Electric power systems principles and challenges in the integration of renewable sources

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Agenda

I. The value of energy

II. Electric power systems: structure and participants

III. Renewable sources characteristics

IV. Ancillary services and example of frequency dynamic

V. Conclusions
A couple of words of the value of energy

- We can divide the sources in two big families:
  - High density energy sources
    - (i.e., coal; gas; oil, nuclear)
  - Low density energy sources
    - (solar; wind; biomass; geothermal; wave; hydro)

- Over a year, the energy coming from the Sun over the Earth surface is 10,000 times the global human energy consumption.
A couple of words on the value of energy

- 4 PV (photovoltaic) modules 250W each (total area 6.4 m²).
- Yearly solar irradiance 1450 kWh/m² (CF 1300 h/year)
- PV plant cost 2500 €
- Energy production cost (including capital and maintenance costs): 20 c€/kWh

Let’s assume to use the produced energy for mobility purposes:
- On average every day, energy charged in EV (Electric Vehicle) = 3.2 kWh (price 0.64 €) → assuming an EV average consume of 5 km/kWh → 16 km range
- BUT! a petrol car, which can drive around 16 km/l would have consumed 1 liter of gasoline (spot market price 0.7 €/l), that means 8.7 kWh of chemical energy

η DC/AC = 90%

1300 kWh/year
- 3.6 kWh/d average (= 0.41 liter oil)
- 4.8 kWh/d summer (= 0.55 l)
- 2.4 kWh/d winter (= 0.27 l)

Note: 1 liter of oil = 8.7 kWh of chemical energy

η charge = 90%
A couple of words on the value of energy

- 4 PV (photovoltaic) modules 250W each (total area 6.4 m²).
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Let’s assume to use the produced energy for heating purposes:

- During winter days, energy in HP (Heat Pump) = 2.4 kWh (price 0.48 €) → assuming a COP (Coefficient of Performance) equal to 3.5 → thermal energy delivered = 8.4 kWh

- A gas heater would have consumed 0.95 m³ of gas in order to produce 8.4 kWh of thermal energy (spot market price 0.4 €)

\[ \eta_{DC/AC} = 90\% \]

1300 kWh/year
- 3.6 kWh/d average (= 0.41 cubic meter gas)
- 4.8 kWh/d summer (= 0.55 m³)
- **2.4 kWh/d winter (= 0.27 m³)**

Note: 1 m³ = 8.8 kWh of chemical energy
A couple of words of the value of energy
lesson learned

• Energy is valuable, especially when it is produced with renewable (i.e. low density) energy sources.

• However, using the energy in a more efficient/smart way (i.e. EV or HP) can make renewable sources more competitive to the one produced by conventional (i.e. high density) energy sources.

• Energy coming from renewable may be matching the request on an “energy” time scale, but not necessarily on a “power” time scale.
Concerning integration...

• **What does integration mean?**

• **Integrate:**
  - from Latin integratus, past participle of integrare "make whole"
  - *to render (something) whole*
  - *to put together parts or elements and combine them into a whole*

• **Integration of wind (and renewable sources in general) with respect to power systems:**
  - Consider them as “normal” source like all the others with “honors” and duties (i.e. provision of ancillary services) needed in order to properly control system voltages and frequency
  - The integration issues can be broadly divided in 2 main categories:
    - Power domain (short time scales: fractions of seconds to several minutes) → power systems operation and control
    - Energy domain (long time scales: hours to years) → power systems optimization and planning
Concerning integration...

**Power** related domain: power system operation and control

**Energy** related domain: power system optimization and planning

- Primary reserve
- Secondary reserve
- Grid stability
- Transmission efficiency
- Congestion management
- Reduced emissions
- Hydro/thermal efficiency
- Adequacy of power
- Adequacy of grid

System wide: 1000-5000 km
Regional: 100-1000 km
Local: 10-50 km

ms...s  s...min  min...h  1...24 h  years
Electric Power Systems

Definitions

• What is a power system? What is it used for? And how big can it be?

• An (electric) power system is a set of power components (loads, generators, transformers, lines), protection devices (breakers, fuses) and metering and communication infrastructure.

• The function of a power system is to convert energy from one of the naturally available forms (chemical, thermal, mechanical) to the electrical form and to transport it to the points of consumption.

