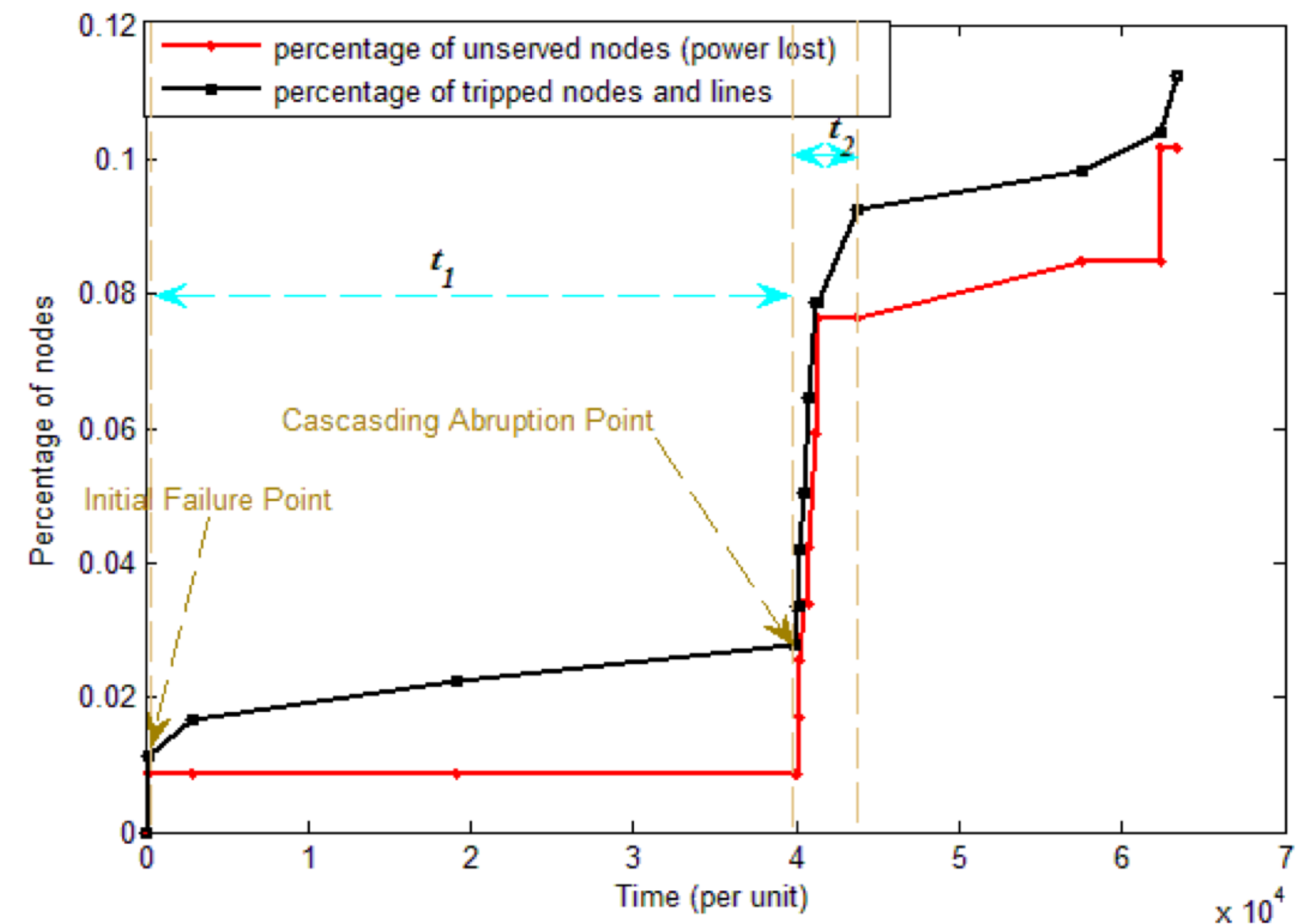
- Deterministic part
 - Power flow model (based on circuit laws)
 - Elements' overloading conditions —> *which element is under high stress?*
- Stochastic part
 - Finding *the next failed element*
 - Predicting *the time for next failure*

