Smart Grids

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Purpose of this lesson

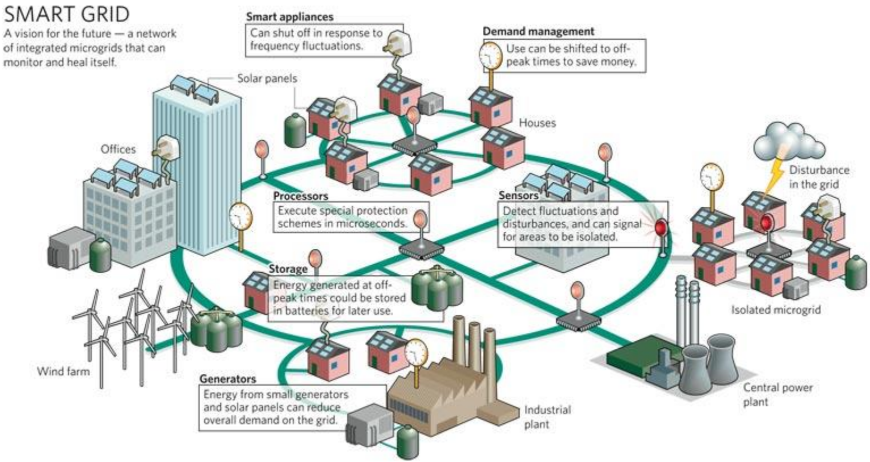
The aim of this lesson is:

1. understand the main challenges due to smart grid implementation
2. detect the main components of electrical smart grids
3. evaluate State Estimation enhancement
4. analyse the Renewable Energy Resources models
5. understand the cyber security problem

Reading Materials

Smart Grid: Fundamentals of Design and Analysis, by James Momoh, John Wiley & Sons, Mar 20, 2012 - Technology & Engineering - 216 pages

What is Smart Grid?



from http://www.consumerenergyreport.com/smart-grid/

Today Power Grid Capabilities

1. Handling uncertainties in schedules and power transfers across regions
2. Accommodating renewable
3. Optimizing the transfer capability of the transmission and distribution networks and meeting the demand for increased quality and reliable supply
4. Managing and resolving unpredictable events and uncertainties in operations and planning more aggressively.

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Today's Grid vs. Smart Grid [1]

Preferred Characteristics	Today's Grid	Smart Grid
Active Consumer Participation	Consumers are uninformed and do not participate	Informed, involved consumers demand response and distributed energy resources
Accommodation of all generation and storage options	Dominated by central generation many obstacles exist for distributed energy resources interconnection	Many distributed energy resources with plug - and - play convenience focus on renewables
New products, services, and markets	Limited, poorly integrated wholesale markets; limited opportunities for consumers	Mature, well - integrated wholesale markets; growth of new electricity markets for consumers
Provision of power quality for the digital economy	Focus on outages slow response to power quality issues	Power quality a priority with a variety of quality/price options rapid resolution of issues
Optimization of assets and operates efficiently	Little integration of operational data with asset management - business process silos	Greatly expanded data acquisition of grid parameters; focus on prevention, minimizing impact to consumers
Anticipating responses to system disturbances (self- healing)	Responds to prevent further damage; focus on protecting assets following a fault	Automatically detects and responds to problems; focus on prevention, minimizing impact to consumers
Resiliency against cyber attack and natural disasters	Vulnerable to malicious acts of terror and natural disasters; slow response	Resilient to cyber attack and natural disasters; rapid restoration capabilities

[1] "The Modern Grid Initiative." GridWise Architecture Council, Pacific Northwest National Laboratory, 2008 .