• The size can vary from few elements to an - almost endless - number of components.
Electric Power Systems
Example: Alpine refuge
European Electric Power Systems
Electric Power Systems

Examples: Danish

Danish TSO (ENERGINET):
http://energinet.dk/Flash/Forside/index.html

Energy market Denmark data:
http://www2.emd.dk/el/

Energinet database:
ftp://ftp.energinet.dk/
User: Endkftp
Pass: martin$!aston

Irish TSO (EIRGRID):
http://www.eirgrid.com/operations/systemperformance/data/

Spanish TSO (Red Electrica):
https://demanda.ree.es/movil/peninsula/demanda/total
Electric Power Systems

**System Requirements**

- A properly designed and operated power system should meet the following requirements:

  - The system must be able **to follow the variable** (but fortunately predictable) **load demand**.

  - The system should supply with minimum ecological impact and at minimum cost.

  - The quality of power supply must meet certain standards, identified by a **constancy of frequency and voltage** and a high level of reliability.
Power systems main actors
Electric Power Systems
Main actors

• The main actors are the generating units. Conventional power stations typically use synchronous generators with a highly predictable supply of “fuel”, be this hydro (when based on substantial water reservoir otherwise it can be also intermittent), nuclear, coal, oil, gas or other resources.

• Along with generators, there are other participants:
  - Transformers (HV/HV; HV/MV; MV/LV)
  - Lines and cables (transmission and distribution)
  - Loads (static, dynamic, inverter-driven)
  - Protection devices (breakers, disconnectors, fuses...)
  - Others (capacitors, reactors, HVDC...)
Electric Power Systems
synchronous machines

• Synchronous generators form the main source of electric energy.

• They are the “workhorses” of power systems and are installed in basically all types of conventional power plants: steam turbine (Rankine cycles) and gas turbine (Brayton cycle) powered.

• Consists of two sets of windings:
  - 3 phase armature winding on the stator distributed with centres 120 deg apart in space
  - field winding on the rotor supplied by DC (may be excited or with permanent magnets)
Electric Power System
synchronous machines
Electric Power System
transformers

• Transformers enable the power transfer at different voltage levels.

• It is the key element that allows energy to be transmitted over long distances.

• Depending on role and voltage levels, it goes under different names:
  
  - Generation transformer (or step-up), generally used in power plants to rise the voltage and inject power in the bulk power system (6-20 kV to 132-220-400 kV)
  
  - Substation/primary transformers used for supplying distribution grid areas (132-220-400 kV to 10-20 kV). Also called HV/MV transformers
  
  - Cabin/distribution transformers used for supplying LV distribution grids (10-20 kV to 400-690 V)
Electric Power System

transformers
Electric Power System
transmission and distribution lines

- Electric power is transferred from generating stations to consumers through overhead lines and cables.

- Overhead lines are used for long distances in open country and rural areas, whereas cables are used for underground transmission and distribution in urban areas.

- Lines are generally characterized by four parameters:
  - series resistance (R) due to conductor resistivity
  - shunt conductance (G) due to currents along insulator strings and corona effect; it is small and usually neglected
  - series inductance (L) due to magnetic field surrounding the conductor
  - shunt capacitance (C) due to the electric field between the conductors
Electric Power System
lines and cables
Electric Power System Loads

• When analyzing relatively big power systems, it is quite often impossible to know in detail the information of every single device connected (and even if known, it would add complexity which not necessarily bring benefits). Therefore most of the times an aggregated load is used.

• Depending on the system scale a load can include a group of houses (a LV feeder) or a large urban area (several MV feeders) or an entire city (several primary substations)

• Loads are traditionally classified into:
  – Static load models
  – Dynamic load models (motors)
Power systems stability
induction machines

- Extremely robust, cheap and efficient
- Cannot be controlled and need reactive compensations (unless equipped with an inverter)
Electric Power Systems

Customer requirements

• **What is that you, as customers, are really interested in?**
  - The power is present in the socket (and the appliances switch on when connected)!

• The quality of power supply is defined by specific standards, the most important of which are:
  - Constancy of voltage (230±23 V or ±10%)
  - Constancy of frequency (50.0±0.1 Hz or ±0.2%)

Some types of load

- Does a load really care about changes in power system variables: (frequency and voltage) – survey!
Electric Power Systems

Load demand

• How big and how variable is the electric consumption for the whole Europe (500 million people)?

