9 Smart Grid: Governor Control

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Outline

- Introduction to smart grids
  - Smart energy system
  - Smart information system
  - Smart communication system
- Speed governor control
- Distribution network control

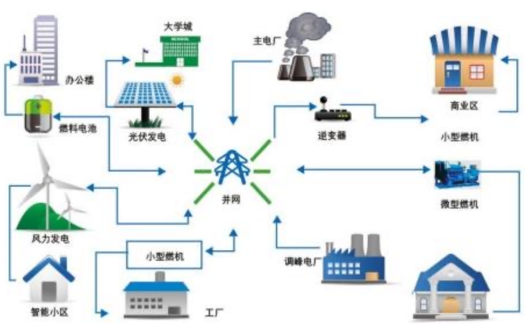
- Fang, X., Misra, S., Xue, G., & Yang, D. (2011). Smart grid—The new and improved power grid: A survey. *IEEE communications surveys & tutorials*, *14*(4), 944-980.
- Shelar, D., & Amin, S. (2016). Security assessment of electricity distribution networks under DER node compromises. *IEEE Transactions on Control of Network Systems*, *4*(1), 23-36.

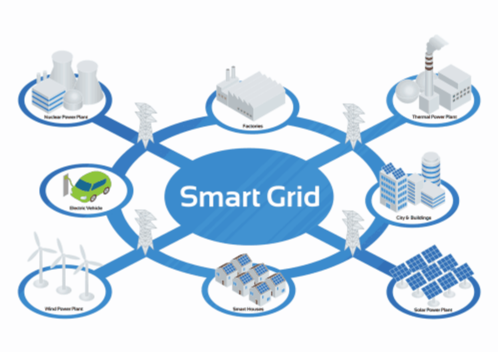
Grid

Traditionally, the term grid is used for an electricity system that may support all or some of the following four operations:

1. electricity generation,
2. electricity transmission,
3. electricity distribution,
4. electricity control.

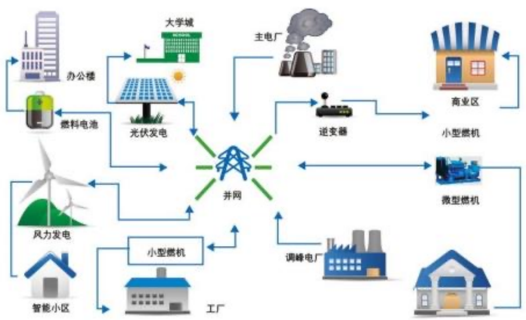
- Smart grid (SG): an enhancement of the 20th century power grid.
- The traditional power grids are generally used to carry power from a few central generators to a large number of users or customers.
- In contrast, the SG uses two-way flows of electricity and information to create an automated and distributed advanced energy delivery network.

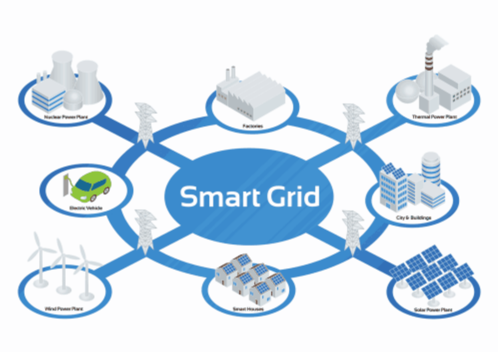




Smart grid

- The Smart Grid, regarded as the next generation power grid, uses two-way flows of electricity and information to create a widely distributed automated energy delivery network.
- Enabling technologies for the Smart Grid: three major systems
  1. smart infrastructure system,
  2. smart management system,
  3. smart protection system.