Smart Grids Definitions I

The European Technology Platform defines the Smart Grid as: *A SmartGrid is an electricity network that can intelligently integrate the actions of all users connected to it generators, consumers and those that do both in order to efficiently deliver sustainable, economic and secure electricity supplies.*

According to the US Department of Energy: *A smart grid uses digital technology to improve reliability, security, and efficiency (both economic and energy) of the electric system from large generation, through the delivery systems to electricity consumers and a growing number of distributed-generation and storage resources.*

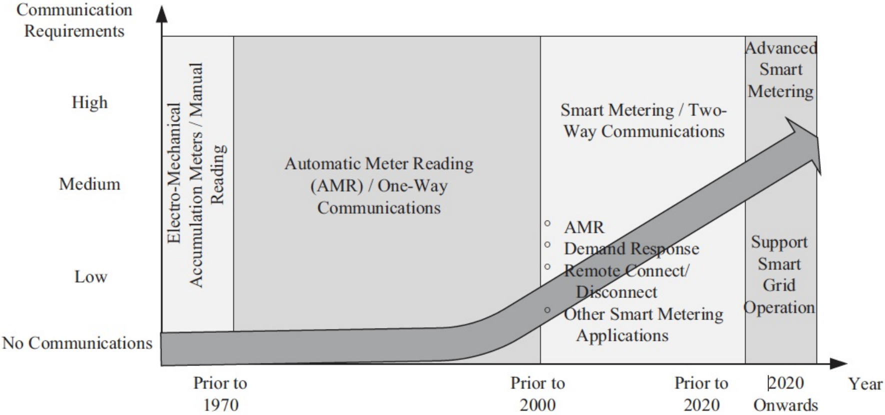
Smart Grids Definitions II

In “Smarter Grids: The Opportunity”, the Smart Grid is defined as: *A smart grid uses sensing, embedded processing and digital communications to enable the electricity grid to be observable (able to be measured and visualised), controllable (able to manipulated and optimised), automated (able to adapt and self-heal), fully integrated (fully interoperable with existing systems and with the capacity to incorporate a diverse set of energy sources).*

Evolution of Smart Metering

The smart grid environment requires the upgrade of tools for sensing, metering, and measurements at all levels of the grid. These components will provide the data necessary for monitoring the grid and the power market. Sensing provides outage detection and response, evaluates the health of equipment and the integrity of the grid, eliminates meter estimations, provides energy theft protection, enables consumer choice, DSM, and various grid monitoring functions.

Evolution of Electricity Metering



Wide Area Monitoring Systems (WAMS)

WAMS are designed by the utilities for optimal capacity of the transmission grid and to prevent the spread of disturbances. By providing real - time information on stability and operating safety margins, WAMS give early warnings of system disturbances for the prevention and mitigation of system - wide blackouts. WAMS utilize sensors distributed throughout the network in conjunction with GPS satellites for precise time stamping of measurements in the transmission system. The integrated sensors will interface with the communication network.

Phasor Measurement Units (PMU)

Phasor Measurement Units or Synchrophasors give operators a time - stamped snapshot of the power system. The PMUs consist of bus voltage phasors and branch current phasors, in addition to information such as locations and other network parameters. Phasor measurements are taken with high precision from different points of the power system at the same instant, allowing an operator to visualize the exact angular difference between different locations. PMUs are equipped with GPS receivers which allow synchronization of readings taken at distant points.
The IEEE standard on Synchrophasors specifies the protocol for communicating the PMU data to the Phasor Data Concentrator.

Smart Meters

Smart meters have two functions: providing data on energy usage to customers (end - users) to help control cost and consumption; sending data to the utility for load factor control, peak - load requirements, and the development of pricing strategies based on consumption information and so on Automated data reading is an additional component of both smart meters and two - way communication between customers and utilities. The development of smart meters is planned for electricity, water, and gas consumption.

Smart Appliances

Smart appliances cycle up and down in response to signals sent by the utility. The appliances enable customers to participate in voluntary demand response programs which award credits for limiting power use in peak demand periods or when the grid is under stress. An override function allows customers to control their appliances using the Internet.

Advanced Metering Infrastructure (AMI) I

AMI is the convergence of the grid, the communication infrastructure, and the supporting information infrastructure. The network - centric AMI coupled with the lack of a composite set of cross industry AMI security requirements and implementation guidance, is the primary motivation for its development. The problem domains to be addressed within AMI implementations are relatively new to the utility industry; however, precedence exists for implementing large - scale, network - centric solutions with high information assurance requirements.