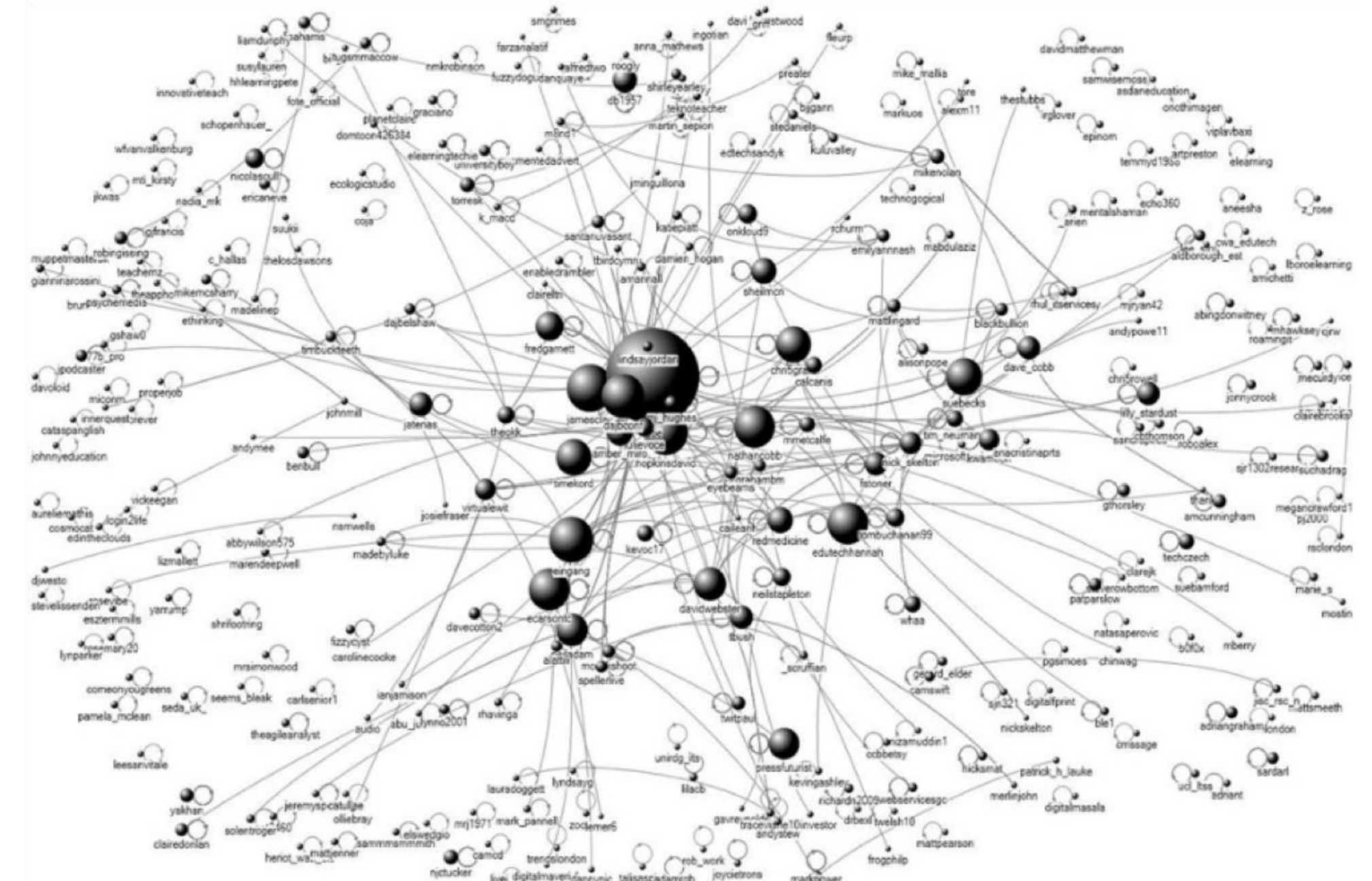
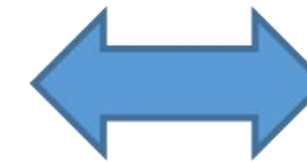