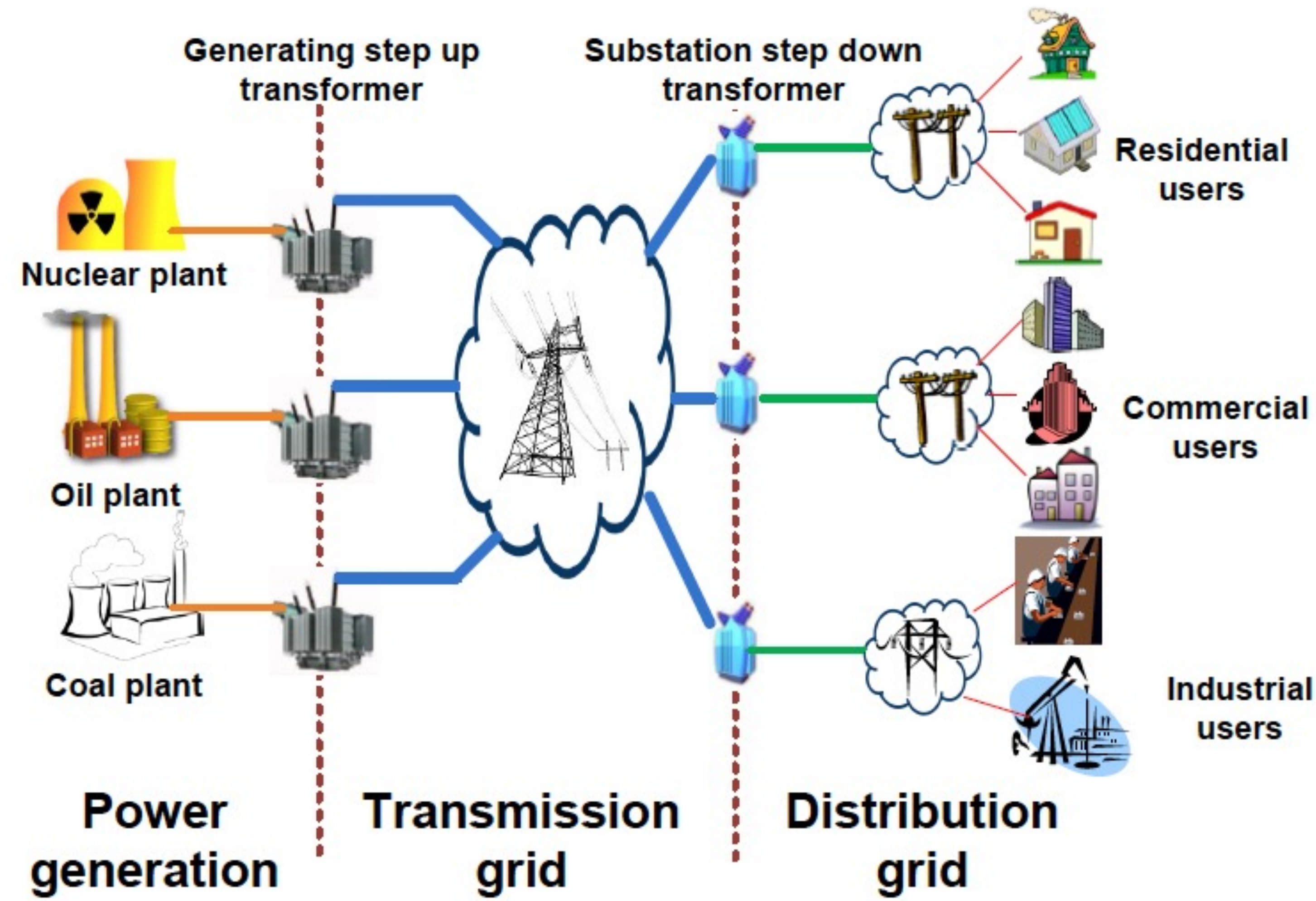




Old grid vs. smart grid

Existing Grid	Smart Grid
Electromechanical	Digital
One-way communication	Two-way communication
Centralized generation	Distributed generation
Few sensors	Sensors throughout
Manual monitoring	Self-monitoring
Manual restoration	Self-healing
Failures and blackouts	Adaptive and islanding
Limited control	Pervasive control
Few customer choices	Many customer choices

Traditional power grid



Traditional power grid

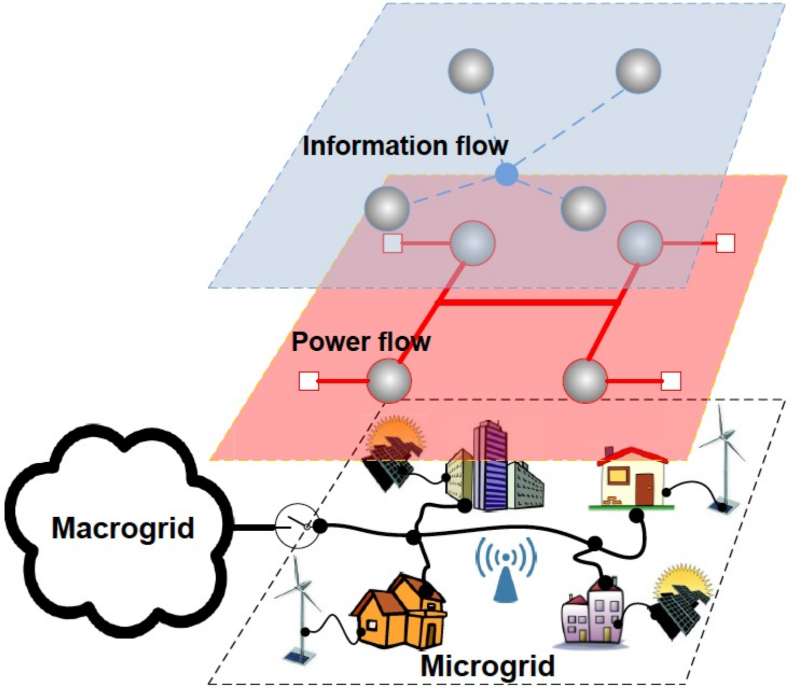
- The traditional power grid is unidirectional in nature.
- Electricity is often generated at a few central power plants by electromechanical generators, primarily driven by the force of flowing water or heat engines fueled by chemical combustion or nuclear power.
- In order to take advantage of the *economies of scale*, the generating plants are usually quite large and located away from heavily populated areas.
- Economies of scale: cost reductions that occur when companies increase production.
  - The fixed costs, like administration, are spread over more units of production.
  - Sometimes the company can negotiate to lower its variable costs as well.

Traditional power grid

- The transmission grid moves the power over long distances to substations.
- Upon arrival at a substation, the power will be stepped down from the transmission level voltage to a distribution level voltage.
- As the power exits the substation, it enters the distribution grid.
- Finally, upon arrival at the service location, the power is stepped down again from the distribution voltage to the required service voltage(s).

