The Andrew & Erna Viterbi Faculty of Electrical Engineering

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Technion

Beyond phasors: Modeling dynamic events in large power systems

presented by

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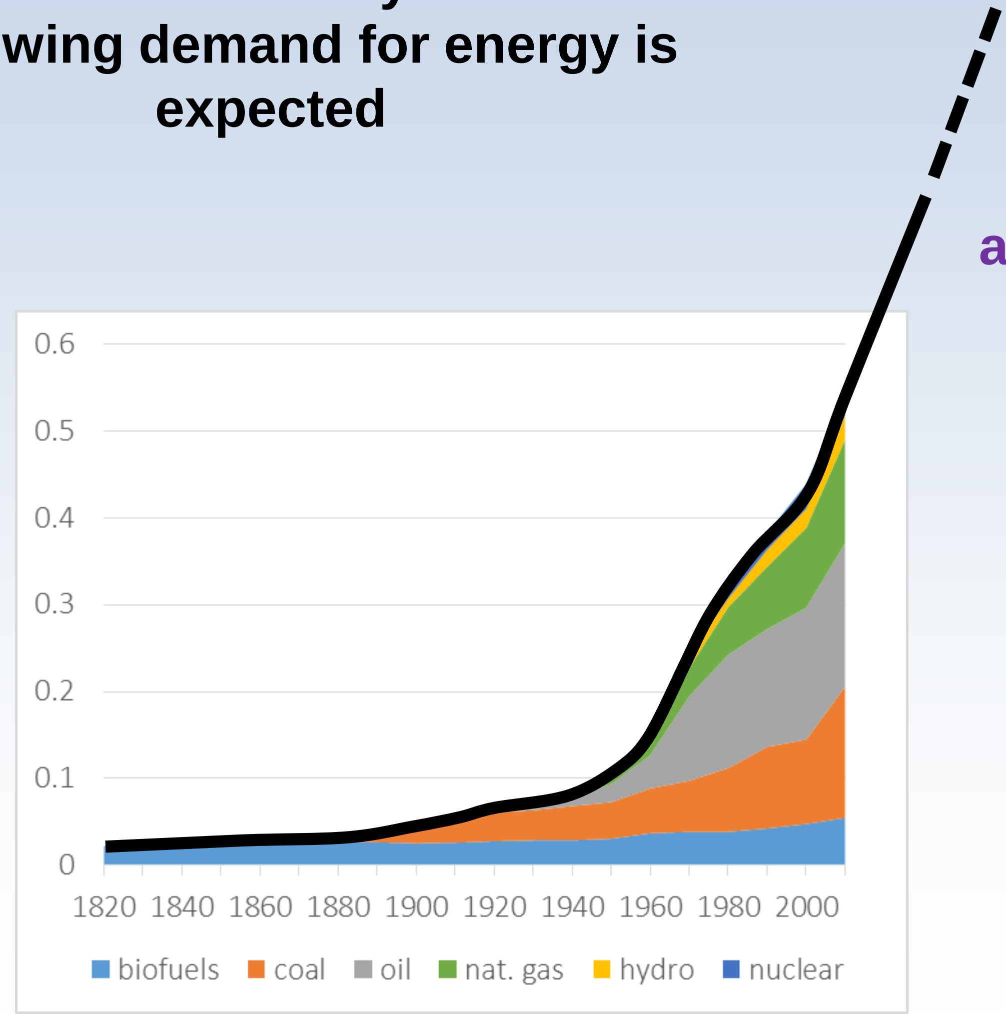
Energy Challenges

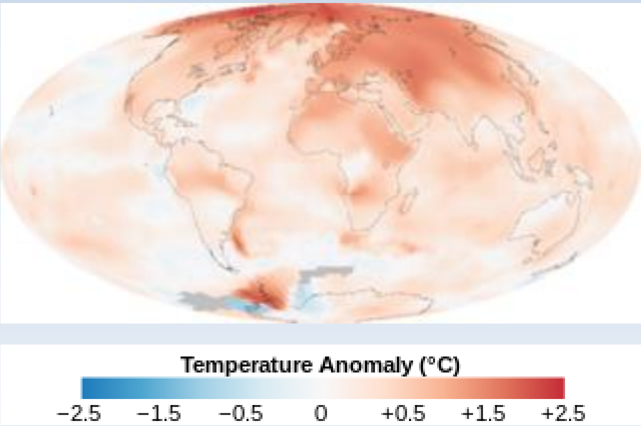
**21st century:
A growing demand for energy is expected**



How long can science and technology support this rate of growth ?

Our increasing energy consumption changes the earth

Climate Change



the Greenhouse Effect is considered a primary cause of global warming.

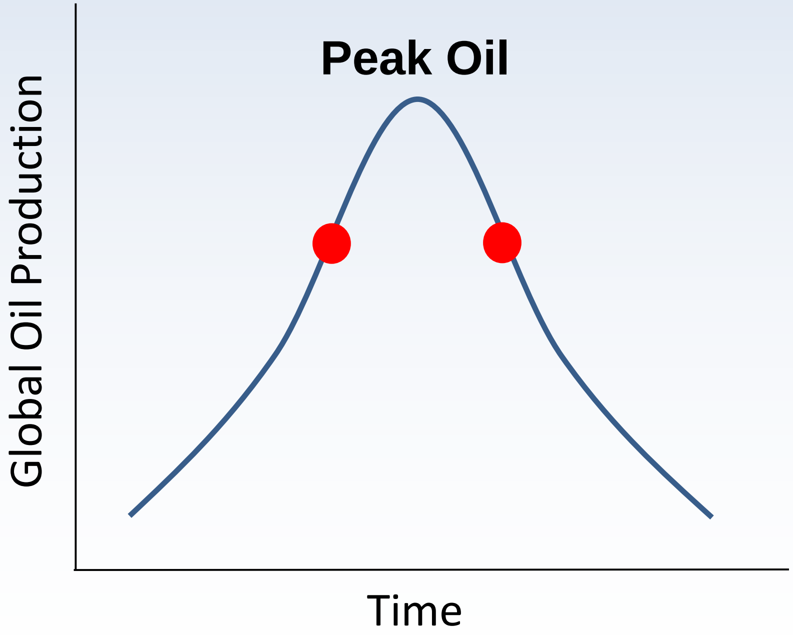
Measured outcomes:

- Concentration of carbon dioxide in the atmosphere is rising.
- Earth average surface temperature is rising.
- Weather patterns are changing.

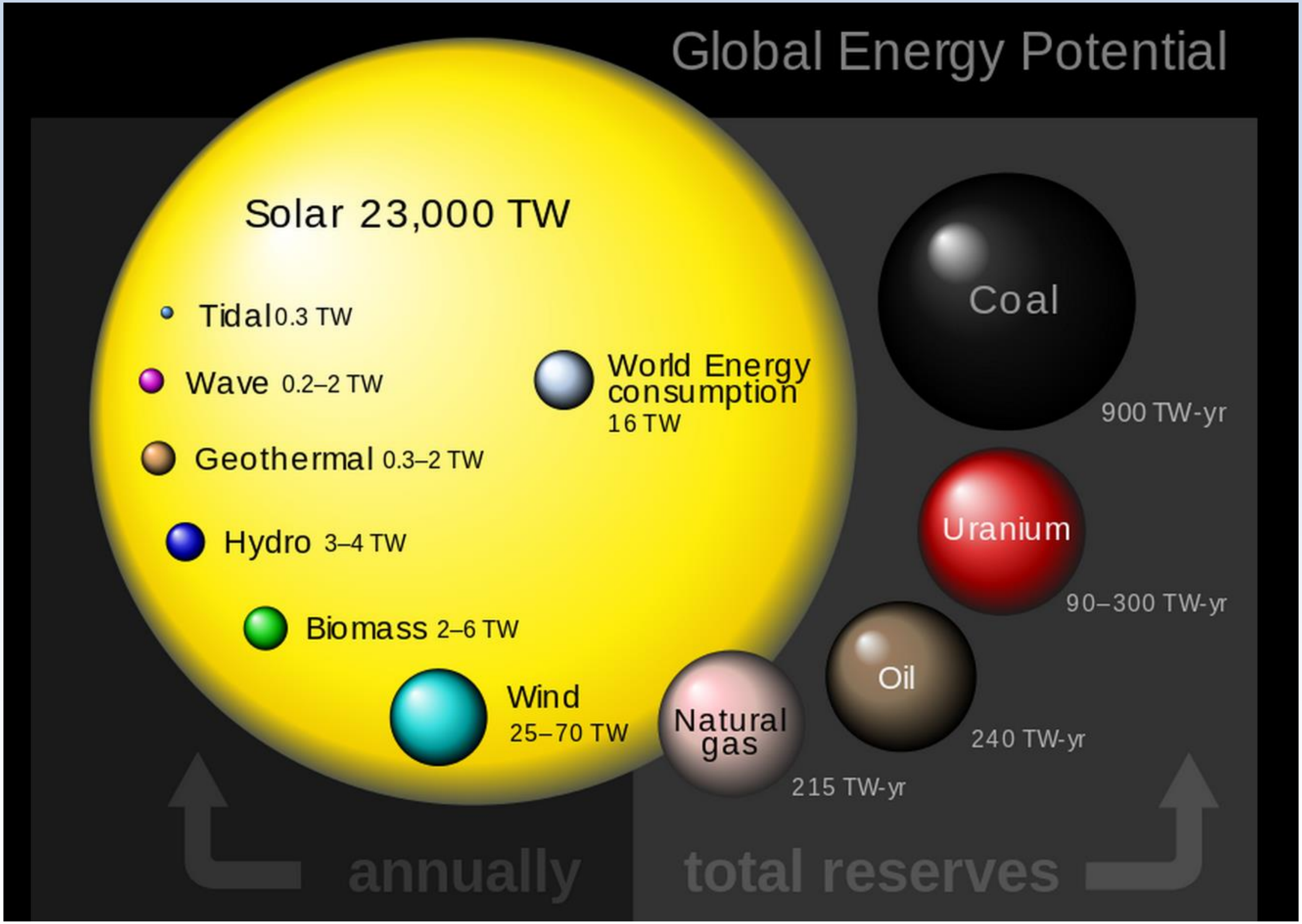
Depletion of Natural Sources

Peak Oil:

Are we before or after the peak ?

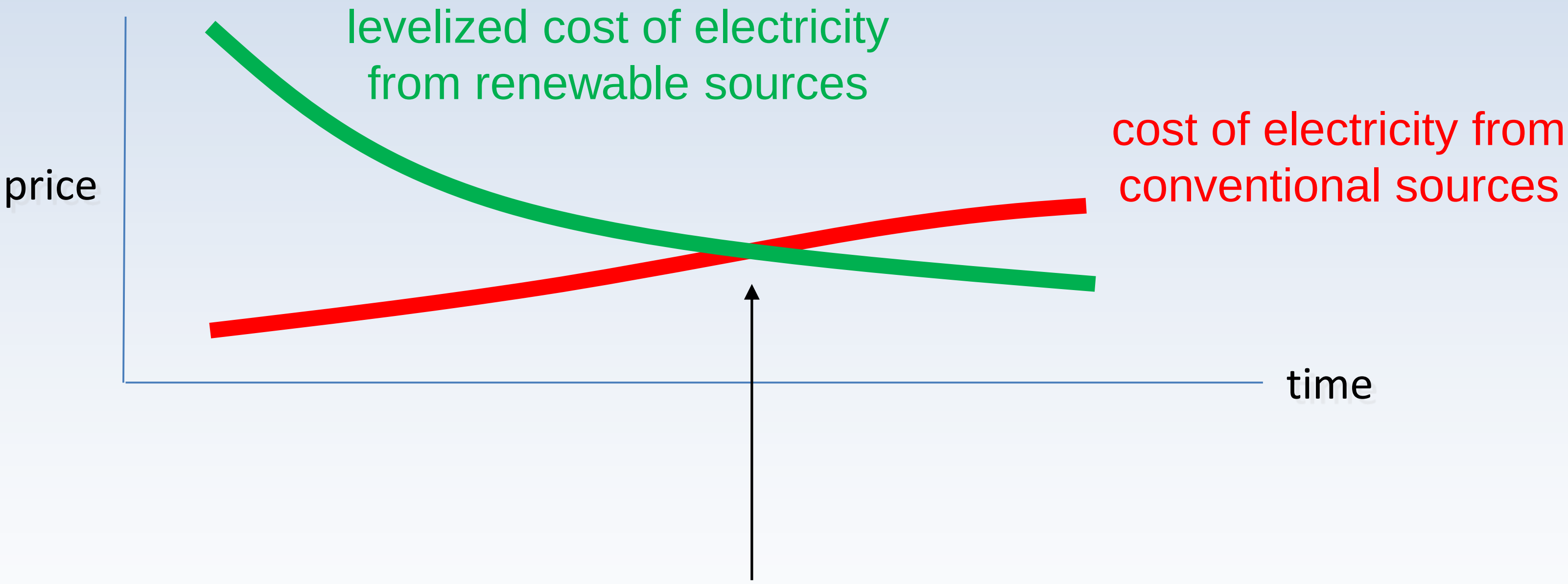


Global Energy Potential



Renewable Energies - Challenges

Cost



“Grid Parity”

A tipping point for renewable energies ?