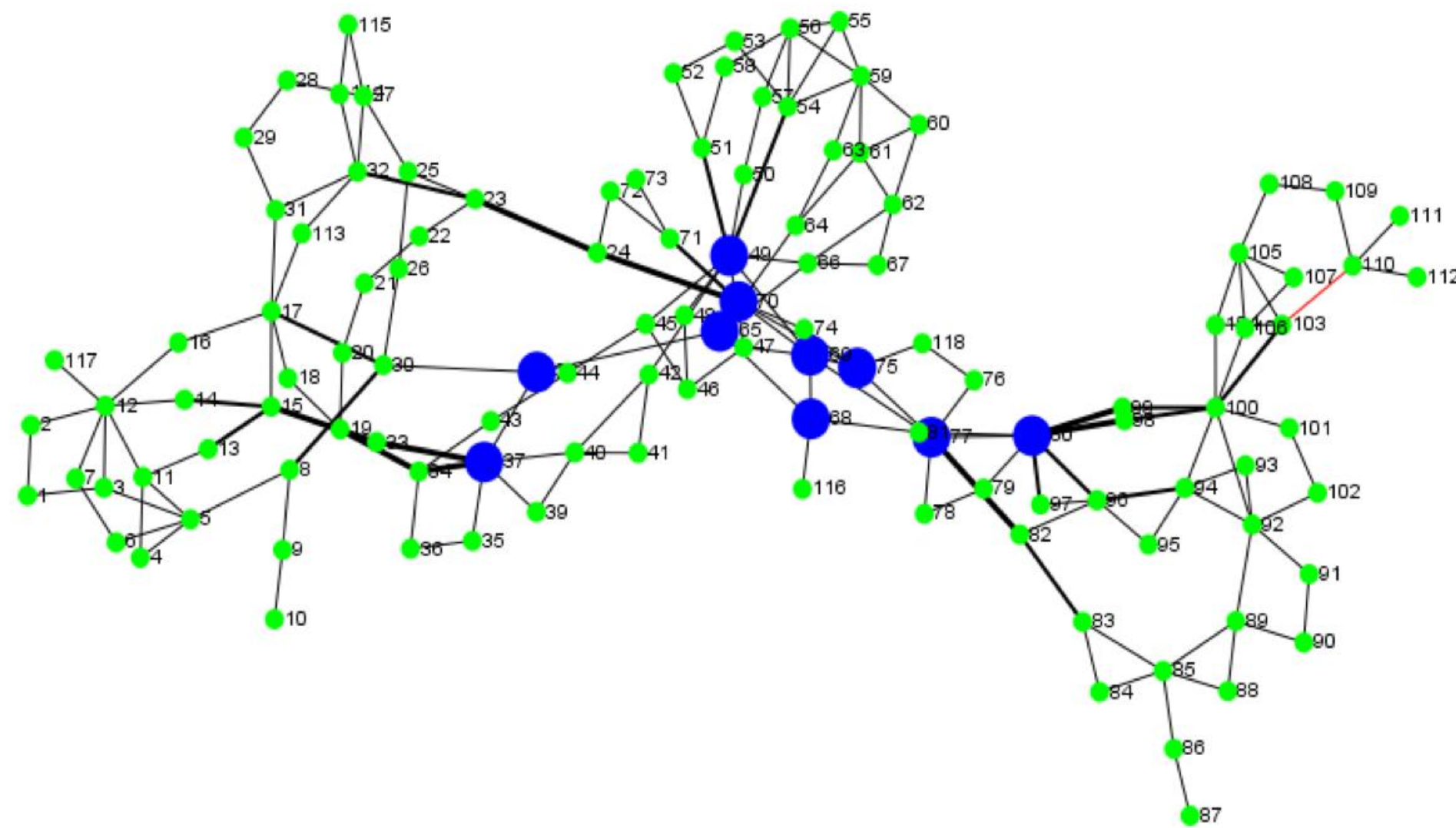