Smart grid

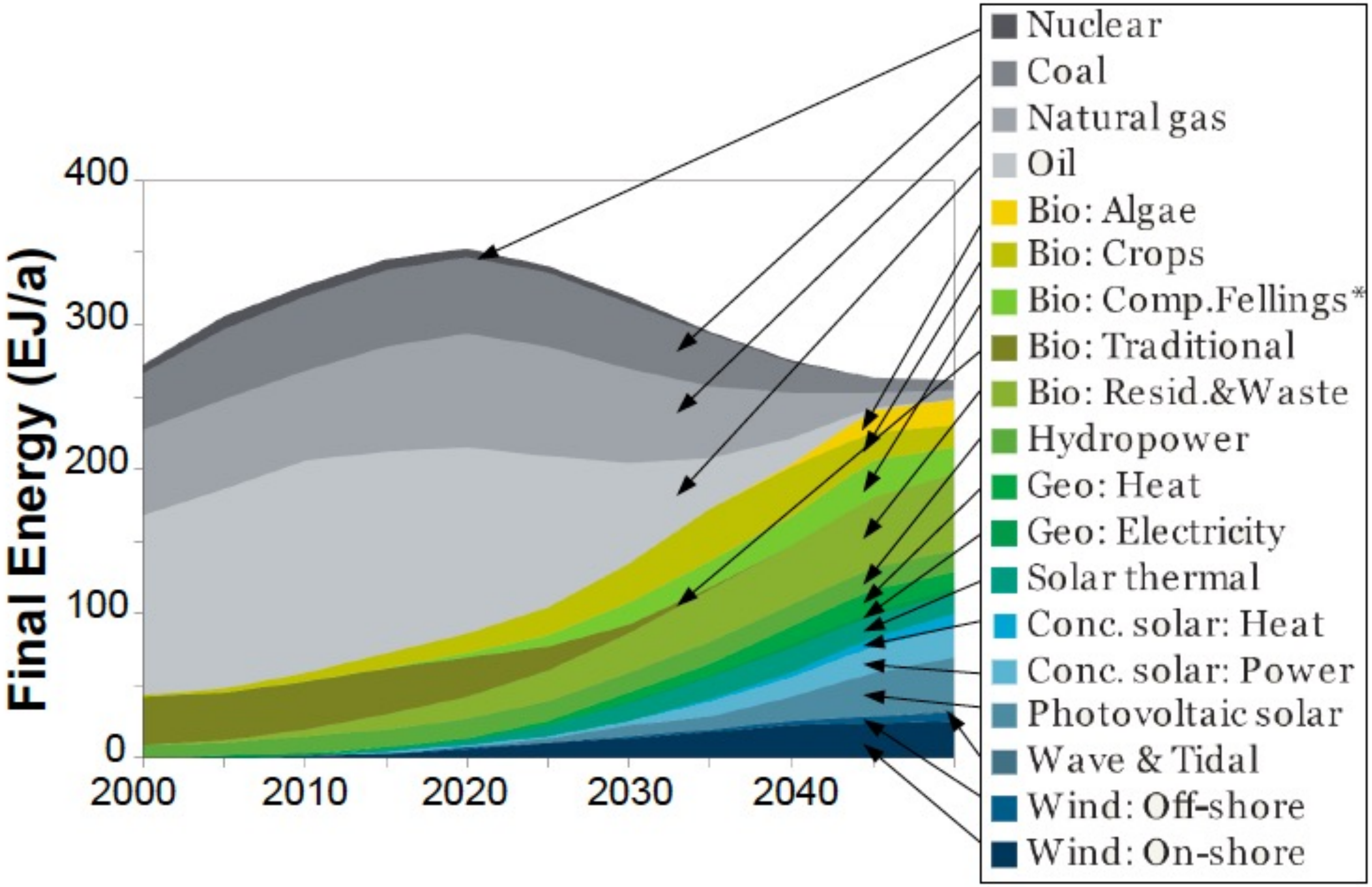
- In contrast with the traditional power grid, the electric energy generation and the flow pattern in an SG are more flexible.
- For example, the distribution grid may also be capable of generating electricity by using solar panels or wind turbines (DERs).



Power generation: Distributed energy resources

- Distributed energy resources (DER) are electric generation units (typically in the range of 3 kW to 50 MW) located within the electric distribution system at or near the end user.
  - Microturbines
  - Solar photovoltaic
  - Solar thermal power generation
  - Natural gas turbines
  - Wind farms
  - ⋮

Non-traditional energy sources



Motivation

- Some reports estimate that by 2050, solar PVs (photovotaics) will contribute up to 23.7% of the total electricity generation in the U.S.
- Large-scale deployment of DERs can be utilized to
  - improve grid reliability,
  - reduce dependence on bulk generators (especially, during peak demand), and
  - decrease network losses (at least up to a certain penetration level).

Power transmission

- Innovative power transmission driven by
  - infrastructure challenges (increasing load demands and quickly aging components) and
  - innovative technologies (new materials, advanced power electronics, and communication technologies).
- The smart transmission grid can be regarded as an integrated system that functionally consists of three interactive components:
  - smart control centers,
  - smart power transmission networks, and
  - smart substations.

Distribution grid

- For the distribution grid, the most important problem is how to deliver power to serve the end users better.
- As many distributed generators will be integrated into the smart distributed grid, this, on one hand, will increase the system flexibility for power generation
- This makes the power flow control much more complicated, in turn, necessitating the investigation of smarter power distribution and delivery mechanisms.

Conclusion

- Smart grid:
  - Distributed power generation
  - Adaptive demand management (curtailment)
  - Adaptive distribution (minimize distribution cost)
- Technological basis
  - New energy technologies
  - Real-time information collection
  - Market mechanisms to regulate demand...

New grid paradigms

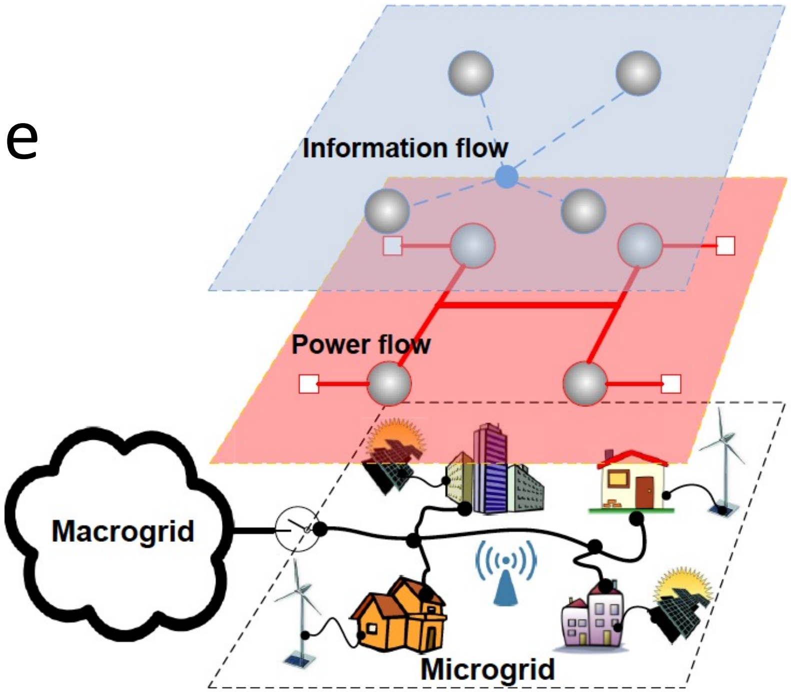
Two of the most important new grid paradigms, which benefit from smart energy subsystem technologies and also further promote the development of SG:

Microgrid & V2G/G2V

- These two paradigms are widely regarded as important components of the future SG.
- Note that these two paradigms also take advantage of other SG technologies.