- People: 500 mil.
- Peak load: 528 GW
- Minimum load: 231 GW
- Yearly consumption:
  - 3300 TWh (of which 400 internally exchanged)
  - losses around 1.5%

• Source: ENTSO-E statistical factsheet
Electric Power Systems

Load demand

- And how is this power & energy provided?
- Installed power capacity in 2000: 445 GW
- Installed power capacity in 2013: 900 GW -> doubled!
- Source EWEA statistical factsheet

**FIGURE 2.3: EU POWER MIX 2000**

- Coal: 133,220 TWh (25%)
- Nuclear: 122,966 TWh (23%)
- Gas: 91,922 TWh (17%)
- Fuel Oil: 62,166 TWh (11%)
- Wind: 12,887 TWh (2%)
- Biomass: 4,568 TWh (1%)
- Geothermal: 592 TWh (0%)
- Peat: 1,667 TWh (0%)
- Ocean: 248 TWh (0%)
- PV: 125 TWh (0%)
- CSP: 0 TWh (0%)

**FIGURE 2.4: EU POWER MIX 2013**

- Nuclear: 122,328 TWh (14%)
- Coal: 171,405 TWh (19%)
- Gas: 201,000 TWh (22%)
- Wind: 117,288 TWh (13%)
- Hydro: 140,054 TWh (16%)
- PV: 80,000 TWh (9%)
- Geothermal: 765 TWh (0%)
- Ocean: 262 TWh (0%)
- Peat: 1,808 TWh (0%)
- CSP: 2,309 TWh (0%)
- Waste: 4,219 TWh (1%)
- Biomass: 11,288 TWh (1%)
Renewable sources
PV and wind
Renewable sources
PV and wind

• The electric behavior of PV and wind sources is determined by the type of generators and by the type and settings of the protections associated.

• Photovoltaic system are today equipped with PWM inverter and DC choppers (with MPPT logic), therefore the type of power system response is determined by the dynamic of the inverter.

• The most relevant issues are:
  – No inertia contribution
  – No fault (very limited) current contribution
  – Limited (but may be extended) reactive power capability
  – No active power regulation capability (over-frequency reduction may be implemented)
  – LVRT capability implemented recently
Electric Power System
PV and wind sources

• Wind turbines are today mainly equipped with full converter (PWM inverter) or DFIG generators, therefore the type of power system response is determined by the dynamic of the inverter and/or doubly fed induction generators.

• Old wind turbines were equipped with squirrel cage induction machines.

• The most relevant issues are:
  - limited inertia contribution (may be extended)
  - limited current contribution (depending on the typology)
  - limited (but may be extended) reactive power capability
  - No active power regulation capability (over-frequency reduction may be implemented)
  - LVRT capability implemented recently
The average wind speed
The average solar irradiance
The average solar irradiance in Europe
The average solar irradiance in Europe
Solar power

In all cases photovoltaic modules are connected to the grid through a PWM converter.
Solar module power curve
Renewable sources
how the power profile looks like

- **Solar power** – Risø 10 kW PV plant – 4th May 2013

![PV Power Graph]
Wind power curve

- Area relative power in the wind flow (blue)
- Maximum wind turbine production with a $c_p$ equal to 0.5 (light blue)
- Practical wind turbine production curve (green)
- Power coefficient (orange)

\[ P_{\text{rotor}} = \frac{1}{2} c_p \cdot \rho \cdot A \cdot U^3 \]

- $A$ (m$^2$), rotor area
- $U$ (m/s), wind speed
- $\rho$ (kg/m$^3$), air density
- $c_p$ (pu), aerodynamic power coefficient (which quantifies the amount of power that the rotor extracts from the wind)
Wind power generators

The first concept, the **type A**, is the oldest and the cheapest wind turbine: it consists of a directly grid-connected squirrel-cage induction machine (SCIM), the rotor of which is connected to the turbine shaft through a gearbox. Because of its nature the induction machine consumes reactive power from the grid whether it is operating as a motor or as a generator.

- **WTG type B** is very similar to type A, except that now there is a variable rotor resistance in the induction machine. This variable rotor resistance can be achieved using a wound rotor induction machine (WRIM), which gives electrical access to the rotor circuits.

- **WTG type C** also uses an induction machine. This time the induction machine is always a WRIM. The stator circuit is connected directly to the grid and the rotor circuit is connected to the grid using a pair of back-to-back pulse width modulated voltage source converters (PWM VSCs).

