ICAI – Master Ingeniería industrial (MII)

Operation of Electric Power Systems
Chapter 1: Overview of technical and economic operation of PS (Part I & II)

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Javier García
Efraím Centeno
Andrés Díaz Casado
Basic technical characteristics and functions

Content

• Part I: Introduction and basic concepts
  • The role of electric power systems in economy
  • The particular characteristics of electricity
  • Activities involved by the electricity sector
  • The need to transport the electricity/some examples

• Part II: Technical and organizational historic evolution
  • Historic evolution of technical aspects and demand
  • Historic evolution on how to organize the sector
  • The future of power systems

• Part III: Basic characteristics and technical aspects
  • Consumption
  • Generation
  • Transport
  • Distribution
  • Control and protection of power systems

• Part IV: Two management paradigms of power systems
Part I

Introduction and basic concepts

• The role of electric power systems in economy
• The particular characteristics of electricity
• Activities involved by the electricity sector
• The need to transport the electricity/some examples
Introduction and basic concepts
The importance of power systems

Earth at Night
More information available at:

Astronomy Picture of the Day
2002 August 11
Introduction and basic concepts

The importance of power systems

• Secondary energy source
  • Transformed from primary energy sources

• It is a versatile and clean (at the consumption place)

• Highly correlated with the GDP

[Graph showing the correlation between Electricity, GDP, Primary sources, and Population]
Introduction and basic concepts
The importance of power systems

• Yearly variation of % electricity growth and GDP in developed countries

Source: EIA
Introduction and basic concepts
The importance of power systems

Yearly Spanish peninsular demand 2015: 248.000 GWh with a peak at 40 GW
Growth rate corrected in 2015: 1.5% (no growth since 2010)

Source: INE y REE
Introduction and basic concepts
The importance of power systems

- Relationship between GDP and electricity consumption worldwide (per capita terms)

Source: Energía y sociedad
Introduction and basic concepts
Elect. in the global energy system

* Transformation of fossil fuels from primary energy into a form that can be used in the final consuming sectors. ** Includes losses and fuel consumed in oil and gas production, transformation losses and own use, generation lost or consumed in the process of electricity production, and transmission and distribution losses.

(*) In 2013, wind/solar/tide accounted for 95 Mtoe (IEA)

1 Mtoe – 11.6 TWh
Introduction and basic concepts

The importance of power systems

### Table: Consumo de Energía Primaria (Ktep)

<table>
<thead>
<tr>
<th>Source</th>
<th>2015</th>
<th>2016</th>
<th>% Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbón</td>
<td>13,686</td>
<td>10,442</td>
<td>-23.7%</td>
</tr>
<tr>
<td>Petróleo</td>
<td>53,171</td>
<td>54,633</td>
<td>2.7%</td>
</tr>
<tr>
<td>Gas natural</td>
<td>24,533</td>
<td>25,035</td>
<td>2.0%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>14,934</td>
<td>15,260</td>
<td>2.2%</td>
</tr>
<tr>
<td>Hidráulica</td>
<td>2,397</td>
<td>3,130</td>
<td>30.6%</td>
</tr>
<tr>
<td>Eólica, Solar y Geotérmica</td>
<td>7,476</td>
<td>7,394</td>
<td>-1.1%</td>
</tr>
<tr>
<td>Biomasa, biocarb. y resid. renovables</td>
<td>6,787</td>
<td>6,688</td>
<td>-1.5%</td>
</tr>
<tr>
<td>Residuos no renovables</td>
<td>252</td>
<td>243</td>
<td>-3.7%</td>
</tr>
<tr>
<td>Saldo imp-exp electricidad</td>
<td>-11</td>
<td>659</td>
<td>5,863,8%</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>123,225</strong></td>
<td><strong>123,484</strong></td>
<td><strong>0.2%</strong></td>
</tr>
</tbody>
</table>

**FUENTE: SEE**

### Pie Chart: Consumo de Energía Primaria en 2016 (Sin Incluir Saldo Eléctrico)

- Eólica, Solar y Geotérmica: 6,0%
- Biomasa, biocarb. y resid. renovables: 5,4%
- Resid. no renovables: 0,2%
- Nuclear: 8,5%
- Gas natural: 20,4%
- Petróleo: 44,5%

**FUENTE: SEE**

### Graph: Intensidad Energética Primaria

- Year range: 2000 to 2018
- Data source: SEE

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**Operation of Electric Power Systems**

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Chapter 1: Overview of technical and economic operation of PS (Part I & II)