Serve to reduce/eliminate labor, transportation, and infrastructure costs associated with meter reading and maintenance, increase accuracy of billing, and allow for time - based rates while reducing bad debts; facilitates informed customer participation for energy management.

Advanced Metering Infrastructure (AMI) II

Serves to increase customer awareness about load reduction, reduces bad debt, and improves cash fl ow, and enhances customer convenience and satisfaction; provides demand response and load management to improve system reliability and performance.

Curtails customer load for grid management, optimizes network based on data collected, allows for the location of outages and restoration of service, improves customer satisfaction, reduces energy losses, improves performance in event of outage with reduced outage duration and optimization of the distribution system and distributed generation management, provides emergency demand response.

Micro Grid And Smart Grid Comparison

Research has been conducted to understand the differences between a microgrid and a smart grid. Basically, a microgrid is a local island grid that can operate as a stand - alone or as a grid - connected system. It is powered by gas turbines or renewable energy and includes special purpose inverters and a link for plug - and - play to the legacy grid. Special purpose filters overcome harmonics problems while improving power quality and efficiency. In summary, think of the micro grid as a local power provider with limited advanced control tools and the smart grid is a wide area provider with sophisticated automated decision support capabilities

State Estimation

Energy management systems (EMS) run in real time to compute and maintain security of operation at minimum cost. The power system measurements provide information to the SE program for processing and analysis. The functions performed include topology processing which gathers data about breakers and disconnect switches. State estimation (SE) of voltage and angles are obtained for all busses using the weighted least square (WLS) method. Detection of inaccurate data is obtained from network parameters, tap changing transformers, shunt capacitors, or breakers.

Detection and Identification of Bad Data

Redundant measurement information allows us to identify and locate bad data consisting of gross measurement errors and/or large modeling errors, for example, wrong network topology, or large parameter errors. Without redundancy the estimates will fit the data perfectly, but it does not provide ways to locate bad data.
The four sources of problems are: gross measurement errors, small modeling errors, small parameter errors and inaccurate knowledge of measurement variances

Pre-Estimation Analysis

The measurement components can undergo a series of so - called consistency tests with the following objectives:

- Detection of obviously bad measurements
- Detection of obviously bad network topology
- Classification of data as (a) valid, (b) suspect, and (c) raw
- Tuning the measurement variance values

Detection of Obviously Bad Measurements.

In this preliminary stage, measurements whose values are outside reasonable limits are automatically discarded. For example, line fl ow limits can be set at twice the theoretical capacity of the line. Power factors, voltage levels, and so on can be safely limited. In most cases, almost all of the bad data will be in this category and can be quickly discarded.

Detection of Obviously Bad Network Topology

Normally, a special network configuration program constructs the system network on the basis of breaker status information. Open lines are not represented in the model forwarded to the state estimator, that is, all lines that are in the model used by the estimator should be closed (energized). However, cases may occur where a breaker is closed but has an open disconnect switch. If the disconnect switch status is not reported, the line is mistakenly assumed to be energized. One way to check for this anomaly is to see if the power fl ow on the line is zero at both ends. If this is the case then the line is most probably open. Other cases of bad topology may be detected from incoming data and are usually peculiar to the system being analyzed.

Classification of Raw Data

Because of the structure of load fl ow equations a considerable number of hypothesis consistency tests can be conducted to verify the validity of most of the data and to tune the values of the measurement variables.

Line flow measured at both ends: For real flows, the magnitudes of flows from both ends differ only by the amount of line losses evaluated This assures that the combined errors of both measurements are within the limit.