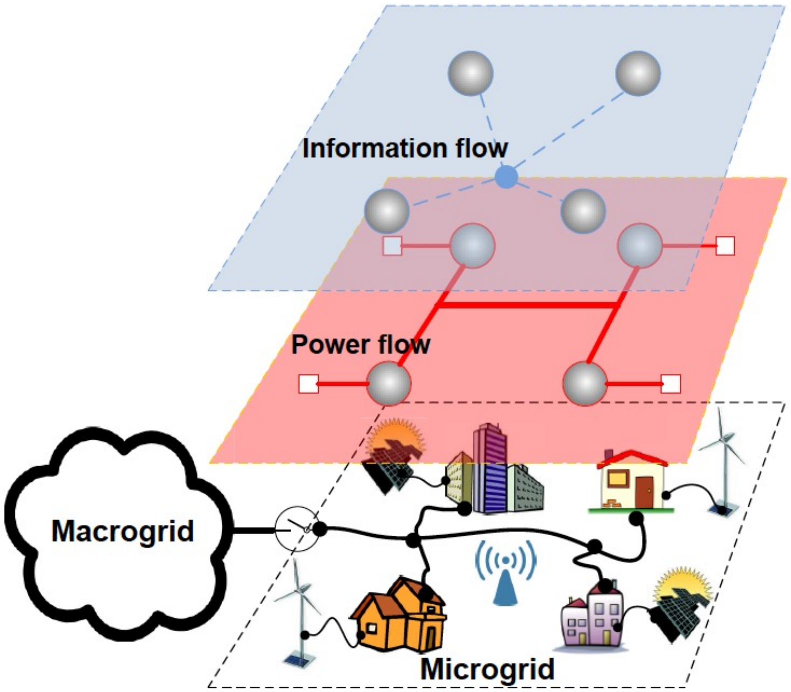
Microgrid

- Distributed generation promotes the development of a new grid paradigm, called microgrid, which is seen as one of the cornerstones of the future SG.
- The organic evolution of the SG is expected to come through the plug-and-play integration of microgrids.
- A microgrid is a localized grouping of electricity generations, energy storages, and loads.



Microgrid

- The lower layer shows a physical structure of this microgrid.
- Buildings and generators exchange power using powerlines.
- Exchange information via an access point-based wireless network.
- Blue (top) layer shows the information flow within this microgrid and the red (middle) layer shows the power flow.



G2V and V2G

- The wide use and deployment of EVs leads to two concepts, namely Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G).
- In G2V, EVs are often powered by stored electricity originally from an external power source, and thus need to be charged after the batteries deplete. This technology is conceptually simple.

G2V and V2G

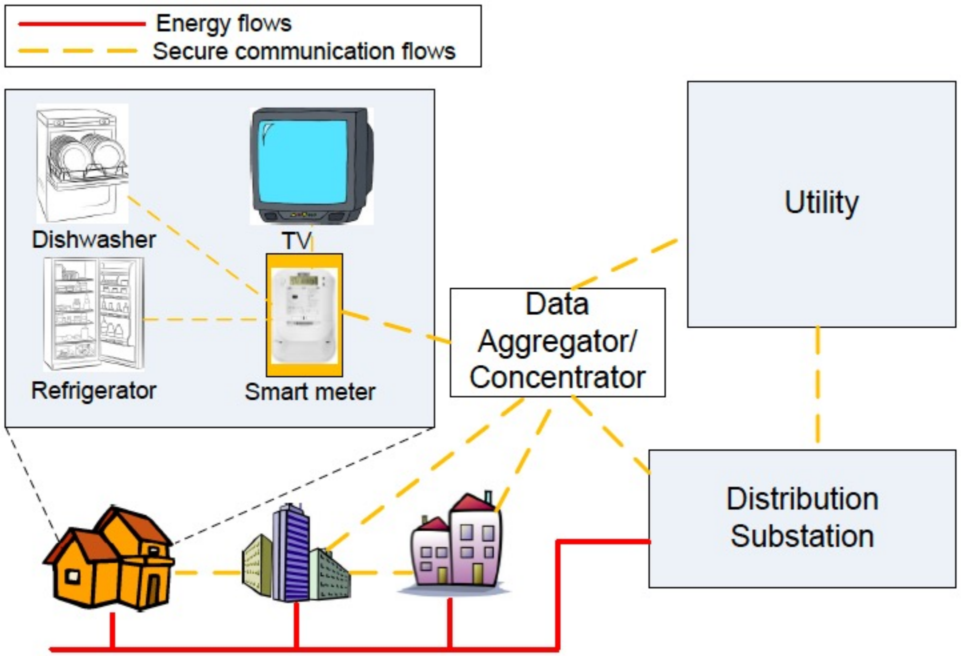
- The wide use and deployment of EVs leads to two concepts, namely Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G).
- In V2G, EVs provide a new way to store and supply electric power. V2G-enabled EVs can communicate with the grid to deliver electricity into the grid, when they are parked and connected to the grid.

Smart Information System

- The evolution of SG relies on not only the advancement of power equipment technology, but also the improvement of sophisticated computer monitoring, analysis, optimization, and control from exclusively central utility locations to the distribution and transmission grids.
- Many of the concerns of distributed automation should be addressed from an information technology perspective, such as interoperability of data exchanges and integration with existing and future devices, systems, and applications.
- Therefore, a smart information subsystem is used to support information generation, modeling, integration, analysis, and optimization in the context of the SG.