Course 2019-2020
## Introduction and basic concepts

### The importance of power systems

#### CONSUMO DE ENERGÍA FINAL (KTEP)

<table>
<thead>
<tr>
<th></th>
<th>2015</th>
<th>2016</th>
<th>Tasa de variación %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbón</td>
<td>1.276</td>
<td>1.100</td>
<td>-13,8</td>
</tr>
<tr>
<td>Gases Derivados del Carbón</td>
<td>239</td>
<td>240,2</td>
<td>0,6</td>
</tr>
<tr>
<td>P. Petrolíferos</td>
<td>40.323</td>
<td>41.266</td>
<td>2,3</td>
</tr>
<tr>
<td>Gas</td>
<td>13.218</td>
<td>13.446</td>
<td>1,7</td>
</tr>
<tr>
<td>Electricidad</td>
<td>19.955</td>
<td>20.115</td>
<td>0,8</td>
</tr>
<tr>
<td>Energías renovables</td>
<td>5.306</td>
<td>5.384</td>
<td>1,5</td>
</tr>
<tr>
<td>Total usos energéticos</td>
<td>80.317</td>
<td>81.550</td>
<td>1,5</td>
</tr>
</tbody>
</table>

#### Usos no energéticos:

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbón</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Prod. Petrolíferos</td>
<td>3.874</td>
<td>3.879</td>
<td>0,1</td>
</tr>
<tr>
<td>Gas natural</td>
<td>436</td>
<td>445</td>
<td>2,0</td>
</tr>
<tr>
<td>Total usos finales</td>
<td>84.628</td>
<td>85.874</td>
<td>1,5</td>
</tr>
</tbody>
</table>

#### INTENSIDAD ENERGÉTICA FINAL

![Graph showing energy intensity]

**FUENTE:** SEE
Introduction and basic concepts
The importance of power systems

Estructura de la generación eléctrica peninsular en el 2017 y 2018 (%)

<table>
<thead>
<tr>
<th></th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>TURBINACIÓN BOMBEO</td>
<td>0,9</td>
<td>0,8</td>
</tr>
<tr>
<td>NUCLEAR</td>
<td>22,4</td>
<td>21,5</td>
</tr>
<tr>
<td>CARBÓN</td>
<td>17,1</td>
<td>14,1</td>
</tr>
<tr>
<td>CICLO COMBINADO</td>
<td>13,6</td>
<td>10,7</td>
</tr>
<tr>
<td>COGENERACIÓN</td>
<td>11,3</td>
<td>11,9</td>
</tr>
<tr>
<td>RESIDUOS NO RENOVABLES</td>
<td>1,0</td>
<td>0,9</td>
</tr>
<tr>
<td>RESIDUOS RENOVABLES</td>
<td>0,3</td>
<td>0,3</td>
</tr>
<tr>
<td>EÓLICA</td>
<td>19,1</td>
<td>19,8</td>
</tr>
<tr>
<td>HIDRÁULICA</td>
<td>7,4</td>
<td>13,8</td>
</tr>
<tr>
<td>SOLAR FOTOVOLTAICA</td>
<td>3,2</td>
<td>3,0</td>
</tr>
<tr>
<td>SOLAR TÉRMICA</td>
<td>2,2</td>
<td>1,8</td>
</tr>
<tr>
<td>OTRAS RENOVABLES</td>
<td>1,5</td>
<td>1,4</td>
</tr>
</tbody>
</table>

2017 2018
RENOVABLES 33,7 40,1
NO RENOVABLES 66,3 59,9

Fuente: REE
Introduction and basic concepts
The importance of power systems

Chapter 1: Overview of technical and economic operation of PS (Part I & II)
Course 2019-2020
Introduction and basic concepts
Basic characteristics of electricity

What makes electricity a particularly complex commodity?

VS
Introduction and basic concepts
Basic characteristics of electricity

It cannot be stored

- Consumption is produced (transported) in real time

It is injected and extracted in the different nodes, but the flow cannot be directed

- It follows Kirchhoff laws (not commercial transactions between two parties)
- From the moment a line is congested, the cheaper generation cannot always be dispatched

The electricity system is a dynamic system which has to ensure the gen-demand balance

- Failure of one element introduces perturbations
- Rapidly spread: reserves needed
Introduction and basic concepts
Basic characteristics of electricity

Power flows can only be directed respecting the laws of electricity:
- Bus voltaje control
- Power injection in buses

Figure 8: Average unscheduled flows for the years 2011 and 2012, MWh/h^2

Source: THEAM Consulting Group, based on data from 16 TSOs
Introduction and basic concepts
Basic characteristics of electricity