Statistical model's prediction



IEEE 118 Bus System, Initial Failure line (98,100) , $\lambda = 0.001$.

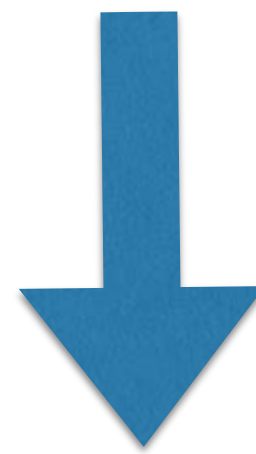




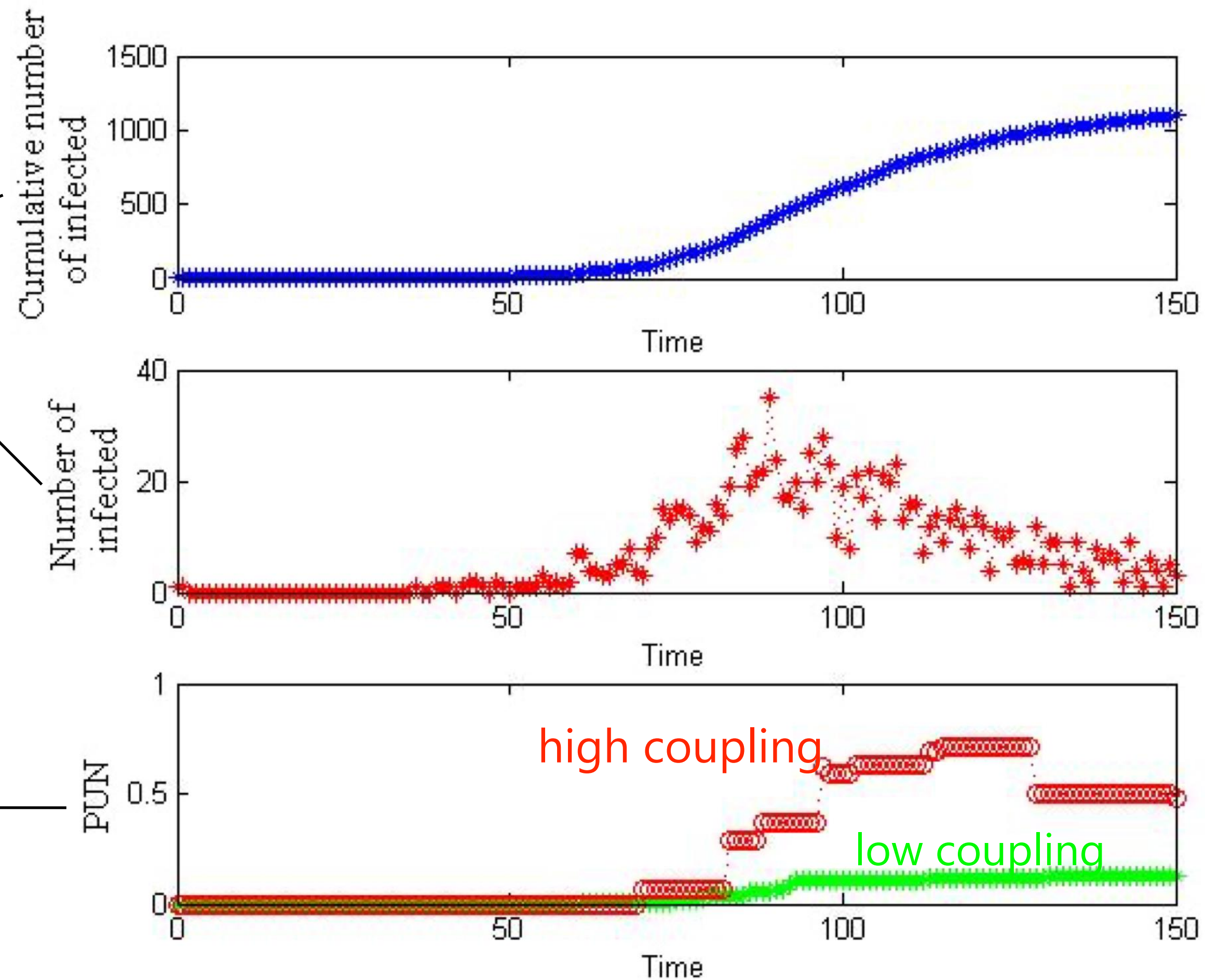
More vulnerable to cascading failure as component failures can be intentionally created via the computer networks.