- **WTG type D** includes all the turbines whose generator (either synchronous or asynchronous) is fully decoupled from the grid, by means of an electronic converter. Hence this converter must be rated at the nominal power of the WT, making it the most expensive concept to manufacture.
Wind power generators – type C

- Wind vane, anemometers
- Lightning arresters
- Obstacle light
- Cooling systems
- Overhead crane
- Disk brake
- Yaw drive
- Machine frame
- Hydraulic unit
- Platform Service-lift
- Tower
- Access to rotor hub
- Rotor hub
- Pitch bearing
- Pitch drive
- Rotor blade
Renewable sources

*how the power profile looks like*

- **Wind power:** Horns rev wind farm 160 MW – January 2005 (sample time 5 min)

![Graph showing power fluctuations during a day with many rain showers](image-url)
Renewable sources
how the power profile looks like

- 10 MW wind farm (2 MW machine)
  South Italy – 1 second sample time
- The first diagram shows 5 wind profiles.
- The respective power output in per unit on machine base (2 MW) follows.
- The park output can be seen in the last diagram, in per unit again but on park base (10 MW).

<table>
<thead>
<tr>
<th></th>
<th>WT 1</th>
<th>WT 2</th>
<th>WT 3</th>
<th>WT 4</th>
<th>WT 5</th>
<th>FARM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avarage Output Power (pu)</td>
<td>0.606</td>
<td>0.577</td>
<td>0.551</td>
<td>0.528</td>
<td>0.367</td>
<td>0.526</td>
</tr>
<tr>
<td>Avarage Power Turbulence (%)</td>
<td>19.3 %</td>
<td>20.1 %</td>
<td>20.9 %</td>
<td>21.7 %</td>
<td>25.7 %</td>
<td>11.8 %</td>
</tr>
</tbody>
</table>
## Renewable sources

### Wind power variation rates

<table>
<thead>
<tr>
<th>Region</th>
<th>Region size</th>
<th>Numbers of sites</th>
<th>10-15 minutes</th>
<th>1 hour</th>
<th>4 hours</th>
<th>12 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max decrease</td>
<td>Max increase</td>
<td>Max decrease</td>
<td>Max increase</td>
</tr>
<tr>
<td>Denmark</td>
<td>300 x 300 km²</td>
<td>&gt; 100</td>
<td>-23%</td>
<td>+20%</td>
<td>-62%</td>
<td>+53%</td>
</tr>
<tr>
<td>West-Denmark</td>
<td>200 x 200 km²</td>
<td>&gt; 100</td>
<td>-26%</td>
<td>+20%</td>
<td>-70%</td>
<td>+57%</td>
</tr>
<tr>
<td>East-Denmark</td>
<td>200 x 200 km²</td>
<td>&gt; 100</td>
<td>-25%</td>
<td>+36%</td>
<td>-65%</td>
<td>+72%</td>
</tr>
<tr>
<td>Ireland</td>
<td>280 x 480 km²</td>
<td>11</td>
<td>-12%</td>
<td>+12%</td>
<td>-30%</td>
<td>+30%</td>
</tr>
<tr>
<td>Portugal</td>
<td>300 x 800 km²</td>
<td>29</td>
<td>-12%</td>
<td>+12%</td>
<td>-16%</td>
<td>+13%</td>
</tr>
<tr>
<td>Germany</td>
<td>400 x 400 km²</td>
<td>&gt; 100</td>
<td>-6%</td>
<td>+6%</td>
<td>-17%</td>
<td>+12%</td>
</tr>
<tr>
<td>Finland</td>
<td>400 x 900 km²</td>
<td>30</td>
<td>-16%</td>
<td>+16%</td>
<td>-41%</td>
<td>+40%</td>
</tr>
<tr>
<td>Sweden</td>
<td>400 x 900 km²</td>
<td>56</td>
<td>-17%</td>
<td>+19%</td>
<td>-40%</td>
<td>+40%</td>
</tr>
</tbody>
</table>

Control of frequency and voltage
Electric Power Systems

Overall structure
Electric Power Systems

Overall structure
Electric Power Systems
role of frequency-voltages-currents

• **Electric power is the product of two quantities: current and voltage.** These two quantities can vary with respect to time (AC power) or can be kept at constant levels (DC power).

• Generally large – conventional – power systems use AC power and three phase systems (i.e. voltages and currents waves shifted 120°).

• A power system is generally operated synchronously and therefore is identified by a nominal – unique – value of frequency.

• Frequency is a derived measure since it identifies the number of zero-crossing of the voltage sine wave every second (i.e. 50 Hz and 60 Hz) and is linked to the rotational speed of generators and motors.

• **Frequency can be considered as a measure of the power balance between production and consumption.**
Considerations about active and reactive power

- In a practical transmission system (high voltage), normally:
  - the active power flow is determined primarily by angular differences between bus voltages
  - the reactive power flow by magnitude differences of bus voltages. It is not advisable to transmit it over long distances, since it would require a large voltage gradient to do so.