Post-estimation Analysis I

Post-estimation analysis looks at the results of state and parameter estimation and attempts to establish hypotheses for the most probable causes of poor performance, if any. This is based on the analysis of the normalized measurement residuals defined as:

$$r'_i = \frac{z_i - h(\hat{x})}{\rho_i}, \qquad i = 1, \dots, m \tag{1}$$

where $\rho_i^2 = \mathrm{var}(z_i - h_i(\hat{x}))$
Statistically, r'_i can vary from zero to three with a high probability. This is true only when all data lie within the specified statistical accuracies. If there are bad data in the measurements and/or parameters, some of the normalized residual terms will have a large magnitude. In many cases, the measurement with the largest normalized residual is a bad measurement, but this has not been mathematically proven.

Post-estimation Analysis II

Without parameter errors and pre - estimation analysis, all measurements are classified as raw with a small probability that some of them are bad. By analyzing the residuals one can start the hypothesis testing process by discarding the measurement with the largest residual and performing the estimation process again. If this fails to yield acceptable estimates, the discarded measurements are put back and the measurement with the largest residual in the new estimate is removed. This process is repeated until a satisfactory answer is obtained.

State Estimation for Smart Grid I

SE is an important tool for detecting and diagnosing errors in measurement such as network error and/or device malfunctions. The technique is used in estimating voltage and power flow errors as a result of system parameters errors.

To solve this, a typical optimization technique could be employed with the following methodology and algorithm:

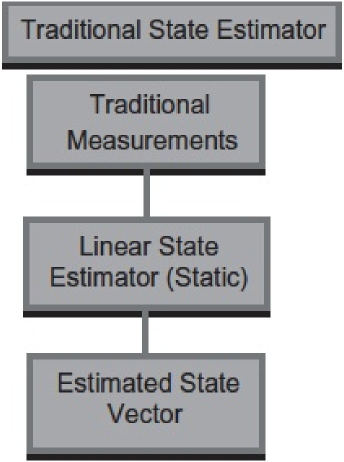
1. Convergence of the algorithm
2. Clearly defined problem location
3. Manage/modify noise server
4. Time and quality of measurements

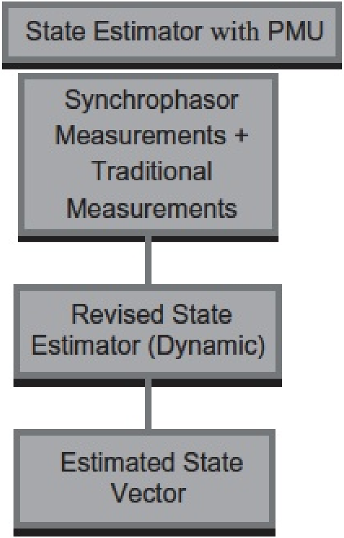
State Estimation for Smart Grid II

Components suggested by SE researchers for the smart grid include:

1. Real PMU - based measurements to account for integrated RER and protected load (stochastic) stored
2. A distributed SE around the different (partitioned) network configuration on appropriate assessment of data performed for subsequent assessment.

State Estimation for Smart Grid III





Sustainable Energy Options for Smart Grid

I

Sustainable energy is derived from natural sources that replenish themselves over of time. Sometimes called green power, because they are considered environmentally friendly and socially acceptable, they include sun, wind, hydro, biomass, and geo - thermal.

Sustainable Energy Options for Smart Grid II

Renewable energy options are meant to provide the smart grid with:

1. Remote utilization and storage of RER resources output
2. Enhancement of functionality of grid - connected renewable energy systems (RES)
   - Facilitating give - and - take of energy from the system
   - Redistribution/reallocation of unused power from grid - connected RES
   - Facilitating storage of grid - generated and RER - generated energy by back - up storage technologies at customer end
   - Tracking interactions for billing and study
3. Enhancement of functionality of grid - connected renewable energy systems (RES)
4. Utilization of vehicle battery packs as energy storage devices

Solar Energy

The PV system generally considers:
Insolation: The availability of solar energy conversion to electricity.
Insolation levels are affected by the operating temperature of PV cells intensity of light (location - dependent), and the position of the solar panels (maximize the power tracking while maximizing perpendicular incident light rays).
Emission: PV emission levels are environmental friendly.