Vulnerability to cyber malware

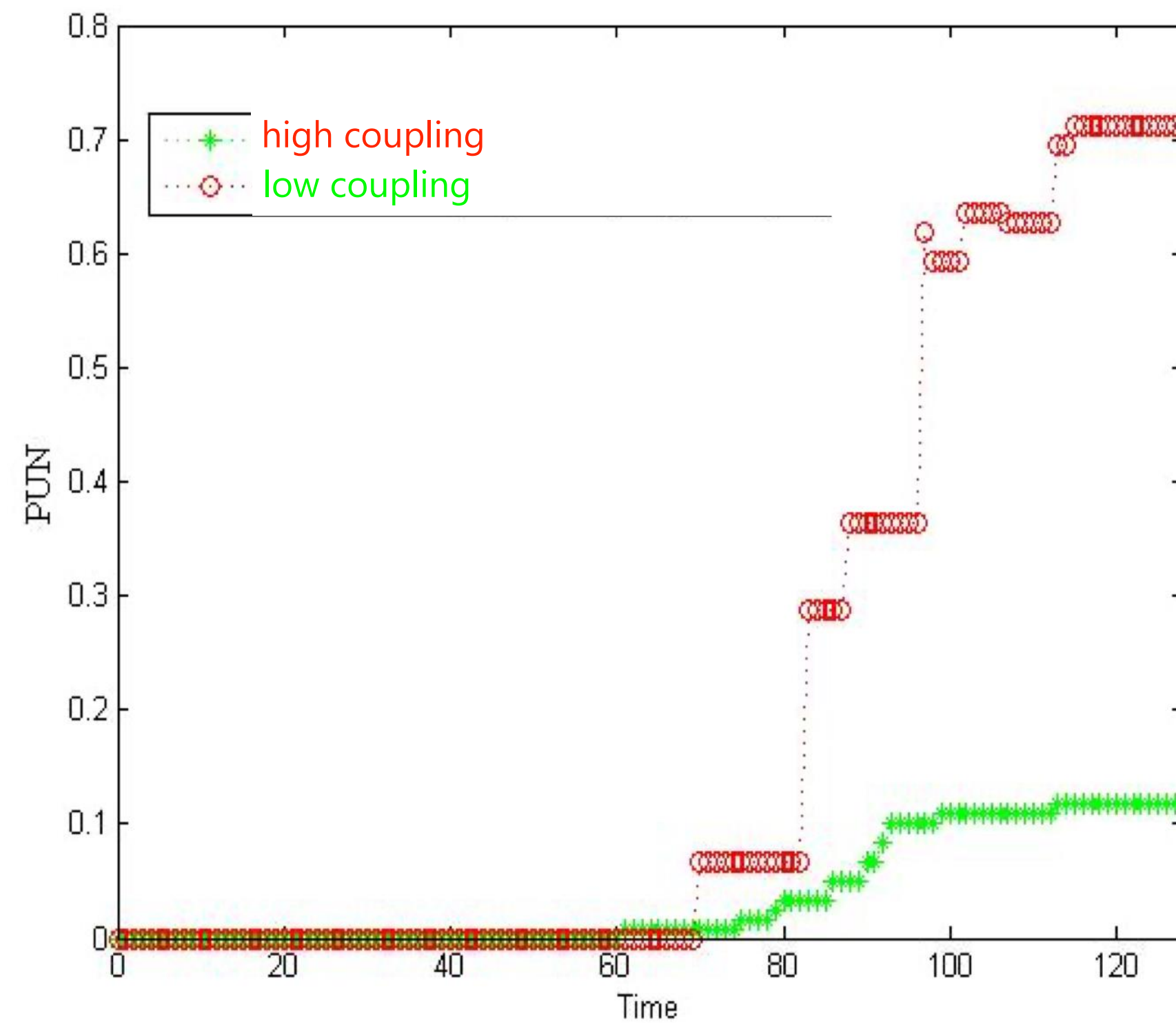
Cyber network is attacked. More nodes get infected as time elapses.