Renewable Energies - Challenges

Power Density

How much power is produced per square meter ?

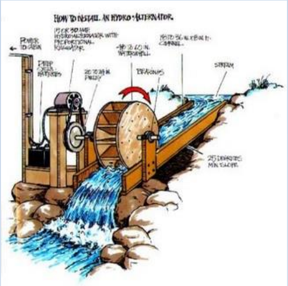
	Wind	solar photovoltaics	bio-fuels
Average Power Watt / m²	**2**	**30**	**1.5**
Energy Yield kWh / (day·m²)	**0.048**	**0.72**	**0.036**

* typical numbers

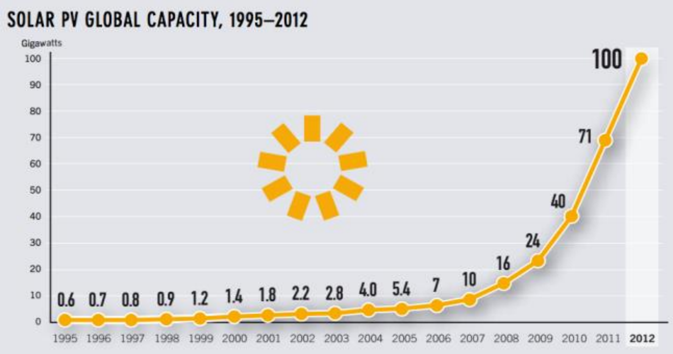
Renewable Energies – an Answer ?

Wind

Solar



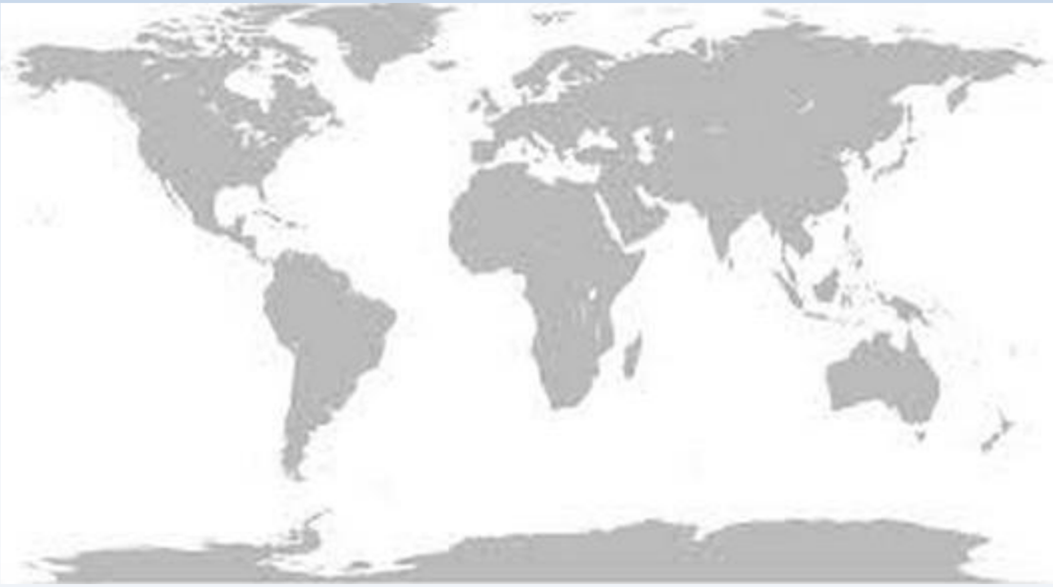
Hydro



Solar Energy Installations Worldwide

Estimated
Land Area

How much area is required to power the world ?
(with nothing but solar photovoltaics)

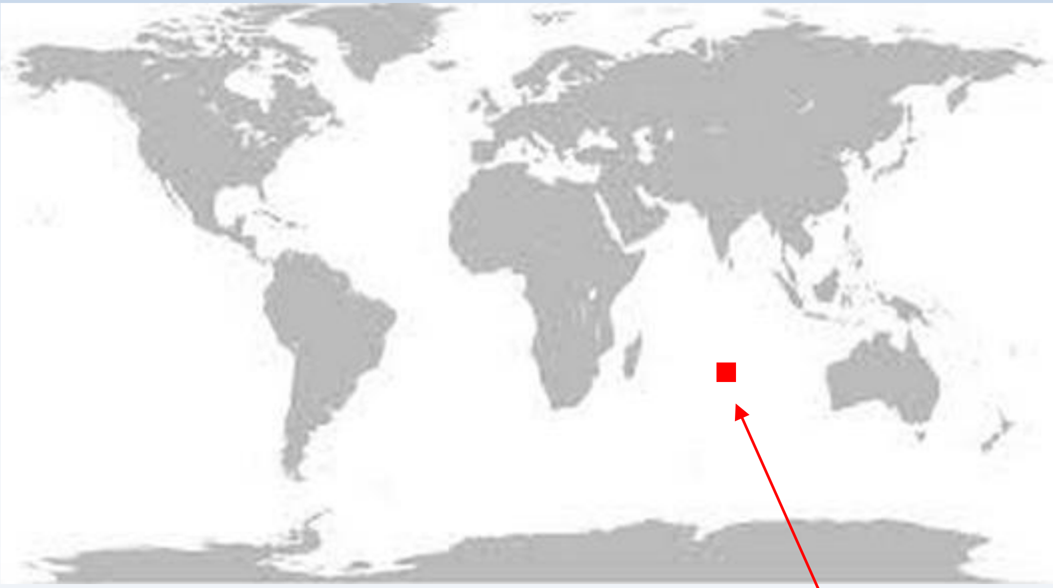


world energy consumption

average power of solar photovoltaics

$$\frac{16\ \mathrm{TW}}{30\ \mathrm{W/m^2}} \sim=$$

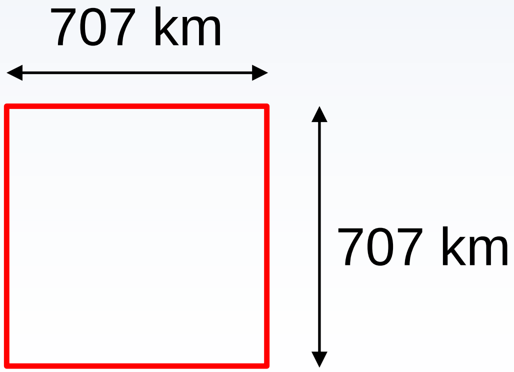
How much area is required to power the world ? (with nothing but solar photovoltaics)



world energy consumption

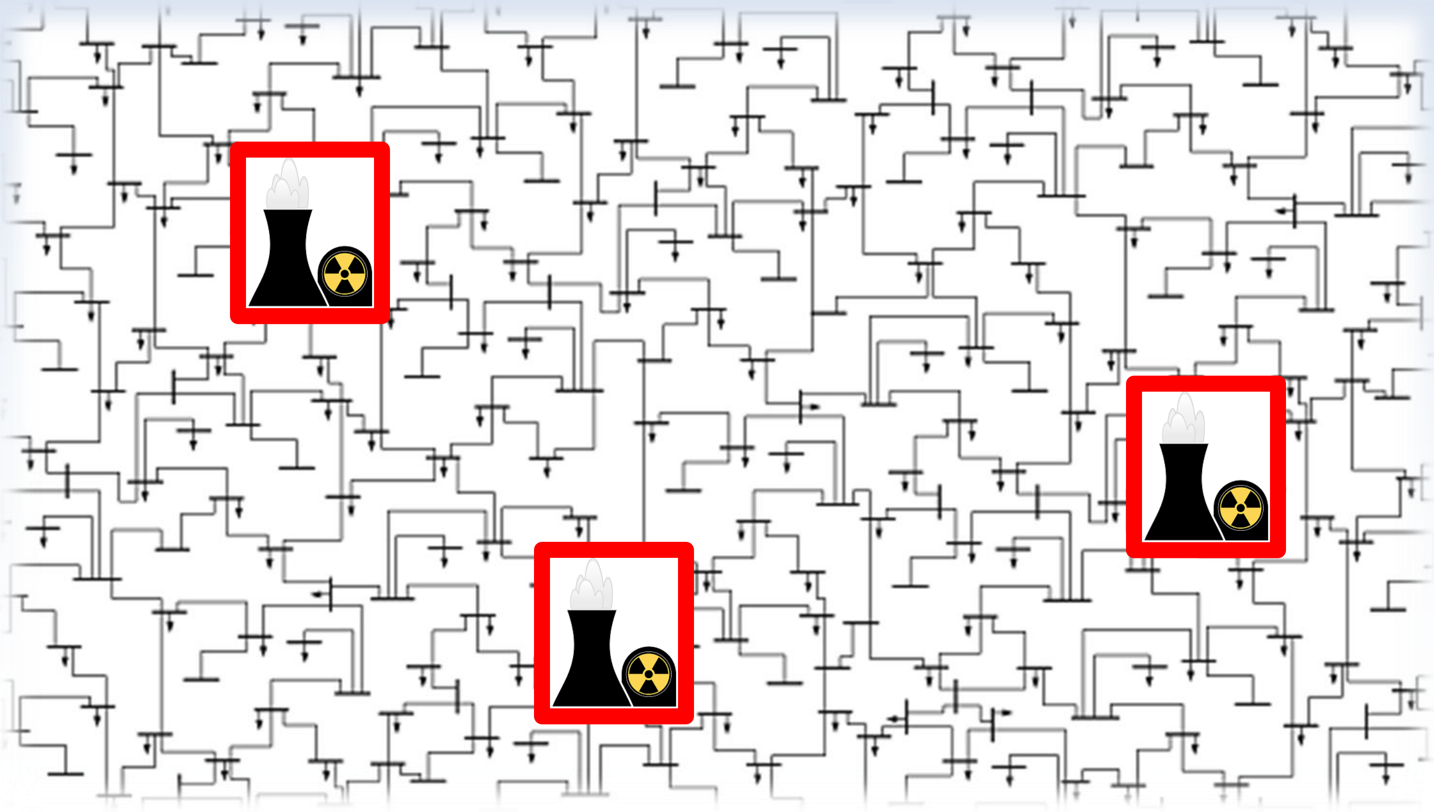
$$\frac{16\ \text{TW}}{30\ \text{W/m}^2} \sim= 500{,}000\ \text{km}^2$$

average power of solar photovoltaics



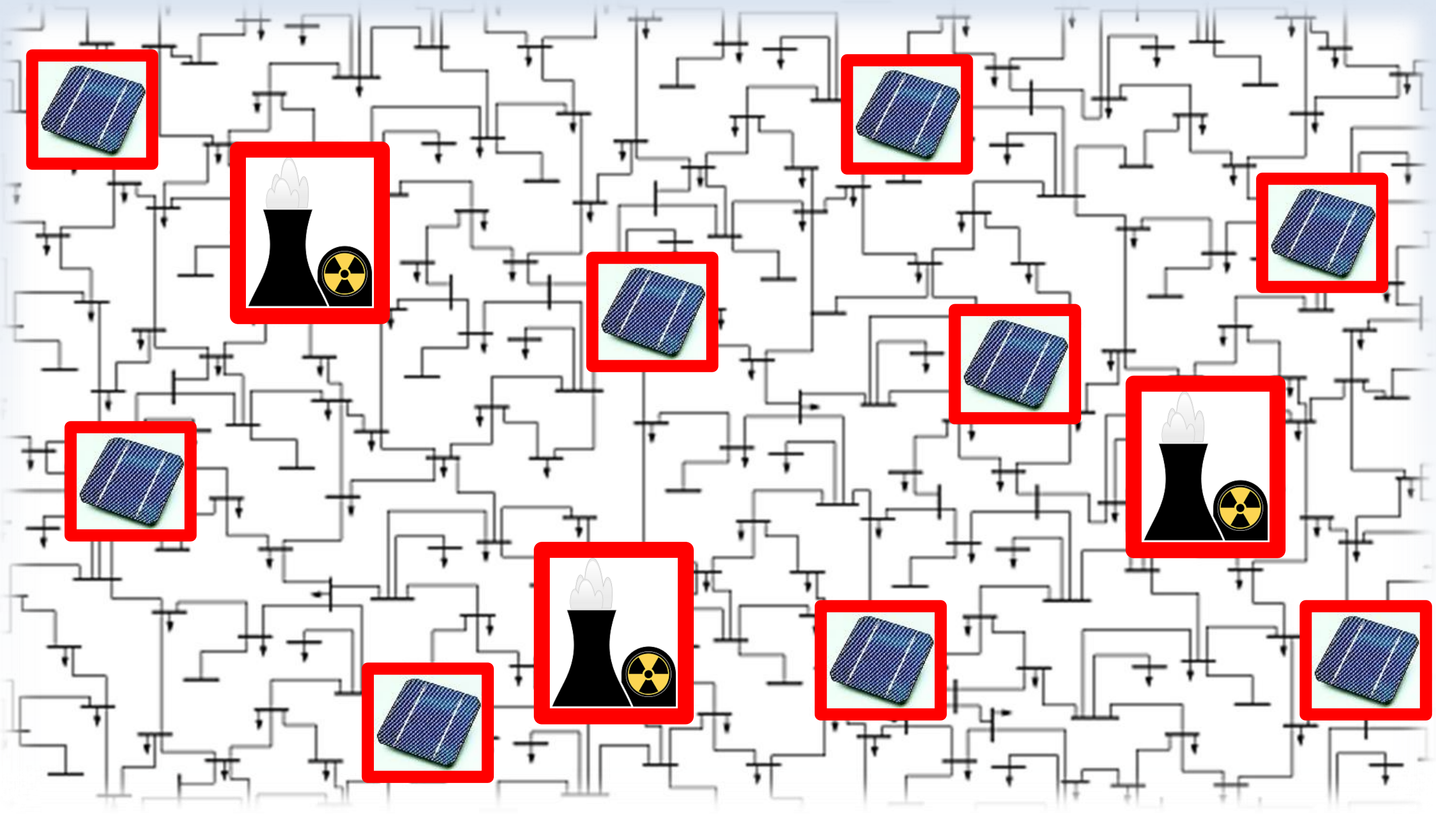
Today– Centralized Power Systems

- Few large power plants
- Efficient & economic – law of scale
- Easy to manage and control