Modelling PV Systems I

Many models exist for the calculation of the power output of a PV cell or bank. Due to the varying efficiencies and numerous technologies presently available, power output is affected by environmental conditions and module specifi cations. The I - V characteristic model of a single cell is commonly used for PV technologies. The model is given by:

$$P_{mp} = \frac{G}{G_{ref}} P_{mp,ref} \left[1 + \gamma(T - T_{ref})\right]$$

G is the incident irradiance
P_{mp} is the maximum power output
$P_{mp,ref}$ is the maximum power output under standard testing conditions
T is the temperature
T_{ref} is the temperature for standard testing conditions reference $(25C)$
$G_{ref} = 1000 Wm^2$
γ is the maximum power correction for temperature

Wind Turbine Systems I

Wind is one of the fastest - growing sources of renewable energy throughout the world. Turbines produce electricity at affordable cost without additional investments in infrastructure such as transmission lines. A wind turbine consists of a rotor, generator, blades, and a driver or coupling device. Compared with PV, wind is the most economically competitive renewable.
Although turbines produce no $\mathrm{CO_2}$ or pollutants, wind has three drawbacks: output cannot be controlled, wind farms are most suited for peaking applications, and power is produced only when there is sufficient wind.

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Wind Turbine Systems II

Machines which consume reactive power and produce real power. The quantification of the capacity/real power output is given by:

$$P_m = \frac{1}{2}\rho \cdot \pi R^2 \cdot V^3 \cdot C_p$$

where

ρ is the air density (kg/m^3)

R is the turbine radius (m)

C_p is the turbine power coefficient power conversion efficiency of a wind turbine

V is the wind speed (m/s)

The electrical power output is given by:

$$P_e = n_o P_m$$

where

$n_o = \eta_m \eta_g$

η_m, and η_g are the efficiency of the turbine and the generator, respectively

Biomass-Bioenergy

Bioenergy is the energy derived from organic matter such as corn, wheat, soybeans, wood, and residues that can produce chemicals and materials. Biopower is obtained from a process called gasifi cation, converting gas to gas turbines to generate electricity. Biomass can be converted directly into fl uid fuels such as ethanol, alcohol or biodiesel derived from corn ethanol.

Small and Micro Hydropower

Hydropower is by far the largest renewable source of power/energy. Small hydropower systems vary from 100 kW to 30 MW while micro hydropower plants are smaller than 100 kW. Small hydropower generators work in variable speed because of water flow. Induction motors provide a generator for a turbine system. The hydraulic turbine converts the water energy to mechanical rotational energy.

Small and micro hydropower systems are RER optimizations to enhance the smart grid. The issues of reliability and modeling are addressed as in PV and wind energy.

Fuel Cell

Fuel cells can also be used to enhance power delivery in the smart grid. They are simply fuels from hydrogen, natural gas, methanol, and gasoline. The efficiency for fuel to electricity can be high as 65% since it does not depend on Carnot limits. Fuel cells are environmentally friendly by efficient use of fuel. Fuel cells produce virtually no emissions. Their cost is significantly high compared with conventional technologies.
The topology of a fuel cell is a stack which consists of the part of the fuel cell that holds the electrodes and electrolytic material. Hydrogen is extracted from gasoline propane, with natural gas refineries to operate fuel cells commercially.

Heat Pumps

This form of power is based on accessing the underground steam or hot water from wells drilled several miles into the earth. Conversion occurs by pumping hot water to drive conventional steam turbines which drive the electrical generator that produces the power. The water is then recycled back into earth to recharge the reservoir for a continuous energy cycle. There are several types of geothermal power plants including dry steam, fl ash stream, and binary cycle. Dry steam plants draw water from the reservoirs of steam, while both fl ash steam and binary cycle plants draw their energy from the recycled hot water reservoir.