Smart meters (for households/industrial users)

- Support two-way communications between the meter and the central system
- Usually an electrical meter that records consumption in intervals of an hour or less and sends that information at least daily back to the utility for monitoring and billing purposes.
- Also, a smart meter has the ability to disconnect-reconnect remotely and control the user appliances and devices to manage loads and demands within the future "smart-buildings."



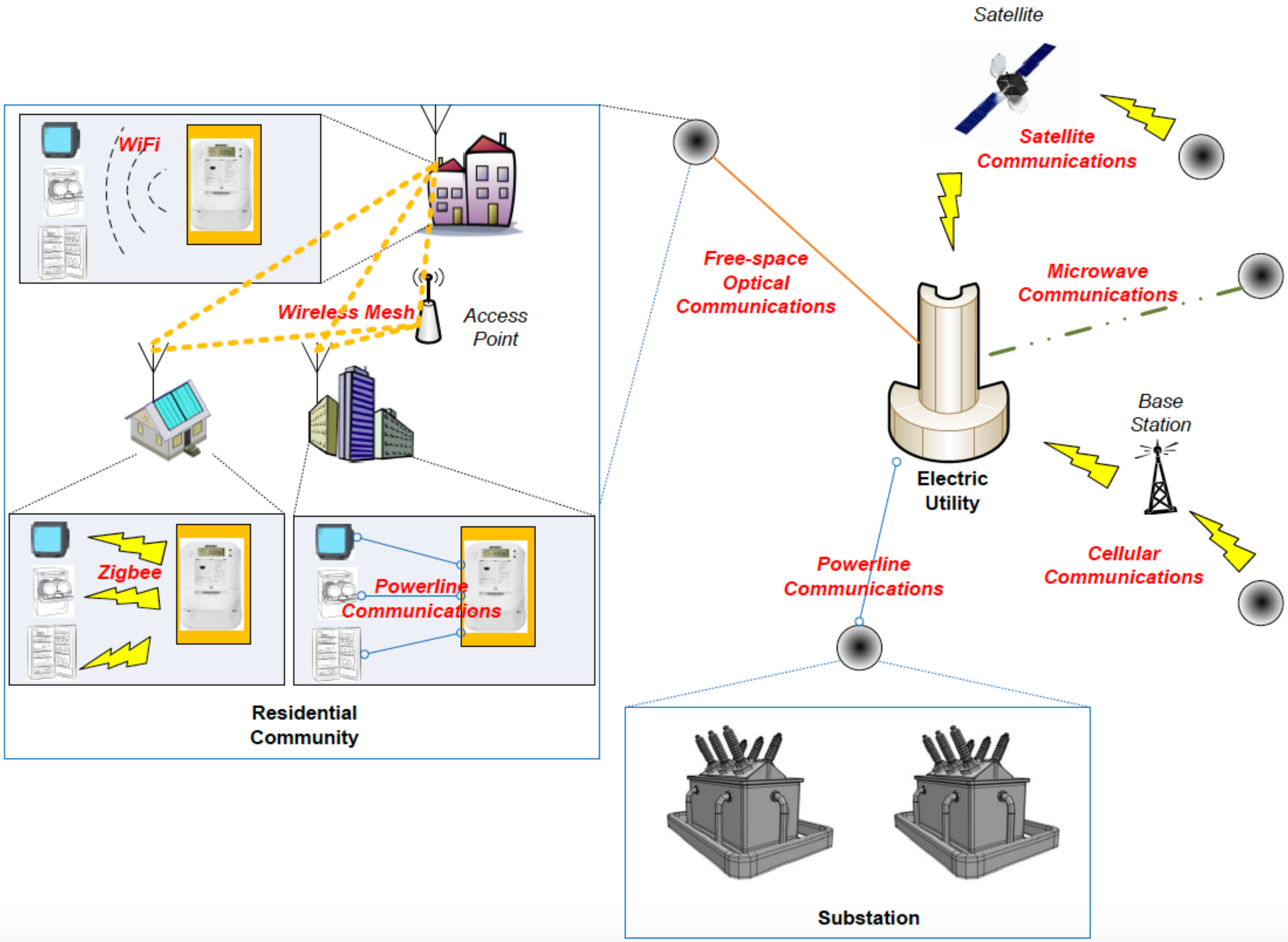
Smart meters

- From a consumer’s perspective, smart metering offers a number of potential benefits. For example, end users are able to estimate bills and thus manage their energy consumptions to reduce bills.
- From a utility’s perspective, they can use smart meters to realize real-time pricing, which tries to encourage users to reduce their demands in peak load periods, or to optimize power flows according to the information sent from demand sides.
- What’s the price for the above benefits?
  - Additional hardware investment
  - Cyber security concerns

Smart monitoring and measurement (for grid itself)

- Sensors:
  - Purpose: detect mechanical failures in power grids such as conductor failures, tower collapses, hot spots, and extreme mechanical conditions
  - Sensor networks should be embedded into the power grid and help to collect information & make decisions
  - Requirements: quality of service, resource constraints, remote maintenance & configuration, high security, robustness against harsh environment
- Phasor measurement unit:
  - Measures the electrical waves on an electrical grid to determine the health of the system
  - Can use such data to analyze grid’s health and make decisions
  - Analogous to EKG