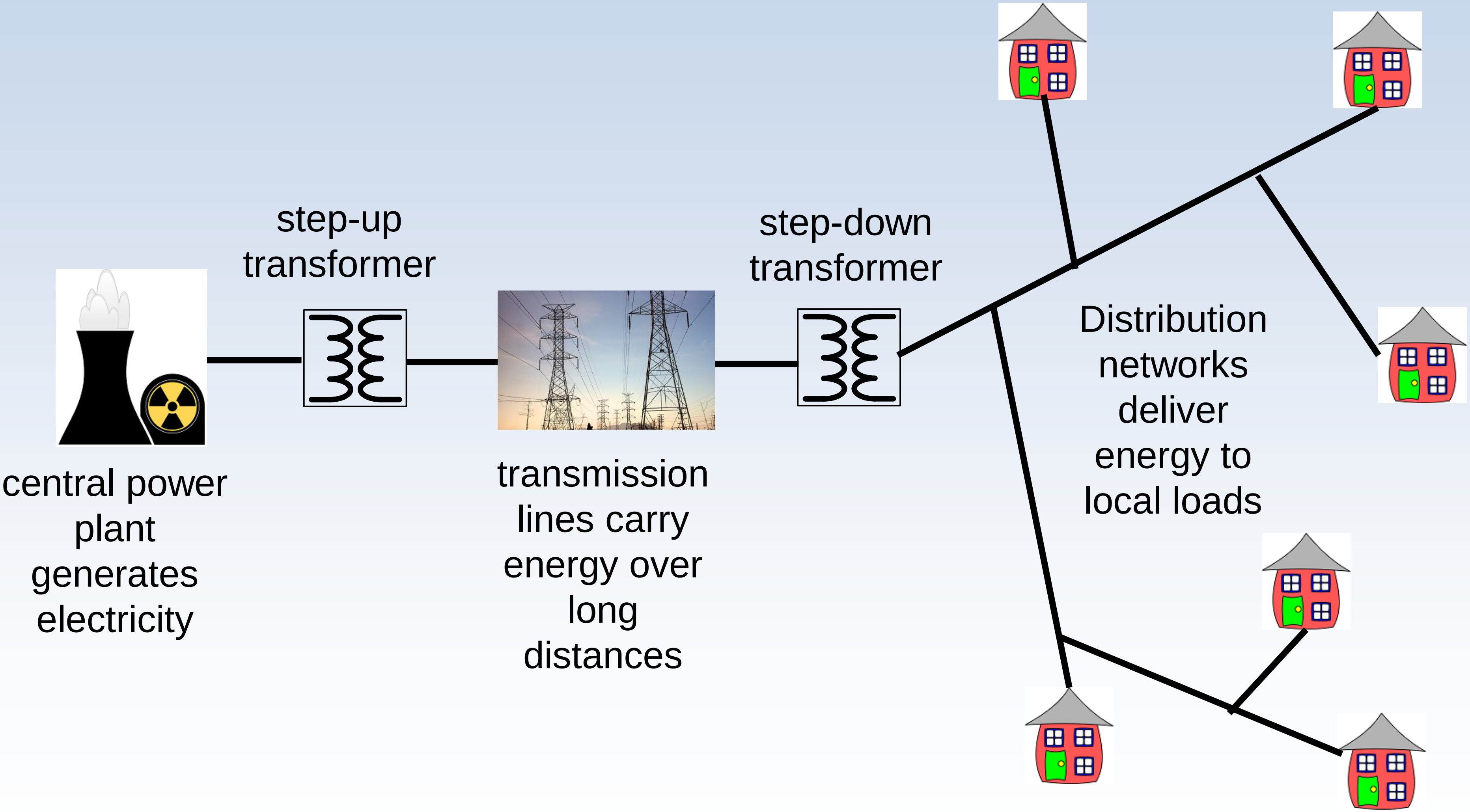


The Future? Distributed Power Systems

- Renewable energy sources are naturally distributed over large areas
- How does one control many independent sources, and make them work as a system ?



Centralized Power Systems - Structure



central power plant generates electricity

step-up transformer

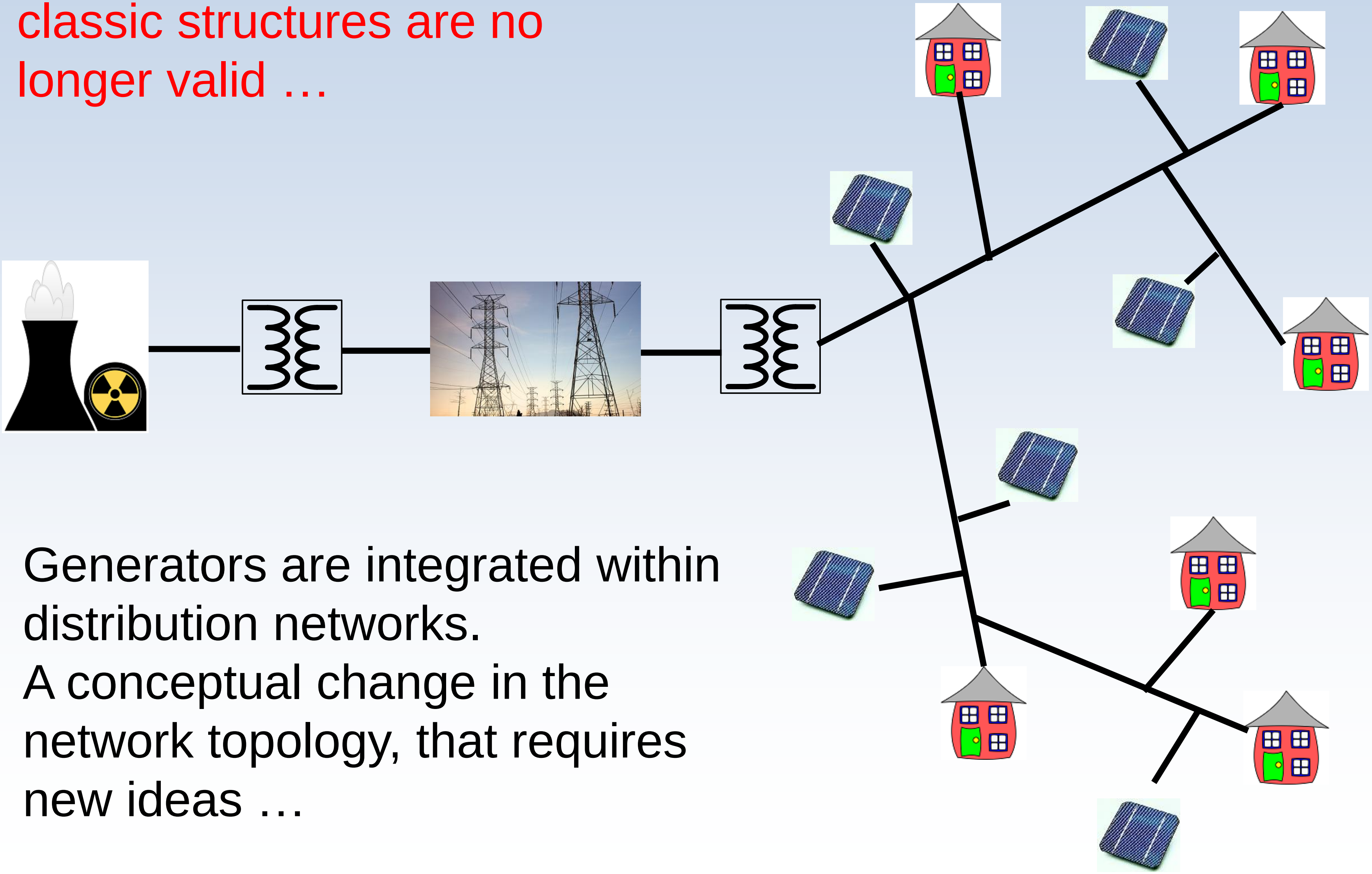
transmission lines carry energy over long distances

step-down transformer

Distribution networks deliver energy to local loads

Distributed Systems: Structure ?

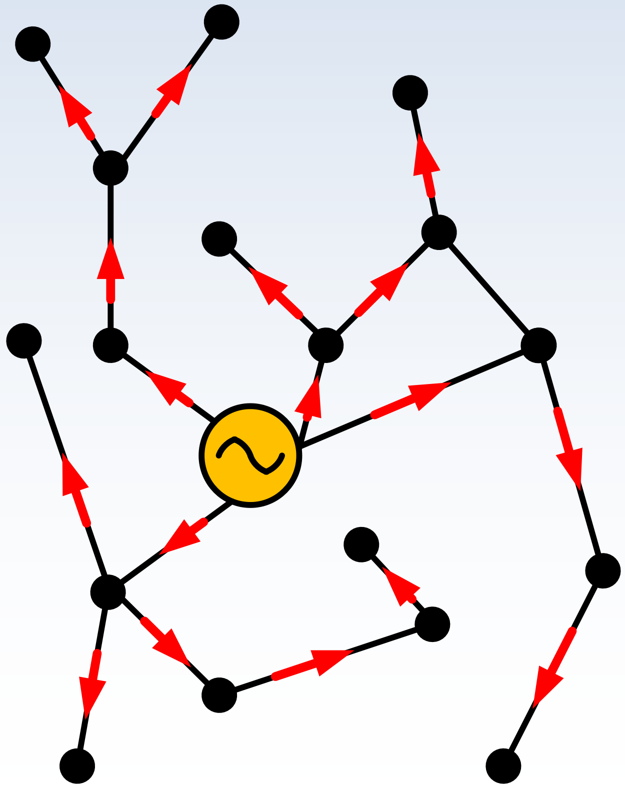
classic structures are no longer valid …



- Generators are integrated within distribution networks.
- A conceptual change in the network topology, that requires new ideas …

From Centralized to Distributed Power Systems

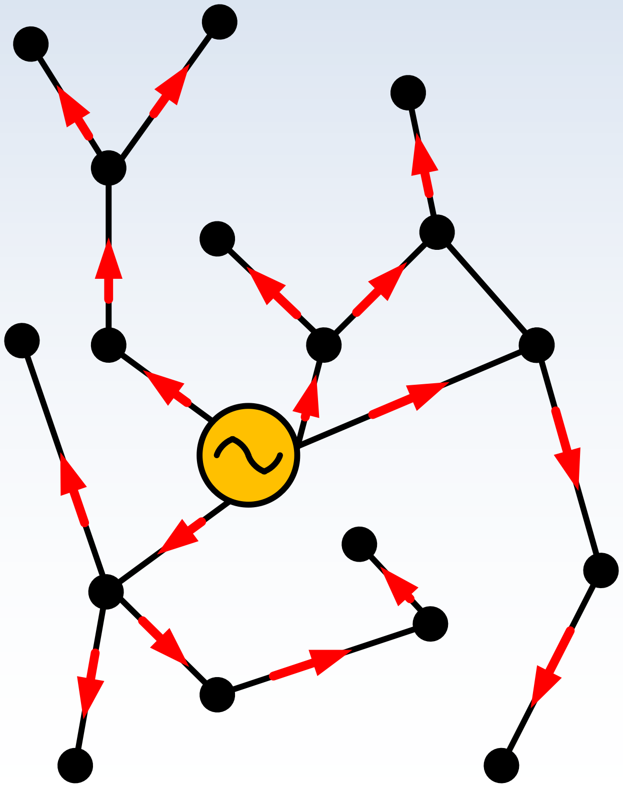
Today's Grid:
Centralized Topology
power flows from central power plants to loads



From Centralized to Distributed Power Systems

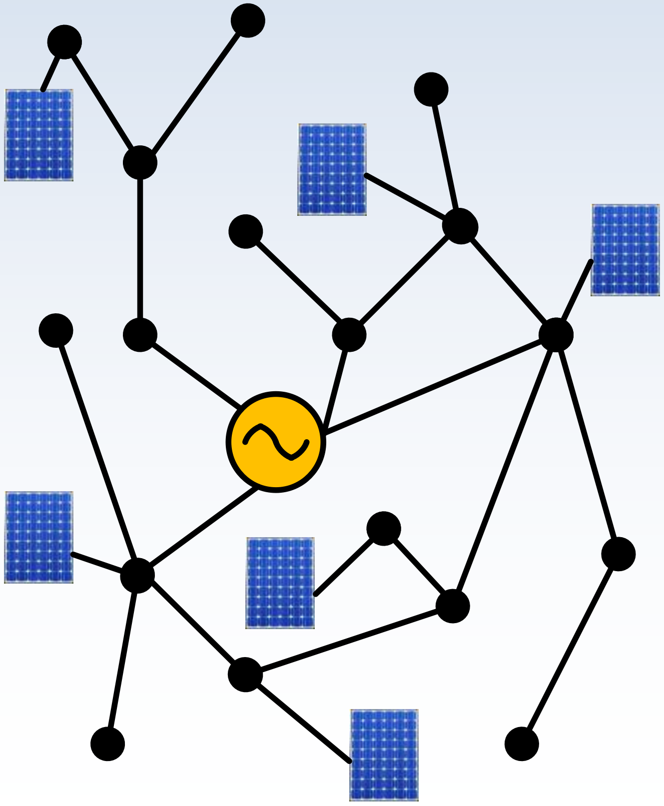
Today’s Grid:
Centralized Topology

power flows from central power plants to loads



Future Grid:
Distributed Topology ?