Electric Vehicles

The integration of electric vehicles and hybrids is another component of the smart grid system. Vehicle - to - grid power (V2G) uses electric - drive vehicles (battery, fuel cell, or hybrid) to provide power for specific electric markets. V2G can provide storage for renewable energy generation and stabilize large - scale wind generation via regulation. Hybridization of electric vehicles and connections to the grid overcome limitations of their use including cost, battery size/weight, and short range of application. PHEVs provide the means to replace the use of petroleum - based energy sources with a mix of energy resources (encountered in typical electric power systems) and to reduce overall emissions.

Impact of PHEV on the Grid

Utilities have become concerned with the number of PHEVs coming on the market because there may be insufficient supply for the increased demand resulting from additional load for battery charging. By 2040, the addition of PHEV battery charging in the United States will increase existing load by 18%. Unfortunately, this increase in load will eventually cause voltage collapse in amounts up to 96% of the nominal voltage in some areas, requiring the integration of transformers, capacitors, and other power distribution devices for mitigation.
It will be critical to study the trends of daily PHEV power usage and the average power consumption over one day to determine the impacts on the grid, market, environment, and economy.

Smart Grid Cyber Security

The interaction of the power, communication, and information networks are critical to facilitating resiliency and sustainability of the infrastructures which further enhance the provision of adequate power and support economic and social growth of the nation. Technologies and protocols are developed for the maintenance of system, network, data, and SCADA security while conducting vulnerability assessment, incident recognition, recording, reporting, and recovery. Protection of network data as well as web - based or stored data is conducted.

Standards for the Various Electric Grid Levels

Level	Standard	Description	Application
Transmission /Distribution Level	IEEE Standards for Synchrophasors for Power Systems (IEEE C37.118-2005)	This standard defines synchronized phasor measurements used in power system applications. It provides a method to quantify the measurement, tests to be sure the measurement conforms to the definition, and error limits for the test. It also defines a data communication protocol including message formats for communicating this data in a real-time system.	Phasor measurement units communication
Transmission /Distribution Level	IEEE Standard for Interconnecting Distributed Resources with the Electric Power System (IEEE 1547-2003)	Itemizes criteria and requirements for the interconnection of distributed generation resources into the power grid.	Physical and electrical interconnections between utilized and distributed generation.
Transmission /Distribution Level	Common Information Model (CIM) for Power Systems (IEC 61968/61970)	Describes the components of a power system and power system software data exchange such as asset tracking, work scheduling and customer billing at an electrical level and the relationships between each component.	Application level energy management system interfaces.
Distribution	Communication networks and systems in substations (IEC 61850, Ed. 1 - 2009) IEC 61850	Standard for the design of electrical substations which addresses issues of interoperability, integration, intuitive device and data modeling and naming, fast and convenient communication. It includes abstract definitions of services, data and common data class, independent of underlying protocols.	Telecontrol /Telemetering Substation automation
Distribution /End User	Advanced Metering Infrastructure (AMI) System Security Requirements—AMI-SEC (June 2009)	Provides the utility industry and vendors with a set of security requirements for Advanced Metering Infrastructure (AMI) to be used in the procurement process, and represent a superset of requirements gathered from current cross-industry accepted security standards and best practice guidance documents.	Advanced metering infrastructure and SG end to end security
Distribution /End User	American National Standard For Utility Industry End Device Data Tables (ANSI C12.19-2008)	Defines a table structure for utility application data to be passed between an end device and a computer. Does not define device design criteria nor specify the language or protocol used to transport that data. The purpose of the tables is to define structures for transporting data to and from end devices.	Revenue metering information model

Threats Facing the Electric Power System

	Traditional Threats faced by Legacy System	Threats faced by the New System
Impact	Direct damage to physical utility	Indirect damage to physical assets through damage to software systems
Location of origination of threat	Local	Local or remote
Target	Individuals	Individuals, competitors, and organizations
Point of Attack	Single site	Multiple point simultaneously
Duration of Damage	Immediate damage causing obvious damage	Attack may be undetected or lie dormant and then be triggered later
Occurrence	Single episode	Continued damage associated with attack
Restoration	Restoration after attack	Attacker may have continued impact preventing restoration

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Thank You!!!

Questions?