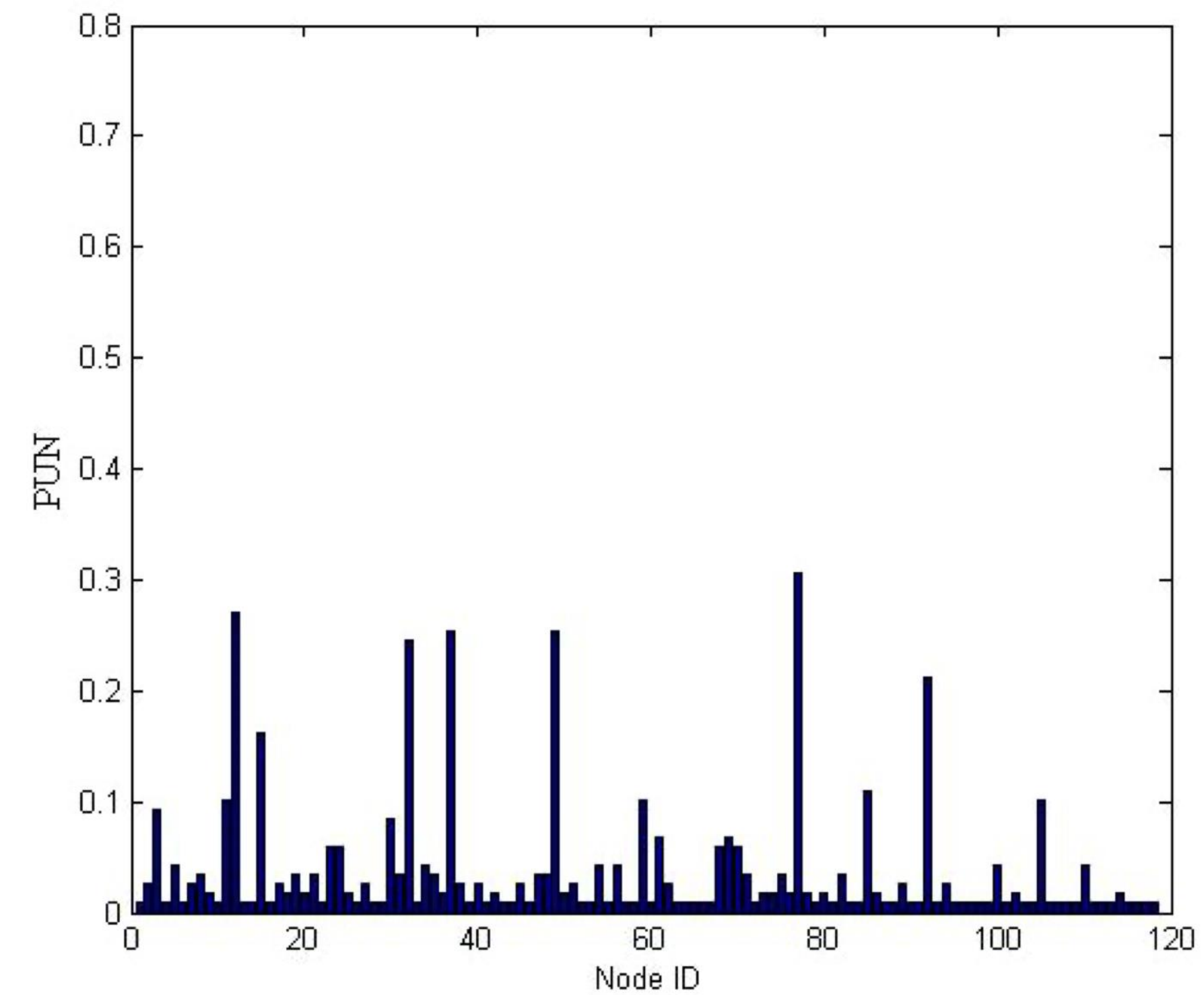
Power network is coupled to the cyber network, causing cascading failure.