Smart Communication System



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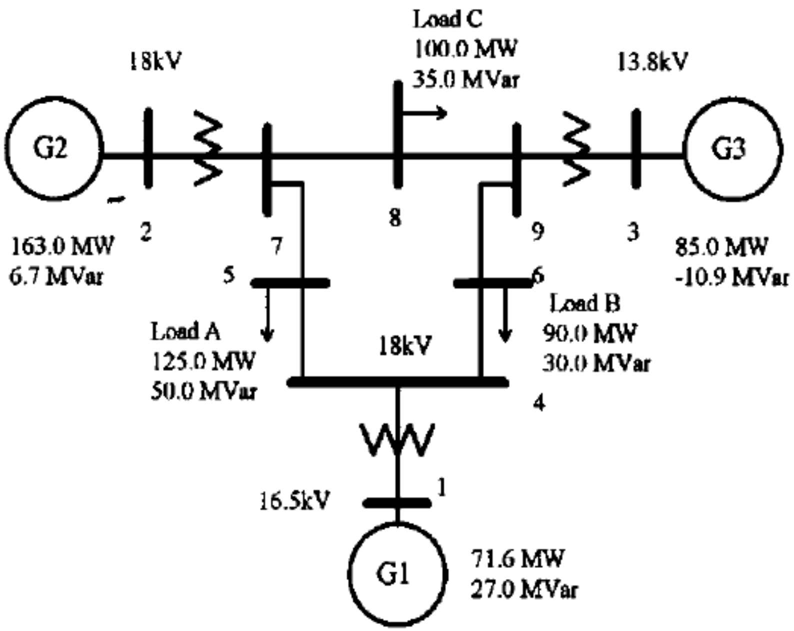
- Bian T , Jiang Y , Jiang Z P . Decentralized Adaptive Optimal Control of Large-Scale Systems With Application to Power Systems[J]. Industrial Electronics IEEE Transactions on, 2015, 62(4):2439-2447.

Multiple-machine power system

- Consider a multiple-machine power system.
- Generators and load are connected via buses.
- We determine mechanical power into each generator.



Mechanical dynamics

- $\delta_i(t)$ = Angle of the ith generator in radian with initial value δ_{i0}.
- ω_0 = Synchronous machine speed, in rad/s.
- $\omega_i(t)$ = Relative speed (w.r.t. ω_0) in rad/s.

$$\dot{\delta}_i(t) = \omega_i(t).$$

- D_i = Per unit (p.u.) damping constant of ith generator.
- H_i = Inertia constant in second.
- $P_{mi}(t)$ = Mechanical input power, in p.u..
- $P_{ei}(t)$ = Electrical power, in p.u..

$$\dot{\omega}_i(t) = -\frac{D_i}{2H_i}\omega_i(t) + \frac{\omega_0}{2H_i}\left(P_{mi}(t) - P_{ei}(t)\right).$$

Governor control

- T_i = governor time constant of ith machine.
- $u_{gi}(t)$ = speed governor control input.

$$\dot{P}_{mi}(t) = \frac{1}{T_i}\left(-P_{mi}(t) + u_{gi}(t)\right).$$

- E'_{qi} = transient electromotive force in quadrature axis, assumed constant.
- $\delta_{ij}(t) = \delta_i(t) - \delta_j(t)$.
- B_{ij}, G_{ij} = imaginary & real parts of the admittance matrix

$$P_{ei}(t) = E'_{qi}\sum_{j=1}^{N} E'_{qj}\left(B_{ij}\sin\delta_{ij}(t) + G_{ij}\cos\delta_{ij}(t)\right).$$

nonlinear

Reformulation

- Reformulate the variables w.r.t. balancing values:
- Relative angle $\Delta\delta_i(t)$. (State)

$$\Delta\dot{\delta}_i(t) = \omega_i(t).$$

- Relative control input $u_i(t) = u_{gi}(t) - P_{ei0}$, P_{ei0} = nominal electrical power. (Reference)
- Relative mechanical power $\Delta P_{mi}(t) = P_{mi}(t) - P_{ei0}$. (Input)
- Relative electrical power $d_i(t) = P_{ei}(t) - P_{ei}0$. (Output)

$$\dot{\omega}_i(t) = -\frac{D_i}{2H_i}\omega_i(t) + \frac{\omega_0}{2H_i}\big(\Delta P_{mi}(t) - d_i(t)\big),$$

$$\Delta\dot{P}_{mi}(t) = \frac{1}{T_i}\big(-\Delta P_{mi}(t) + u_i(t)\big).$$

State-space model

- Consider the ith generator with state $\begin{bmatrix} \Delta\delta_i(t) \\ \omega_i(t) \\ \Delta P_{mi}(t) \end{bmatrix}$.
- Control input is $u_i(t)$.
- Output exchanged among generators $d_i(t)$.
  - Can be derived from the states of all generators.
  - Influences evolution of every generator.
- We actually have two ways of modeling inter-connected generators:

1. Consider a mega system lumping states of all generators.
2. Consider a network of subsystems with both internal mechanisms and interconnections. (Preferred)

State-space model

$$
\begin{bmatrix} \Delta\dot{\delta}_i(t) \\ \dot{\omega}_i(t) \\ \Delta\dot{P}_{mi}(t) \end{bmatrix}
= \begin{bmatrix} & 1 & \\ & -\frac{D_i}{2H_i} & \frac{\omega_0}{2H_i} \\ & & -\frac{1}{T_i} \end{bmatrix}
\boxed{\begin{bmatrix} \Delta\delta_i(t) \\ \omega_i(t) \\ \Delta P_{mi}(t) \end{bmatrix}}
+ \begin{bmatrix} 0 \\ -\frac{\omega_0}{2H_i} \\ \end{bmatrix} \boxed{d_i(t)}
+ \begin{bmatrix} \\ \\ \frac{1}{T_i} \end{bmatrix} u_i(t)
$$

local information

global information (nonlinear)

$\longleftarrow$ can cancel out nonlinearity

[Not required] Interconnected systems

- Recall from vehicle platooning:

A cascaded system is stable if disruptions never get amplified as they propagate downstream.

Cascaded

Interconnected

- Analogy for interconnected systems:

An interconnected system is stable if disruptions never get amplified as they circle in the loop.