How will power flow ?

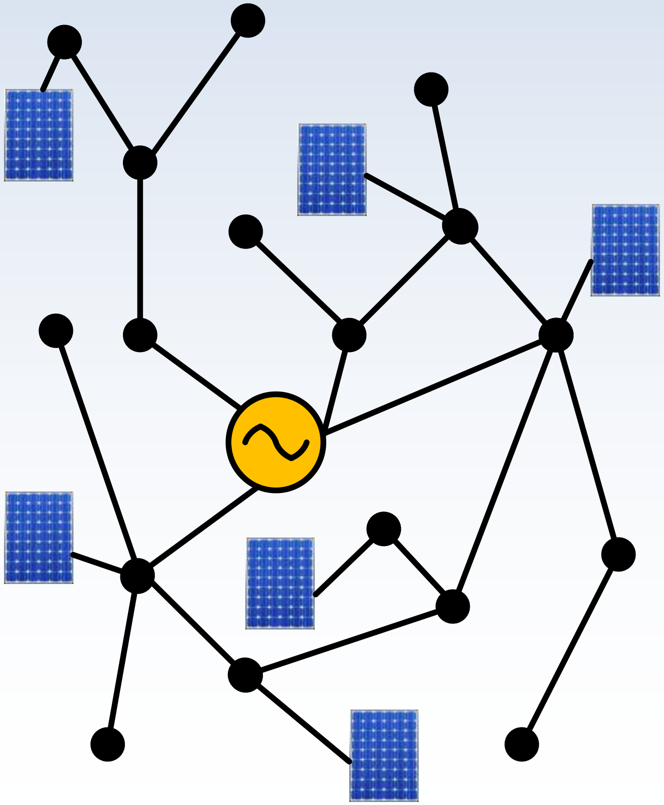


From Centralized to Distributed Power Systems

Future Grid:
Distributed Topology ?

Many Challenges:

- How do we control this network ?
- How do we design it ?
- How do we synchronize the elements to work together ?
- How does energy flows in such a network ?
- Is the network stable ?
- Is it reliable ?
- Is it efficient ?



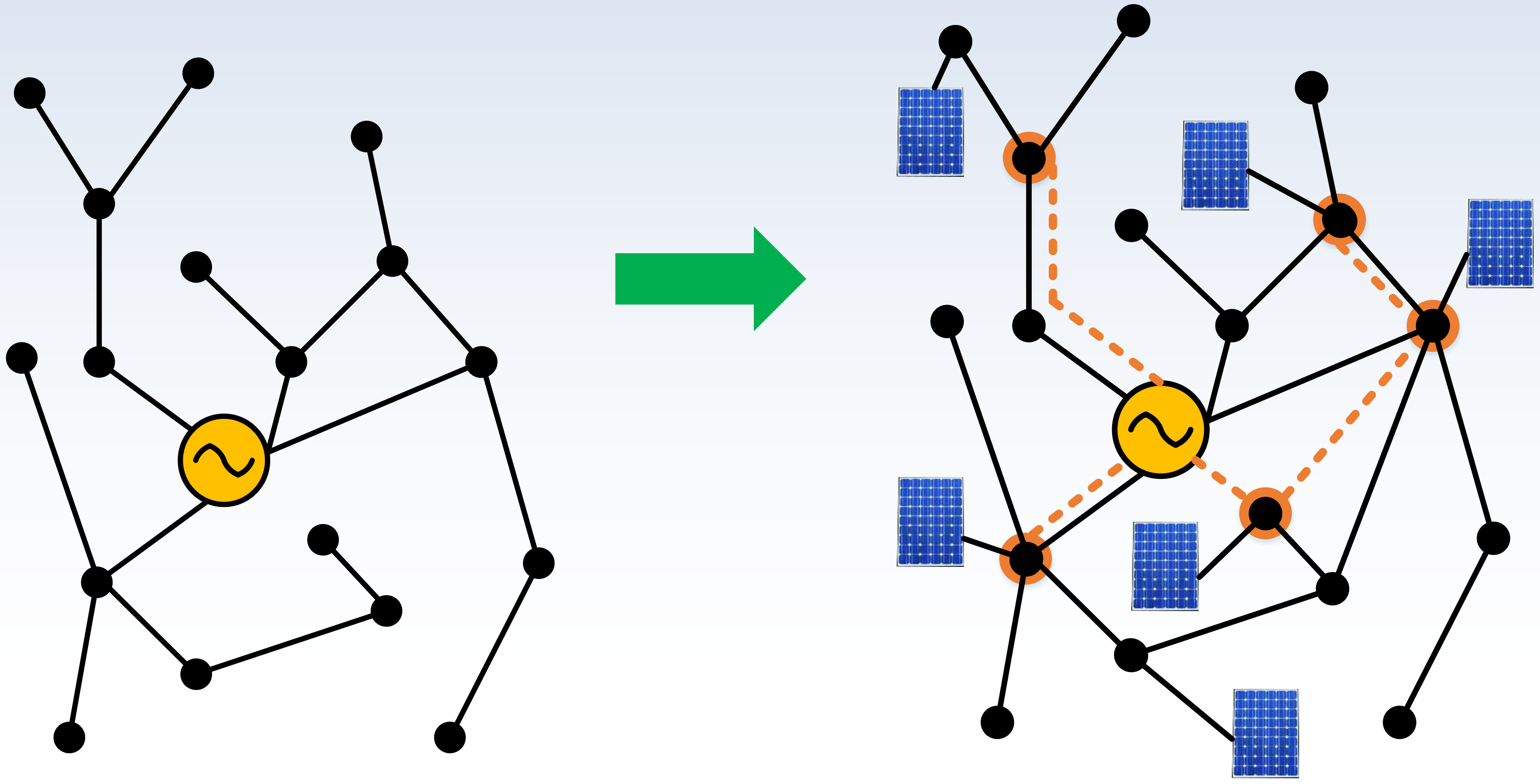
“Smart” Grids

The missing link: **Information Technology**

Power networks that are integrated with advanced capabilities of sensing, communication and control