Cyber attack is more destructive



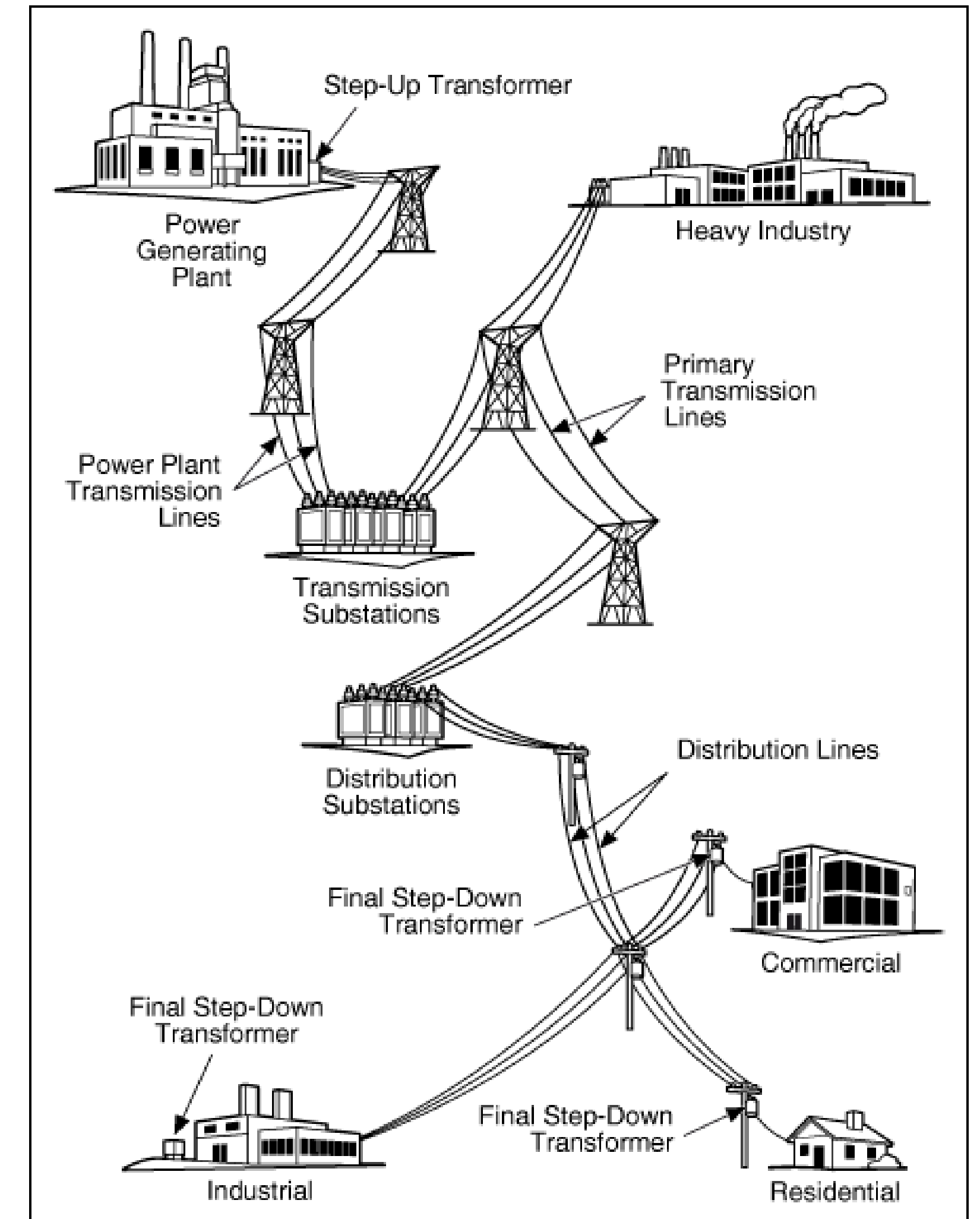
power grid cascade failure



Power grid cascade failure due to single point failure

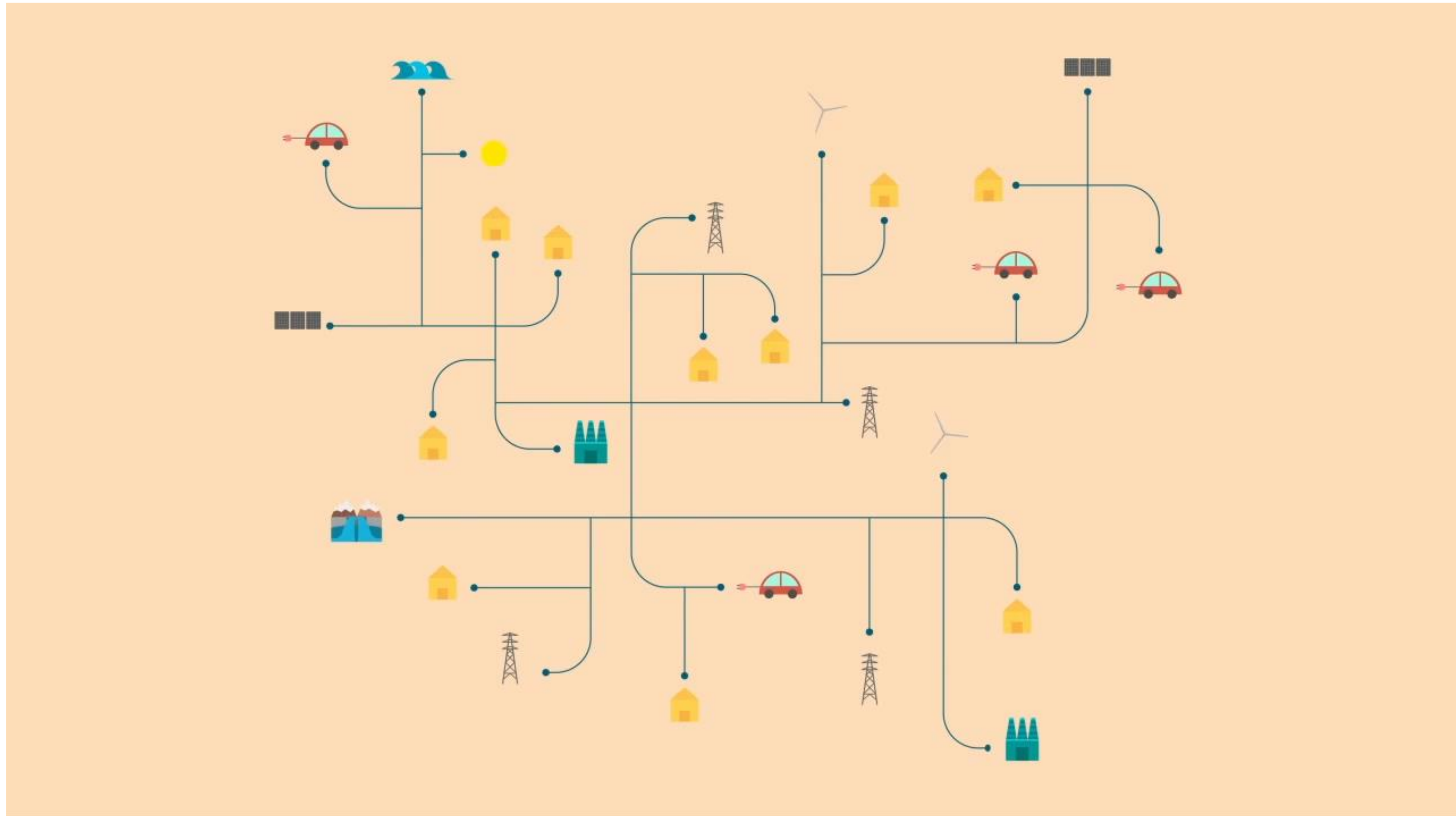
Current Work & Future Trends

- Propose an appropriate model to describe a power system in network context that enables characterisation of vulnerability or robustness
- Quantitatively measure the robustness of a power system
- Explore the factors that would impact robustness
 - Structure of network
 - Crucial parameters
 - *Power electronics penetration* that weakens inertia and affects stability
- Future work
 - Identify design rules
 - Best structure and control strategies



Current Work & Future Trends

Understanding the Smart Grid



Access to TLQ

EE3123 Intro to Electric Power System

- Login to
 - <https://onlinesurvey.cityu.edu.hk/>
 - Course Site on Canvas
- Invitation email
 - “Teaching and Learning Questionnaire (TLQ) for EE3123”
- Scan QR code



Your positive comments will do me a great favor and encourage me a lot!