"Small-gain theorem" ← **frequency response function**

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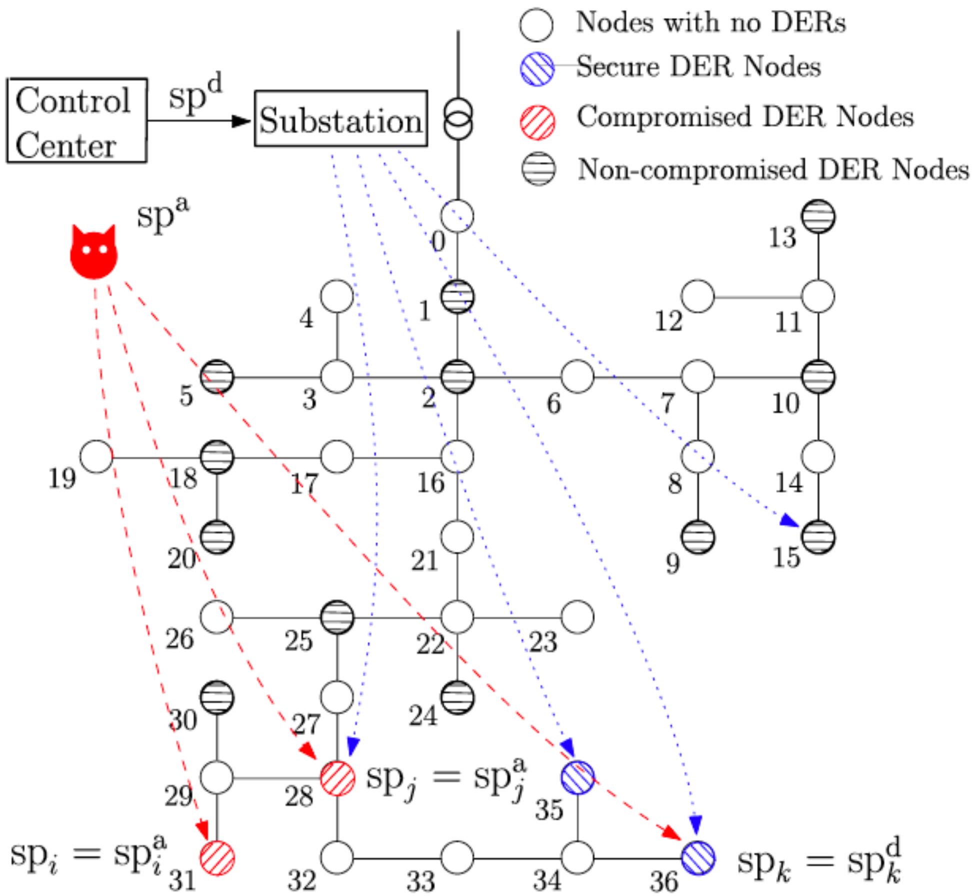
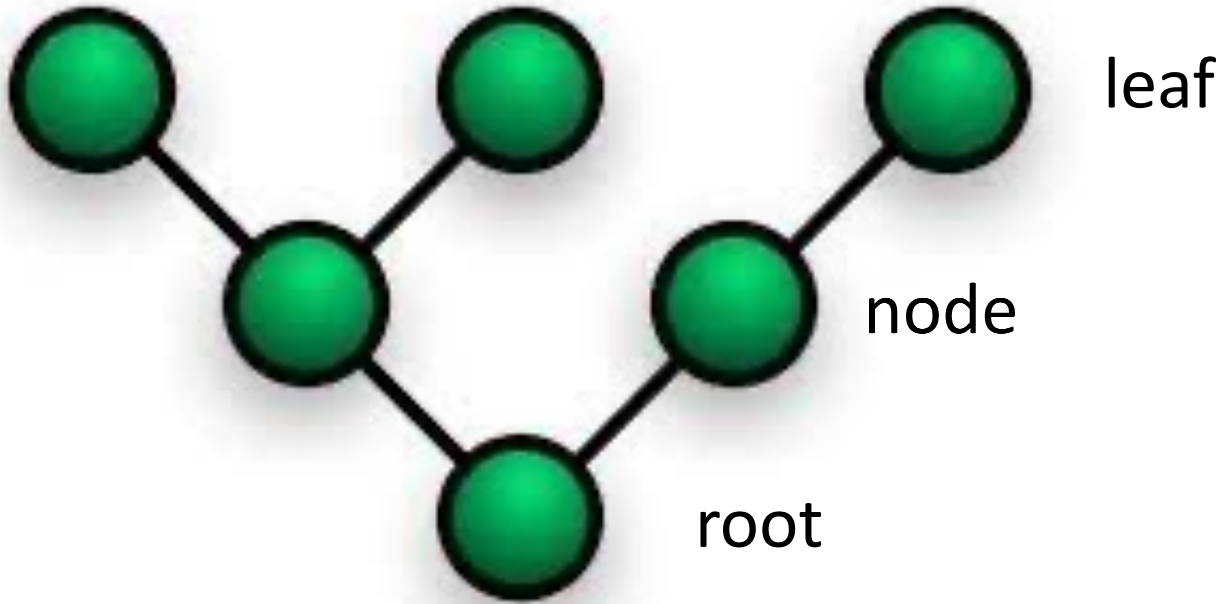
Distribution network model

- Tree network with nodes N and edges E
- Substation labeled as node 0 (root)



Tree network



Distribution network model

- Network state: complex voltage $V_i \in \mathbb{C}$ for node i
- Background: complex numbers $\mathbb{C}$
  - $z = x + y\mathrm{i}$, where $\mathrm{i} = \sqrt{-1}$
  - Real part x, imaginary part y
  - Exponential function
$$e^{x+y\mathrm{i}} = e^x e^{\mathrm{i}y} = e^x(\cos y + \mathrm{i}\sin y)$$
$$|z| = \sqrt{x^2 + y^2}.$$
- Trigonometric functions are often used to describe alternate current (AC)
- AC voltage: e^{V_i}
- Square of voltage magnitude $v_i = |V_i|^2$
- Assume constant substation power $v_0 = 1$. (Normalized)

Distribution network model

- Voltage regulation requirement
  - $\forall i \in N. \underline{v}_i \leq v_i \leq \bar{v}_i$

  $\underline{v}_i$ & $\bar{v}_i$ are soft lower & upper bounds for maintaining voltage quality
  - $\forall i \in N. \underline{\mu} \leq v_i \leq \bar{\mu}$