- Active power is supplied only by generators:
  - the desired flow of active power from a generator is achieved by control of prime mover mechanical torque.
  - Increasing the mechanical torque advances the generator rotor and hence, the "internal voltage" position with respect to other system voltages.

- Reactive power may be supplied by a large set of components (generators in primis, but also capacitors, reactors...)

Electric Power Systems
Ancillary services

• In order to control:
  – power balance (i.e. constancy of frequency),
  – power transfer capability (i.e. constancy of voltage),
  – loading capability (i.e. current capacity of line/transformer)

• A number of services are required by the power systems components – namely ancillary services:
  – Scheduled power generation (market based – merit order)
  – f/P Control (frequency/active power control)
  – Inertial response
  – V/Q control (voltage/reactive power control)
  – Fault current contribution
  – Fault ride through
Electric Power Systems
Ancillary services provision by renewables

- Wind and PV generation can in principle be used for the provision of most the previously described services, depending on the resource availability at a specific time.

- Naturally, as is also the case for conventional generation used for this purpose, wind generators would then not be operated at their maximum power production capability, but instead at a reduced value.

- It should be pointed out that an important difference is that, in the case of curtailing wind energy, this ‘green’ form of energy gets lost, whereas in hydro and fossil power plants the energy source is saved and can be used later.

- The “fuel” costs of the power plant do not decrease during curtailment, which causes some reluctance by wind/PV operators towards curtailment as virtually all production costs consist of capital costs.
Electric Power Systems

*Power balancing – let’s analyze it*

- Power balancing needs to be addressed at all time scales (from seconds to seasons).
- While it may be (sometime) more clear/straightforward the need for balancing at longer timescales (day-weeks-months)...
- ...the instantaneous power balance is something a little bit more elegant!

\[ P_m - P_e = J \omega \frac{d\omega}{dt} \]

- Where:
  - \( P_m \) is the produced and \( P_e \) the consumed power at system level
  - \( J \) is the system inertia (sum of all rotating masses)
  - \( \omega \) is the electric rotational speed of the machines (equal to \( 2\pi f \))
Frequency dynamic in power systems

Reserve size: biggest unit outage of a system, generally equal to 1-2\% of the current power.
Frequency dynamic in power systems

A numerical example

- \( P_m - P_e = J\omega \frac{d\omega}{dt} \) comes from \( T_m - T_e = J \frac{d\omega}{dt} \)

- By defining the inertia constant: \( H = \frac{1}{2} \frac{J\omega_m^2}{V A_{\text{base}}} \) (H ranges from 2 to 6 seconds)

- And expressing in pu system (where \( f \) is frequency in pu and \( p \) is power in pu):

- \( p_m - p_e = 2H \frac{df}{dt} \)

- Hp: \( p_m - p_e = -0.01 \) (load step 1%); \( 2H = 10 \) seconds

- \( \Rightarrow \frac{df}{dt} = -0.01/10 = -0.1 \%/s;\)

- it means that, with a load step of 1%, every second the system frequency will be declining 0.1% (i.e. 50 mHz) from the nominal value (50 Hz).

- In 10 seconds the frequency will drop from 50 Hz to 49.5 Hz!
Frequency dynamic in power systems

Considerations

• What will happen when the amount controllable share of $p_m$ will decrease due to increase of “uncontrollable” sources?

$$p_m - p_e = 2H \frac{df}{dt}$$

- In the past the share of controllable $p_m$ was close to 100% and $p_e$ very close to 0% (a part from under-frequency load shedding).
- By increasing renewable share, we have introduced a part which is not controllable, in certain situations it may happen that $p_{m\text{- uncontrollable}}$ may reach 50% or even more
- Moreover, the overall system inertia is getting lower and lower!

• Possible solutions?

- Move the controllability part to the load ($p_e$)
- Accepting a power quality degradation (i.e. no more 50.0±0.2%)
Electric Power Systems

Conclusions

• We went through the **working principles of modern power systems** analyzing their functionality, structure, purpose and participants.

• We listed the **customer power quality requirements** and the problem which may be encountered if these values are not respected.

• We analyzed the power demand at system level and investigated the challenges in integrating renewable sources in power systems – focusing on the short term balancing.

• (Renewable sources) integration is challenging!

• **Power systems tend to be conservative systems** because any error in the operation can suddenly lead to blackouts and wrong planning decision can lead in power shortage in some years (or increase of energy prices!).
Electric Power Systems

References

• ENTSOE reports
• EWEA reports
• http://en.wikipedia.org/wiki/List_of_largest_power_stations_in_the_world