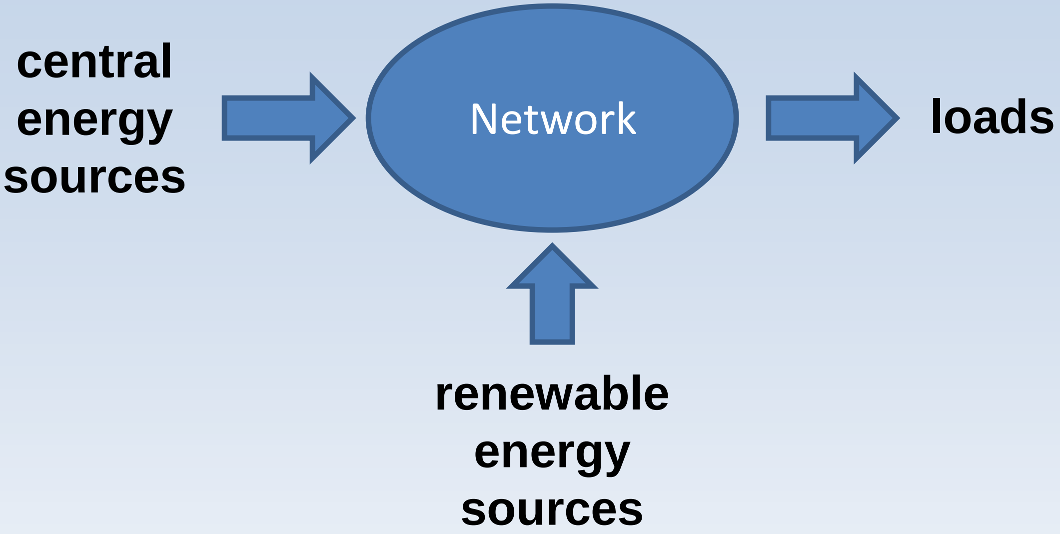
Today
Centralized “Passive” grids

The future - “smart” grids ?
Power networks combined with information networks



Distributed Generation – Challenges

Global energy balance must be maintained


central energy sources

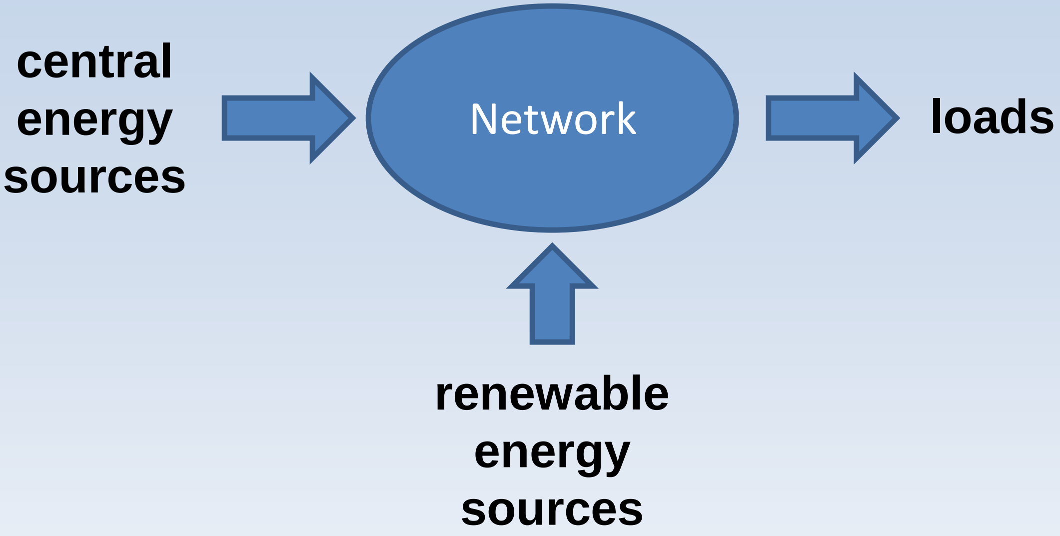
Network

loads

renewable energy sources

Distributed Generation –Challenges

Global energy balance must be maintained



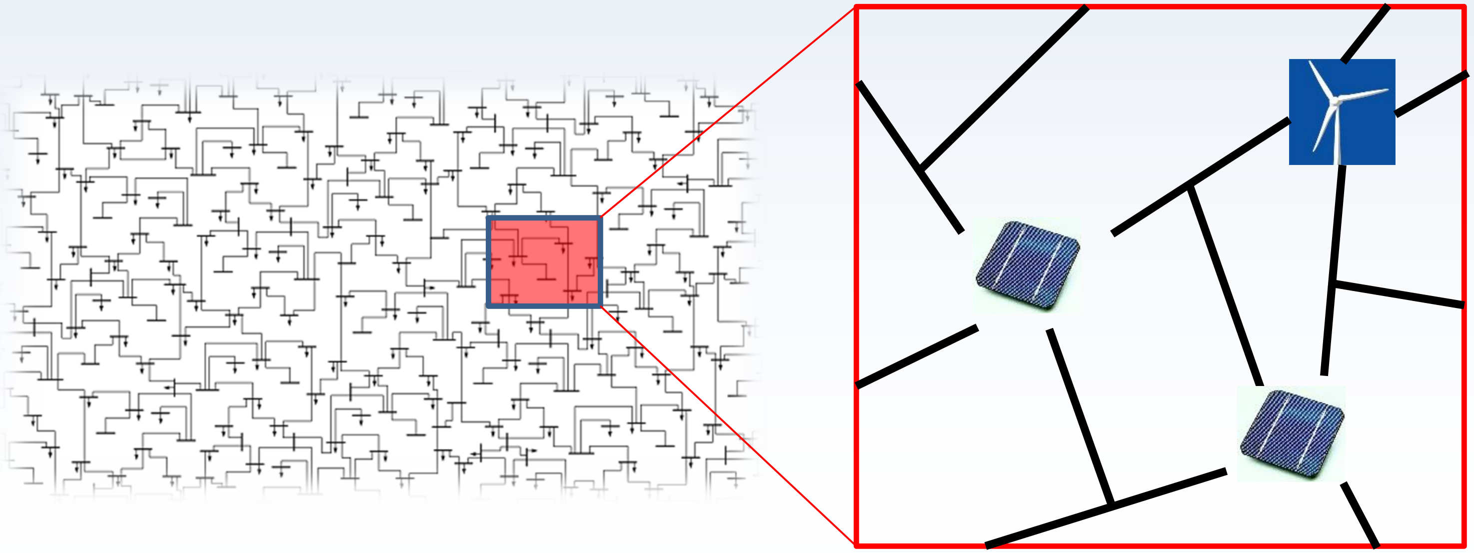
central energy sources

Network

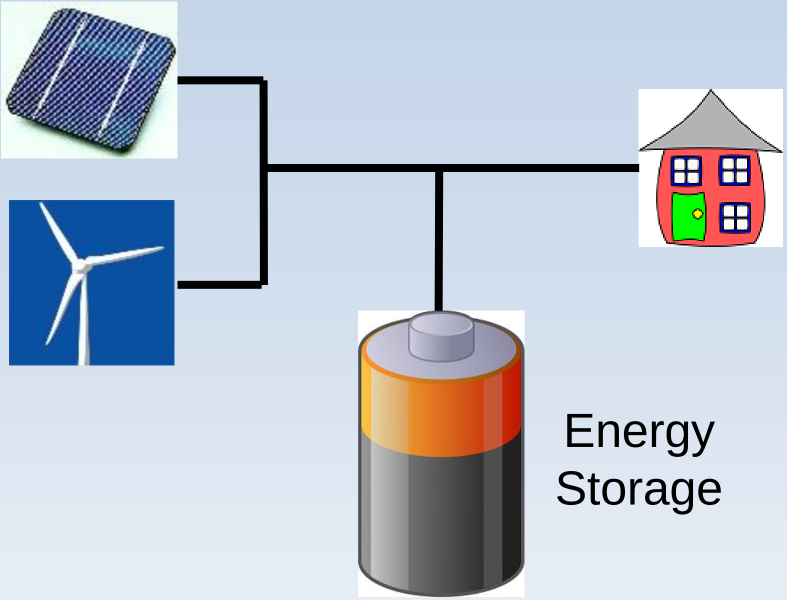
loads

renewable energy sources

Local stability must be maintained



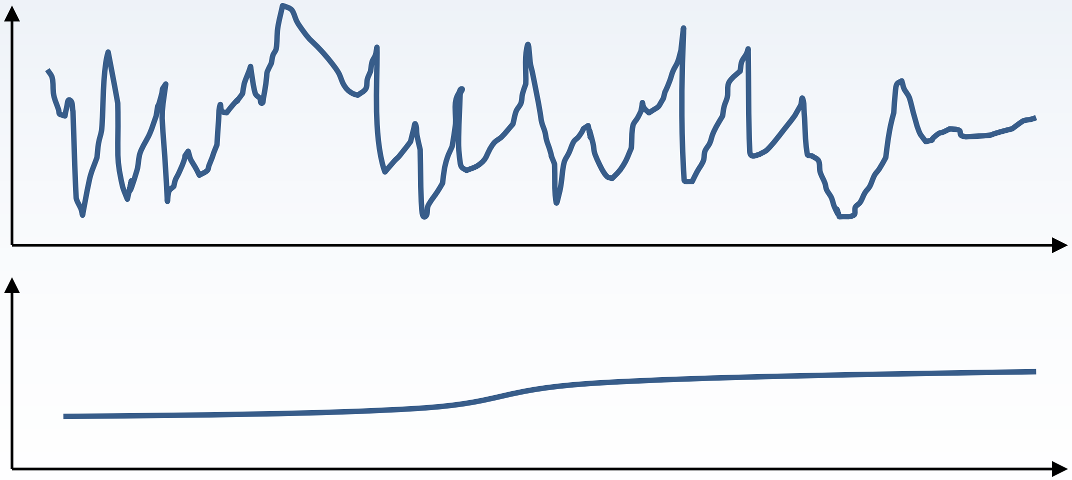
Energy Storage



renewable
energy sources

load

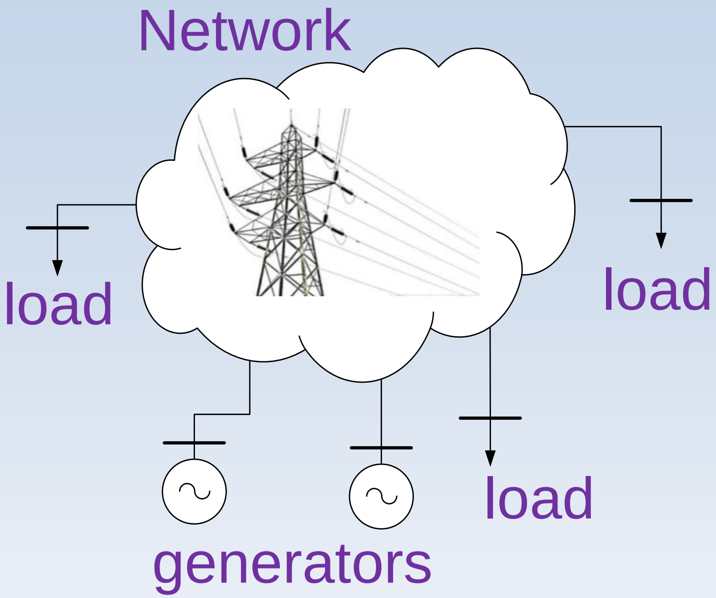
Energy
Storage

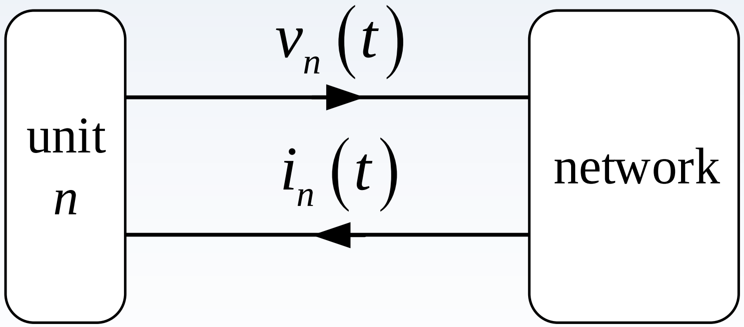


Energy
Balance
?

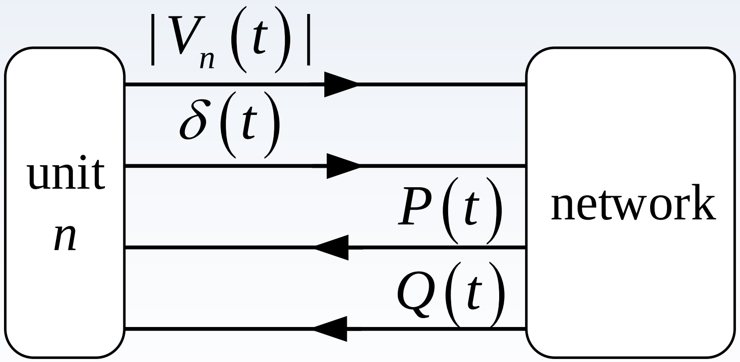
Studying Dynamic Events in Large Systems

How do we model dynamic events ?



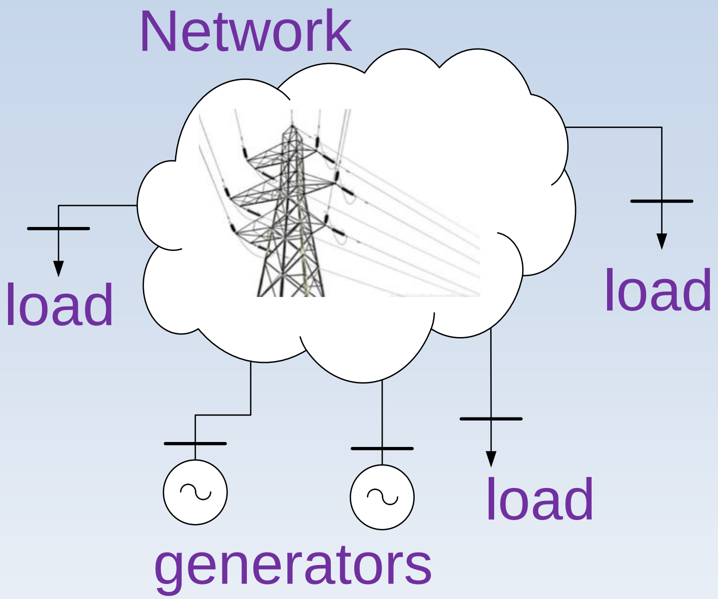


voltages & currents



amplitude, phase & powers

The Nonlinear Dynamics of Power Systems

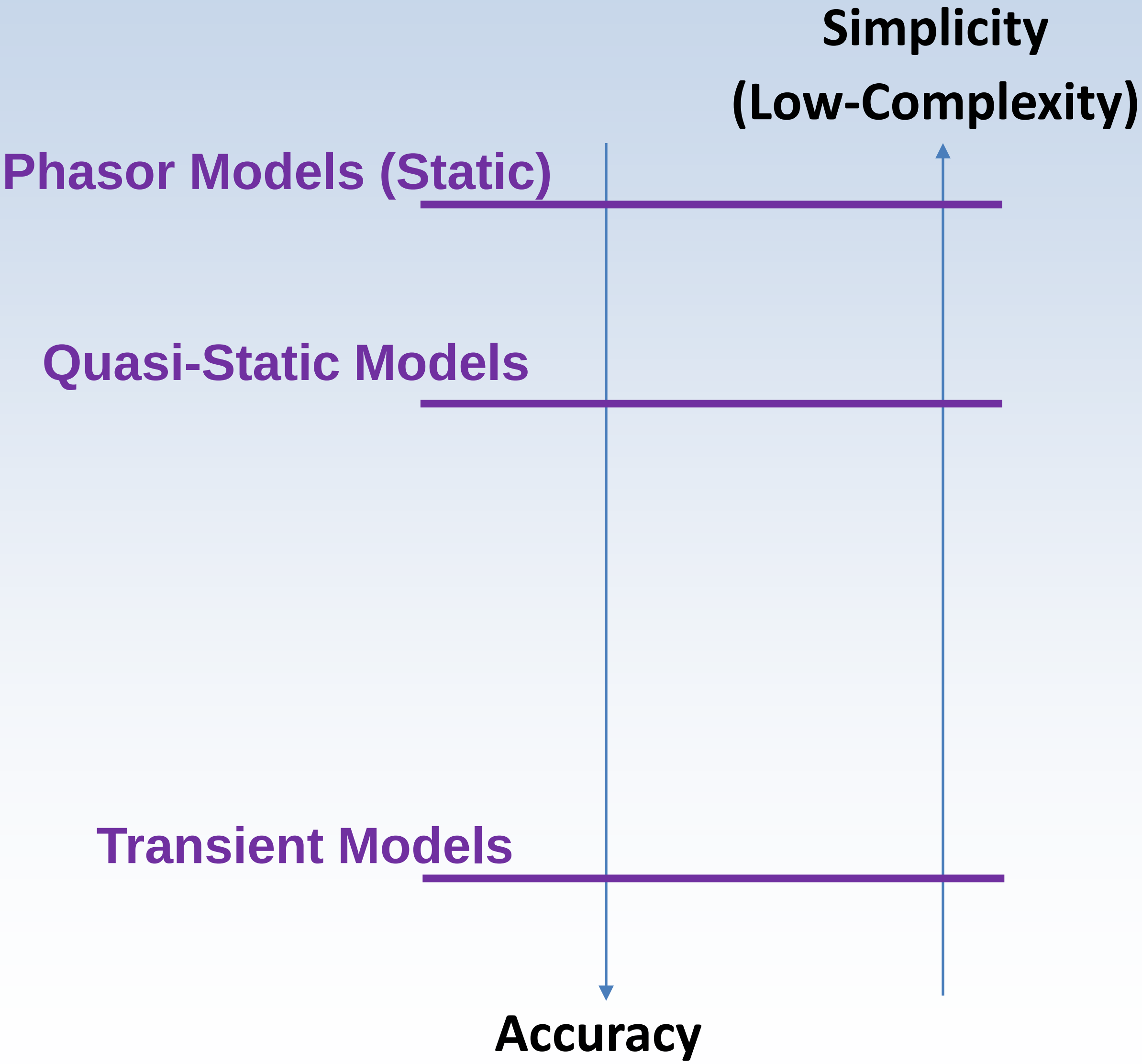


Why use two types of signals ?

- The generators & loads are nonlinear in voltages & currents.
- The network is nonlinear in powers, magnitudes and phases.

In both cases, the system is high-dimensional & nonlinear.