  $\underline{v}_i$ & $\bar{v}_i$ are hard lower & upper bounds for safety
- Current into node j = $I_j \in \mathbb{C}$
- $\ell_j = |I_j|^2$
- Impedance of distribution line $z_j = r_j + \mathrm{j}q_j$, where $\mathrm{j} = \sqrt{-1}$
- r_j = resistance, q_j = inductance

Demand & supply models

- Constant, complex load model

$$sc_i = pc_i + \mathrm{j}qc_i$$

  - pc_i = real power
  - qc_i = reactive power
  - Load is upper-bounded by demand

$$sc_i = \gamma_i sc_i^{nom} = \gamma_i(pc_i^{nom} + \mathrm{j}qc_i^{nom})$$

  - $\gamma_i \in [0,1]$ is selected by system operator (SO): “load curtailment”
  - Demand is determined by the market
- DER model: complex power

$$sg_i = pg_i + \mathrm{j}qg_i$$

  - pg_i = active power
  - qg_i = reactive power
  - We can select sg_i from a set of admissible configurations $\mathcal{S}_i$

Power flow equations

- Three-phase balanced nonlinear power flow (NPF)
  - $S_j = \sum_{(j,k)\in E} S_k + sc_j - sg_j + z_j\ell_j$ (power conservation)
  - $v_j = v_i - 2\mathrm{Re}\left(\bar{z}_j S_j\right) + \left|z_j^2\right|\ell_j$ (voltage drop)
  - $\ell_j = \frac{\left|S_j\right|^2}{v_j}$ (current-voltage-power relationship)
- $S_j = P_i + \mathrm{j}Q_j$ complex power flowing into node j
- Linear power flow (LPF) approximation (locally valid)
  - $\hat{S}_j = \sum_{(j,k)\in E} \hat{S}_k + \widehat{sc}_j - \widehat{sg}_j$ (power conservation)
  - $\hat{v}_j = \hat{v}_i - 2\mathrm{Re}\left(\bar{z}_j \hat{S}_j\right)$ (voltage drop)
  - $\hat{\ell}_j = \frac{\left|\hat{S}_j\right|^2}{\hat{v}_j}$ (current-voltage-power relationship)

[Not required] Cost function

- State $x = [v, \ell, sc, sg, S]$
  - v = vector of square of voltages
  - ℓ = vector of square of currents
  - sc = vector of complex load
  - sg = vector of complex supplies (from DER)
  - S = vector of complex powers into each node
- Cost $L(x) = L_{VR}(x) + L_{LC}(x) + L_{LL}(x)$
  - $L_{VR}(x)$ = monetary cost due to loss in voltage regulation
  - $L_{LC}(x)$ = monetary cost due to loss in unsatisfied demand
  - $L_{LL}(x)$ = monetary cost due to total line loss

[Not required] Cost function

- Cost $L(x) = L_{VR}(x) + L_{LC}(x) + L_{LL}(x)$
  - $L_{VR}(x)$ = monetary cost due to loss in voltage regulation
$$L_{VR}(x) = \max_i W_i\left(\underline{v}_i - v_i\right)_+$$
$$(\xi)_+ = \begin{cases} \xi & \xi \geq 0 \\ 0 & o.w. \end{cases}$$
  - $L_{LC}(x)$ = monetary cost due to loss in unsatisfied demand
$$L_{LC}(x) = \sum_i C_i(1 - \gamma_i)pc_i^{nom}$$
  - $L_{LL}(x)$ = monetary cost due to total line loss
$$L_{LL}(x) = \sum_i r_i \ell_i$$

Comments on notations

- Never get scared of heavy notations
- Heavy notation = people have extensively studied the problem = good news
- Light notation = either very simple or people don't know how to proceed...
- High school math: $L_{VR}(x) = \max_i W_i \left(\underline{v}_i - v_i \right)_+$
- PhD math: $L_{VR}(x) = \left\| W \circ \left(\underline{v}_i - v_i \right) \right\|_\infty$
  - Hadamard product: $a \circ b = [a_1 b_1 \; a_2 b_2 \; \ldots a_n b_n]^T$
  - H_∞ norm: $\|c\|_\infty = \max_i c_i$
- Same thing

Formulation

- Data
  - Demand
  - Attainable supply
- Decision variables
  - Load (demand to satisfy)
  - Supply (power to be generated by DER)
- Constraints
  - Linear power flow model
- Objective
  - Minimize operational cost

Mathematical formulation

$$\min\ L(x) = L_{VR}(x) + L_{LC}(x) + L_{LL}(x)$$

s.t. $\hat{S}_j = \sum_{(j,k)\in E} \hat{S}_k + \widehat{sc}_j - \widehat{sg}_j$ (power conservation)

$\hat{v}_j = \hat{v}_i - 2\mathrm{Re}\left(\bar{z}_j \hat{S}_j\right)$ (voltage drop)

$\hat{\ell}_j = \dfrac{|\hat{S}_j|^2}{\hat{v}_j}$ (current-voltage-power relationship)

$sc_i = \gamma_i sc_i^{nom}$ (demand curtailment)

$$L_{VR}(x) = \max_i W_i\left(\underline{v}_i - v_i\right)_+$$

$$L_{LC}(x) = \sum_i C_i(1-\gamma_i)pc_i^{nom}$$

$$L_{LL}(x) = \sum_i r_i \ell_i$$

$$\underline{v}_i \le v_i \le \bar{v}_i,\ \underline{\mu} \le v_i \le \bar{\mu},\ \gamma_i \in [0,1]$$

Reformulation

- The original problem is nonlinear
- Voltage regulation cost $L_{VR} = \max_i W_i \left(\underline{v}_i - v_i\right)_+$
- However, we can reformulate it as a set of linear constraints
  - $L_{VR} \geq W_i(\underline{v}_i - v_i)$ for all i
  - $L_{VR} \geq 0$
- If we are minimizing L_{VR}, then the above reformulation is valid
- Otherwise, we cannot do this!

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