Common Types of Dynamic Models



Simplicity
(Low-Complexity)

Phasor Models (Static)

Quasi-Static Models

Transient Models

Accuracy

Transient Models

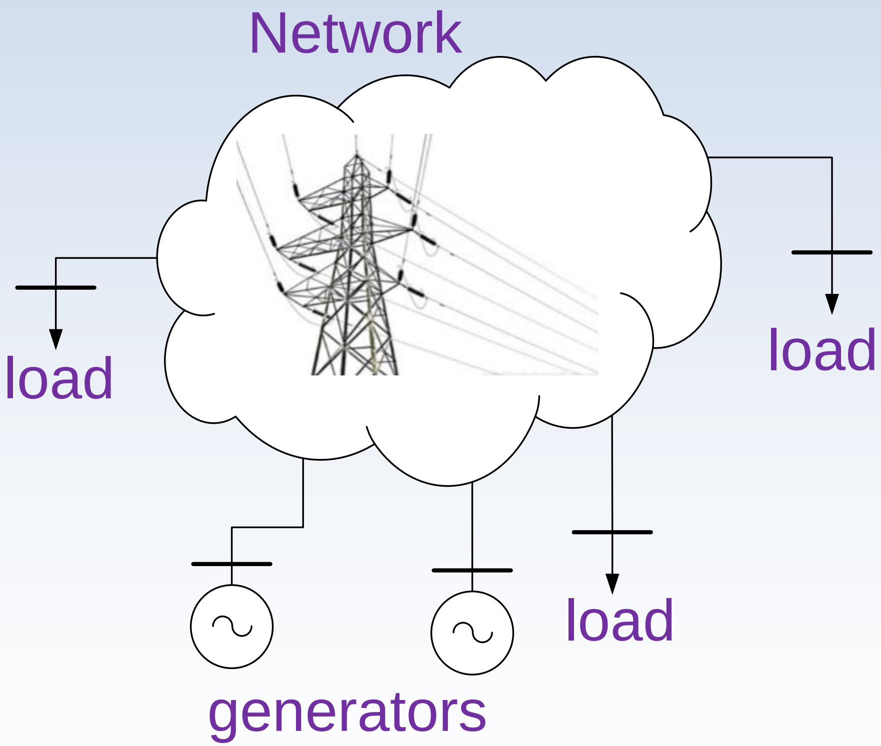
Fully detailed models, based on differential equations

High accuracy & High complexity

Differential equations

$$\frac{\mathrm{d}}{\mathrm{d}t}x = f\left(x, I\right)$$

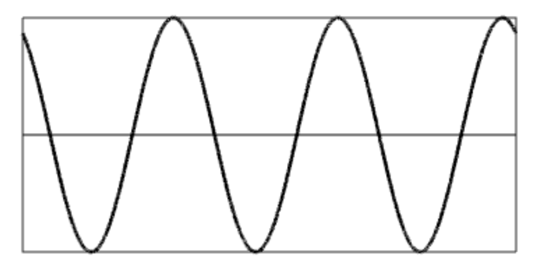
$$V = g\left(x, I\right)$$

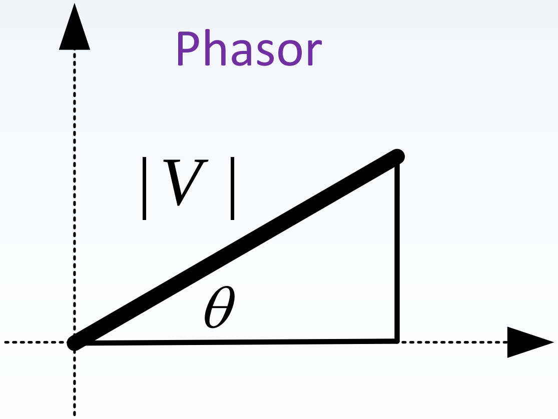


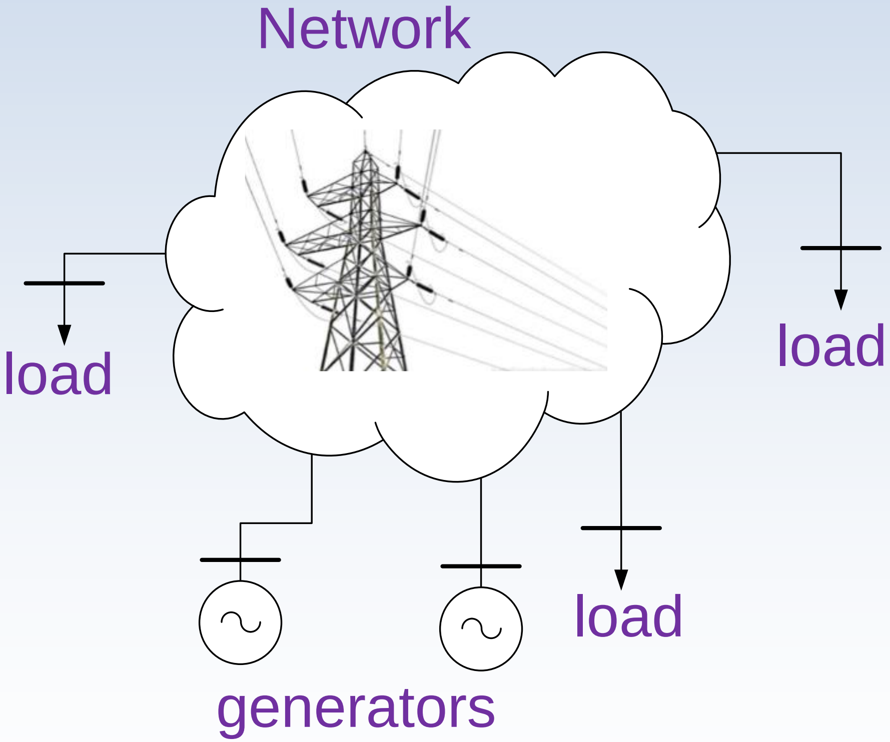
Phasor Models (Static)

Represent the system in steady-state using phasors

Only applies in steady-state, system dynamics ignored



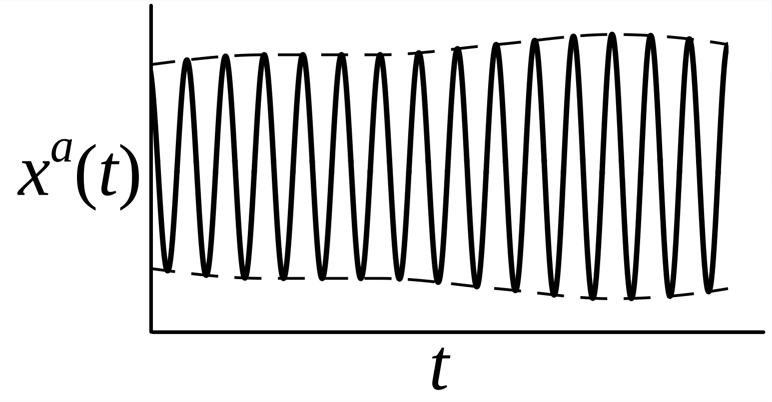


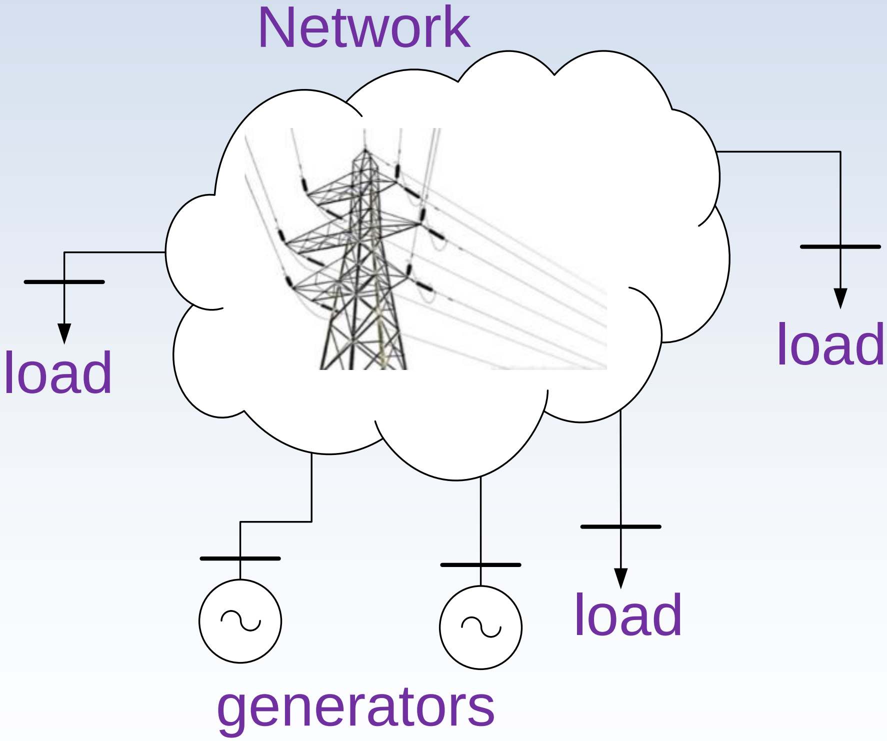


Quasi-Static Phasors

“Time-varying Phasors”

Main idea: assume that phasors vary “very-slowly” in comparison to 50/60 Hz, and use them to model dynamic events.

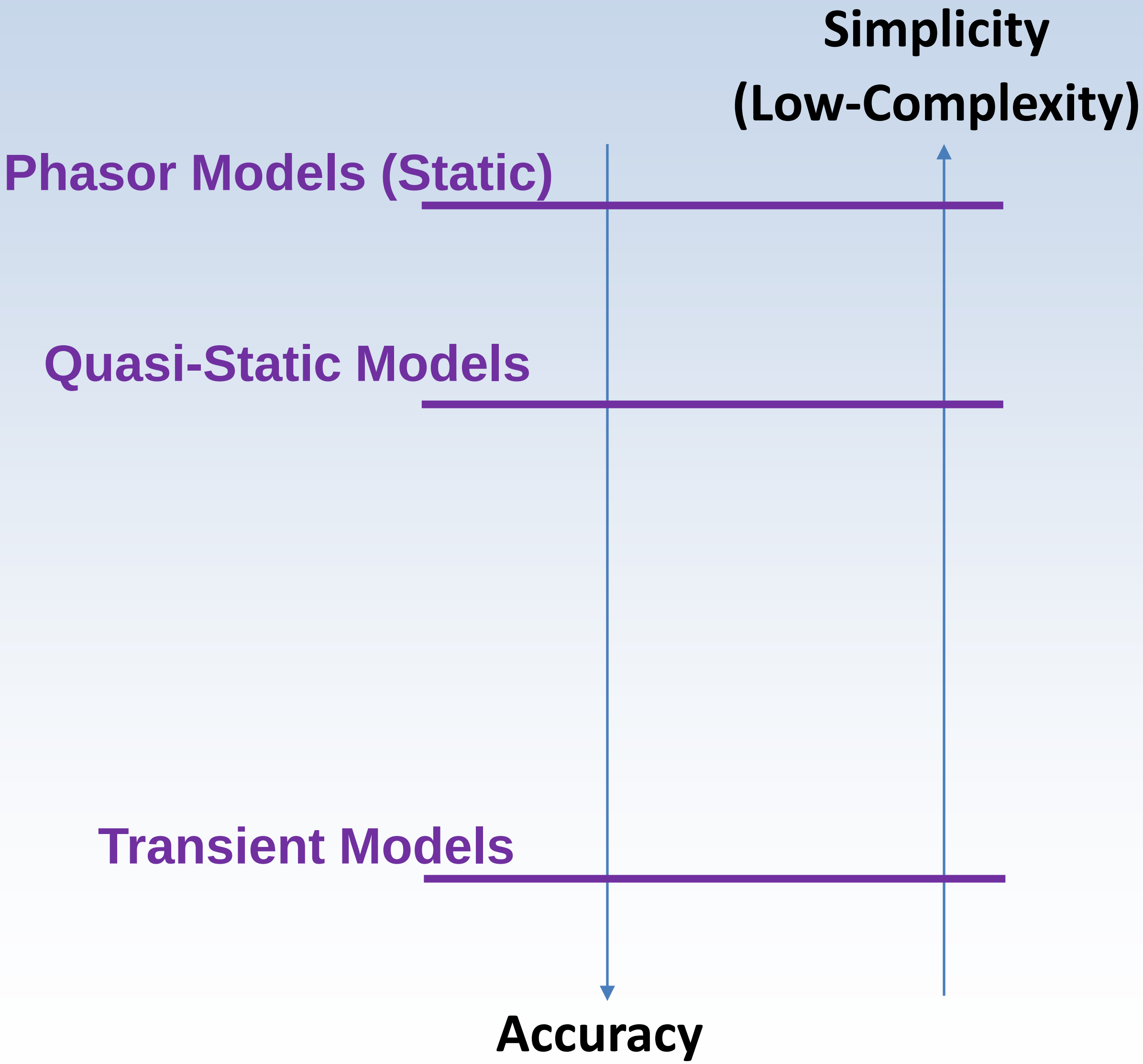




Modeling – Open Challenges

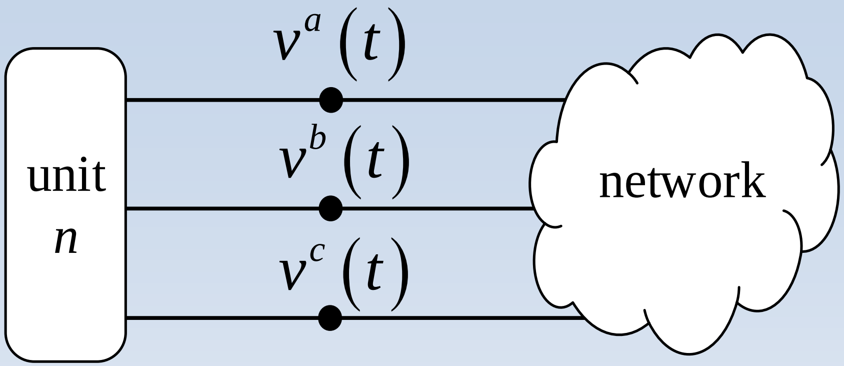
What we know today:

- **Static models** – Used most often
- **Transient models** – complex dynamics in small systems
- ***Quasi-static models* -** simulations of large power systems.



From static to dynamic phasors

Balanced
unit
(three-phase)

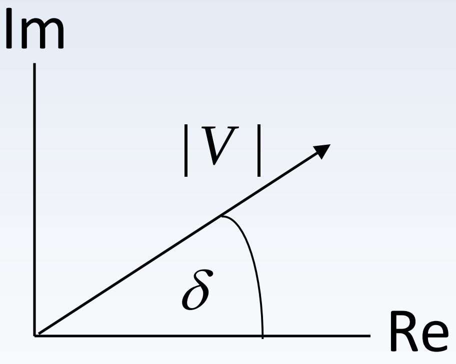


In balanced & static systems:

$$v^a(t) = \sqrt{2}\,|V|\cos(\omega_s t + \delta)$$
$$v^b(t) = \sqrt{2}\,|V|\cos(\omega_s t - 2\pi/3 + \delta)$$
$$v^c(t) = \sqrt{2}\,|V|\cos(\omega_s t + 2\pi/3 + \delta)$$

time-domain
a-b-c reference frame

equivalent
phasor



$$V = |V| \angle \delta$$

phasor

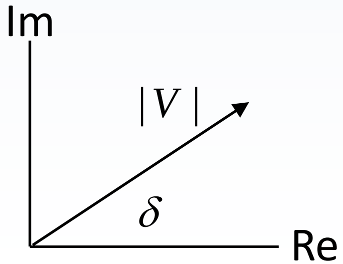
From static to dynamic phasors

Using few trigonometric identities:

$$v^a\left(t\right)=\sqrt{2}\,\underbrace{|V|\cos\left(\delta\right)}_{\mathrm{Re}\{V\}}\cos\left(\omega_s t\right)-\sqrt{2}\underbrace{|V|\sin\left(\delta\right)}_{\mathrm{Im}\{V\}}\sin\left(\omega_s t\right)$$

$$v^b\left(t\right)=\sqrt{2}\,\underbrace{|V|\cos\left(\delta\right)}_{\mathrm{Re}\{V\}}\cos\left(\omega_s t-2\pi/3\right)-\sqrt{2}\underbrace{|V|\sin\left(\delta\right)}_{\mathrm{Im}\{V\}}\sin\left(\omega_s t-2\pi/3\right)$$

$$v^c\left(t\right)=\sqrt{2}\,\underbrace{|V|\cos\left(\delta\right)}_{\mathrm{Re}\{V\}}\cos\left(\omega_s t-2\pi/3\right)-\sqrt{2}\underbrace{|V|\sin\left(\delta\right)}_{\mathrm{Im}\{V\}}\sin\left(\omega_s t-2\pi/3\right)$$

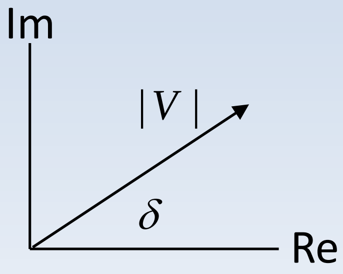


From static to dynamic phasors (cont.)

In matrix form:

$$\begin{pmatrix} v^a(t) \\ v^b(t) \\ v^c(t) \end{pmatrix} = \begin{pmatrix} \cos(\omega_s t) & -\sin(\omega_s t) & 1 \\ \cos(\omega_s t - 2\pi/3) & -\sin(\omega_s t - 2\pi/3) & 1 \\ \cos(\omega_s t + 2\pi/3) & -\sin(\omega_s t + 2\pi/3) & 1 \end{pmatrix} \begin{pmatrix} \sqrt{2}\,\mathrm{Re}\{V\} \\ \sqrt{2}\,\mathrm{Im}\{V\} \\ 0 \end{pmatrix}$$

Phasor components

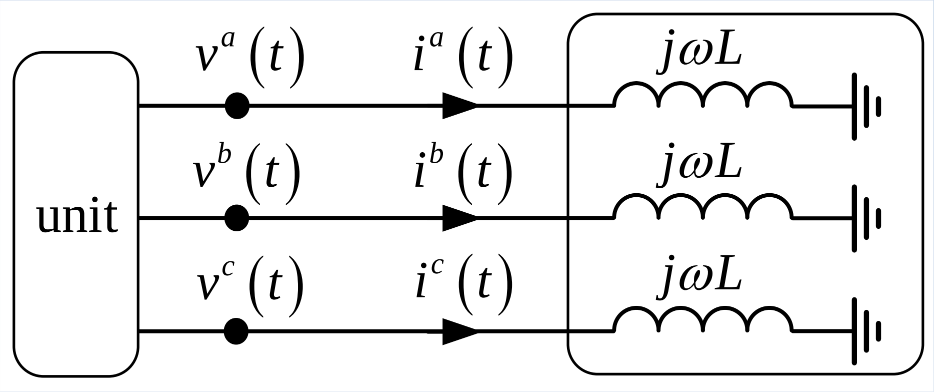


Quasi-static phasor :

$$\boxed{V(t) = \mathrm{Re}\{V(t)\} + j\,\mathrm{Im}\{V(t)\}}$$

Modeling with Dynamic Phasors

Here is a simple example:



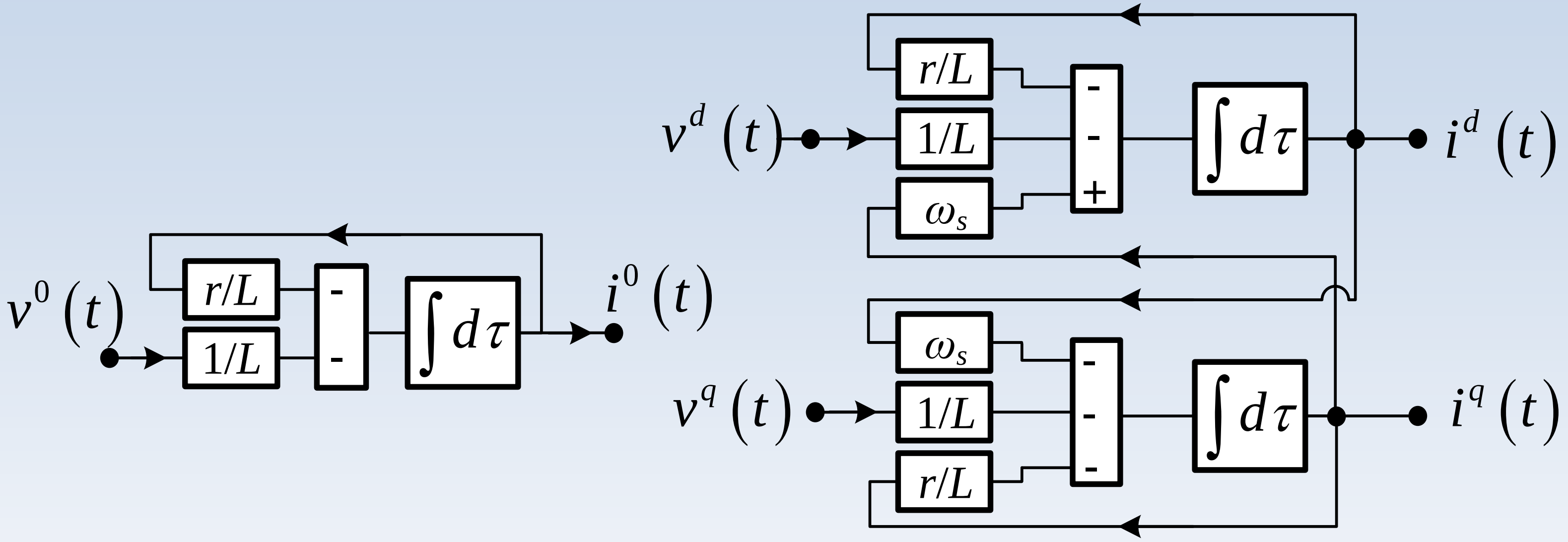
<u>quasi-static model</u>

$$V = jX_L I = j\omega_s LI$$

Or,

$$\mathrm{Re}\{V(t)\} = -\omega_s L \cdot \mathrm{Im}\{I(t)\}$$
$$\mathrm{Im}\{V(t)\} = \omega_s L \cdot \mathrm{Re}\{I(t)\}$$

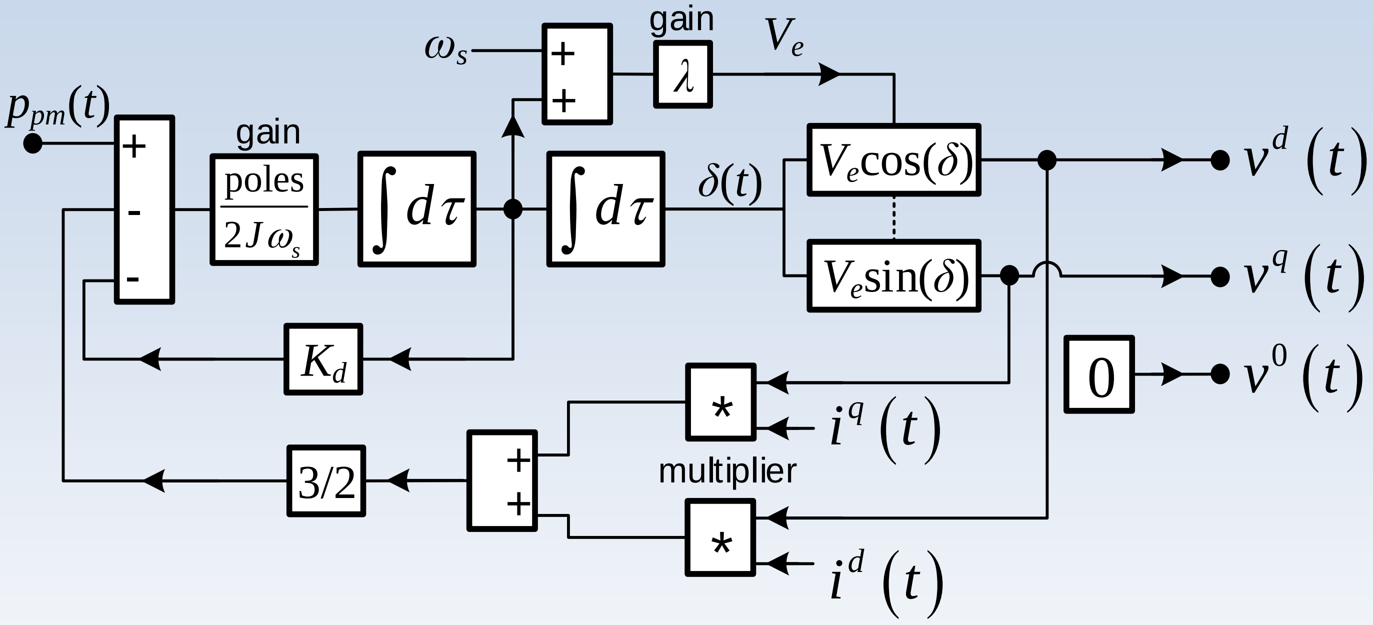
Modeling – Symmetric Three-Phase Series Load



- Complete model of a three-phase series R-L load:

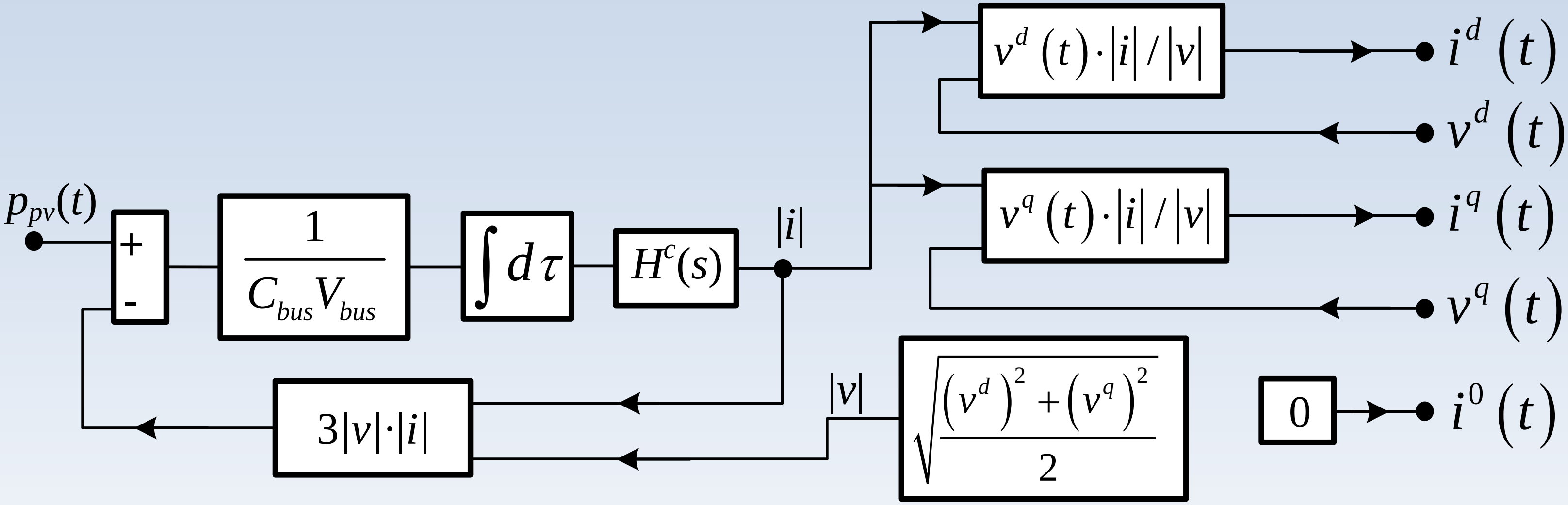
$$Z = r + j\omega L$$

Modeling – the Synchronous Generator



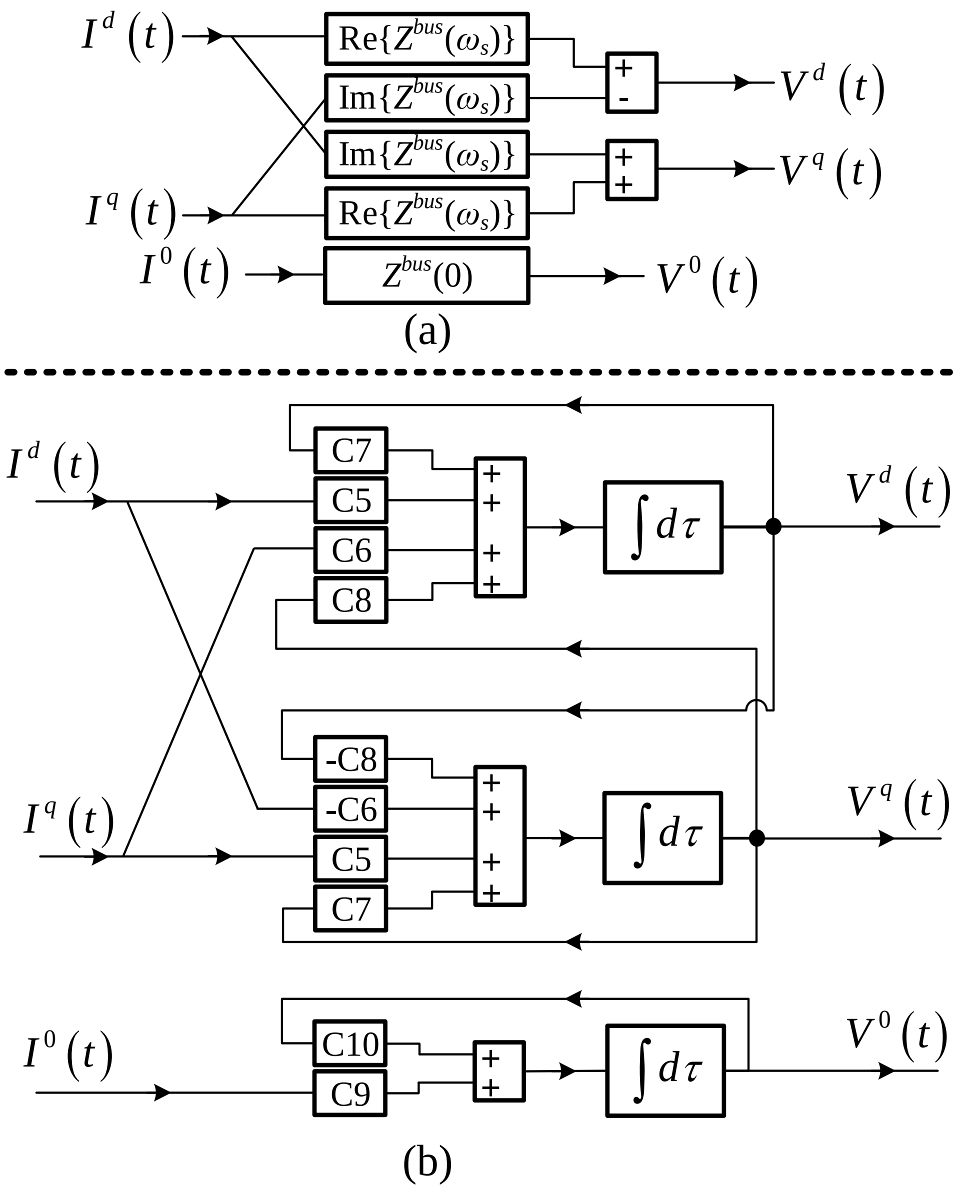
- Model based on the *swing equation.*
- Corresponds to a variable-frequency voltage source.
- Synchronous impedance (Z_s) is not included.
- More detailed models are available in the literature.

Modeling – Photovoltaic Three-Phase Inverter



- Model of a typical power electronics inverter.
- Power factor is unity (zero reactive power)
- Model based on energy balance in the internal *bus capacitor.*

Low Complexity Dynamic Models



Quasi-Static Model
(zero order Taylor series)

First-order model
(first order Taylor series)

- **More accurate, yet**
- **Simple & Linear**

Numerical Results

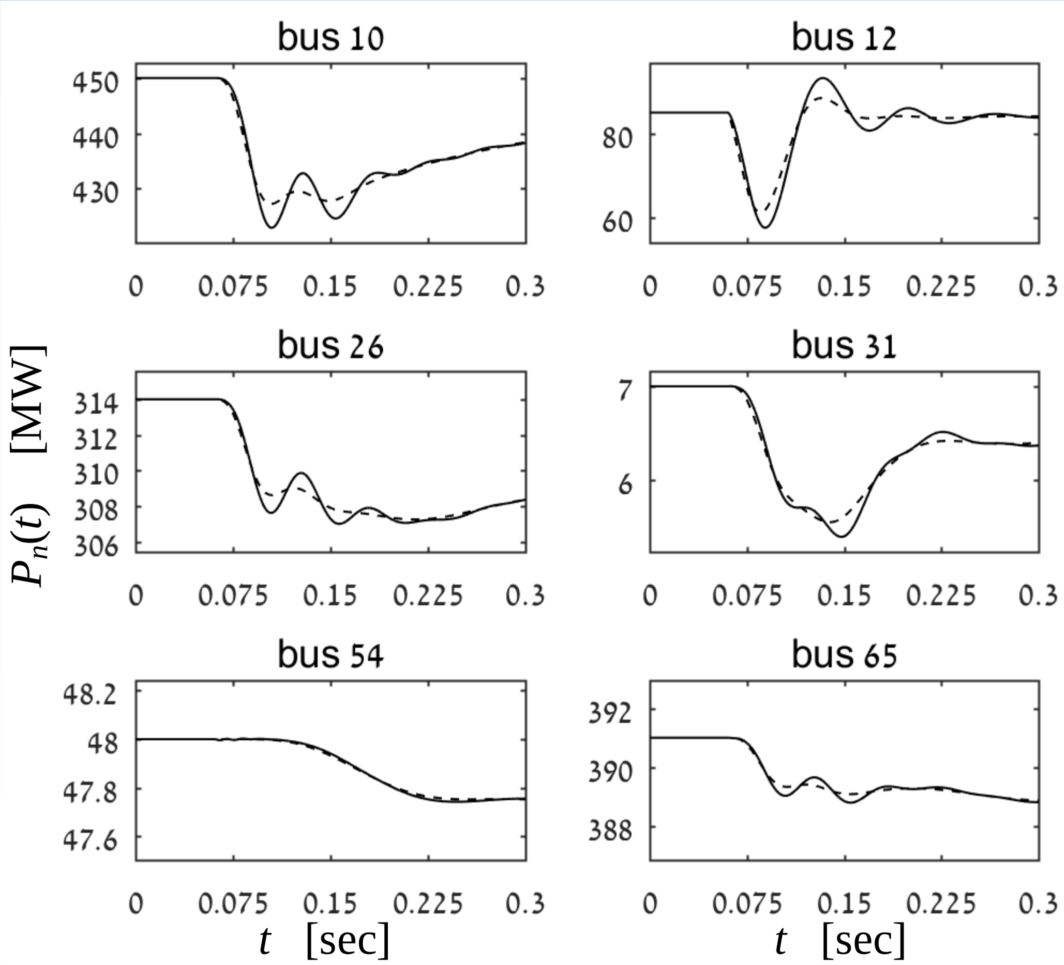
118 bus system,
active power of
several generators

quasi-static model

------------ (dashed)

First-order model

(solid)



Numerical Results

57 bus system, active power of several generators

quasi-static model

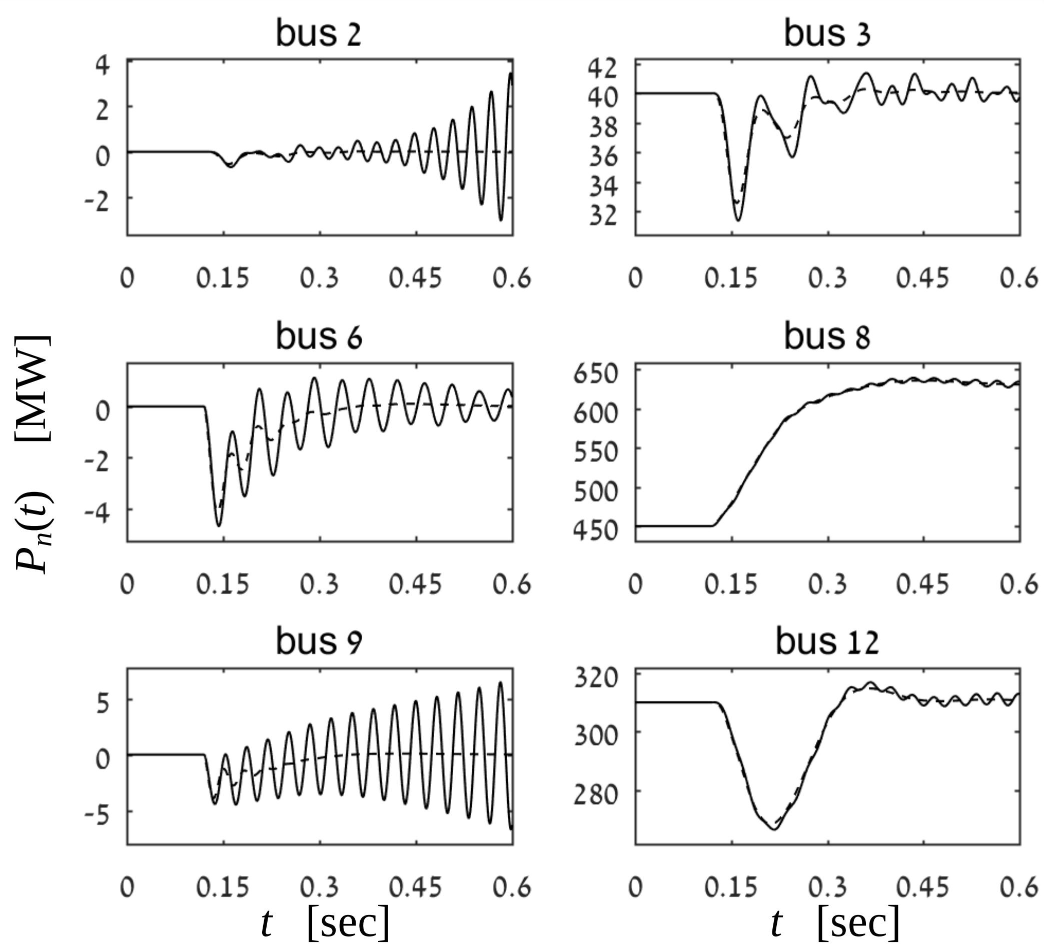
------------ (dashed)

First-order model

———— (solid)

quasi-static model: stable
first-order model: unstable

(which model is correct?)



Numerical Results

Simulation Run-Time, ms/s

	3 BUS NETWORK	9 bus network	30 bus net.	57 bus net.	118 bus net.
Transient model	289.6	956.2	-	-	-
First-order dq0 model (M=1)	20.5	37.2	40.4	137	289.8
Quasi-static model (M=0)	9.8	15.6	22.4	24.6	100.4

Order of magnitude improvement in simulation run- time compared to transient models.

דיון

- מערכות אנרגיה מתקדמות חיוניות לעתיד של מדינת ישראל.
- מערכות אנרגיה מתקדמות נמצאות בחזית המחקר והפיתוח העולמי.

איך אנחנו מסבירים את זה לתלמידים שלנו ?