• Control center REE (CECOEL y CECORE)

• Control centre REE (CECRE)

Continuous monitoring is needed

Powerful computers run models
• Estimate demand
• Simulate the generation
• Network flows
• Contingencies
Several available technologies
Investments (optimal mix)
Planning/Operation

Coordination by the System Operator:
- Feasible production program
- International interchanges

Color Key:
Red: Generation
Blue: Transmission
Green: Distribution
Black: Customer

Networks: Transmission / Distribution
Investments
Maintenance
Operation

Metering
Billing
Introduction and basic concepts
The need to transport electricity

• Electricity systems are conditioned by:
  • Location of demand
    • Urban and industrial areas
  • Location of generation
    • Large scale generation is conditioned by the availability of resources
    • Distributed generation is conditioned to a much lesser extent
  • System’s geographical typology (e.g. radial or not)

Introduction and basic concepts
The need to transport electricity

- Spain (conventional generation and consumption)
Introduction and basic concepts

The need to transport electricity

- Spain (transmission)
Introduction and basic concepts
A global perspective

- Some systems
Introduction and basic concepts
A global perspective

• Typologies
Introduction and basic concepts
A global perspective

United States transmission grid
Source: FEMA
Introduction and basic concepts
A global perspective

• EU-27
  • 4,3 Mkm²,
  • 493 Mhab,
  • 11597 b€ GDP
  • 741 GW installed capacity
  • 3309 TWh/year

  (Installed capacity, annual production)
  • Germany (___ GW, ___ TWh)
  • France (___ GW, ___ TWh)
  • UK (___ GW, ___ TWh)
  • Italy (___ GW, ___ TWh)
  • Spain (108 GW, 248 TWh)

• USA
  • 9,8 Mkm²,
  • 300 Mhab,
  • 13195 b$ GDP
  • 1076 GW installed capacity
  • 4200 TWh/year

  • PJM (___ GW, ___ TWh)
  • ERCOT (___ GW, ___ TWh)
  • California (___ GW, ___ TWh)
  • NY-ISO (___ GW, ___ TWh)
  • NE-ISO (___ GW, ___ TWh)
Introduction and basic concepts
A global perspective

- **EU-27**
  - 4.3 Mkm²,
  - 493 Mhab,
  - 1,159,700 b€ GDP
  - 741 GW installed capacity
  - 3,309 TWh/year

(Installed capacity, annual production)
  - Germany (194 GW, 651 TWh)
  - France (129 GW, 546 TWh)
  - UK (81 GW, 336 TWh)
  - Italy (121 GW, 269 TWh)
  - Spain (108 GW, 248 TWh)

- **USA**
  - 9.8 Mkm²,
  - 300 Mhab,
  - 13,195 b$ GDP
  - 1,076 GW installed capacity
  - 4,200 TWh/year

- PJM (183 GW, 837 GWh)
- ERCOT (80 GW, 347 TWh)
- California (79 GW, 195 TWh)
- NY-ISO (39 GW, 142 TWh)
- NE-ISO (31 GW, 136 TWh)
Introduction and basic concepts
A global perspective

• Generation location is changing
Introduction and basic concepts
A global perspective

• Generation location is changing

Source: Matt Mcdonald, 2015, “Integration of Variable Renewable Energy”, prepared for the IEA
Introduction and basic concepts
A global perspective

- Generation location is changing

Source: Matt Mcdonald, 2015, “Integration of Variable Renewable Energy”, prepared for the IEA
Part II

Historic evolution of power systems

• Evolution of consumption
• Evolution technical aspects
• Evolution of the structure and organization
  • Who takes the decisions?
• The future of power systems
Historic evolution of power systems

History of Power Systems

<table>
<thead>
<tr>
<th>ORIGIN</th>
<th>DEVELOPMENT</th>
<th>GOLDEN AGE</th>
<th>LIBERALIZATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1796 Volta Battery</td>
<td>1831 Electromagnetic induction</td>
<td>1947 CEGB</td>
<td>1982 REE</td>
</tr>
<tr>
<td>1879 Incandescence lamp</td>
<td>1896 Niagara Waterfalls power plant (AC)</td>
<td>1946 EDF</td>
<td>1988 ABB</td>
</tr>
<tr>
<td>1877 Street arc lamps in Paris</td>
<td>1882 First power plant. Edison.</td>
<td>1962 ENEL</td>
<td>2000</td>
</tr>
<tr>
<td>1884 ZBD: first transformer</td>
<td>1891 First three-phase system. Germany.</td>
<td>1973 Oil crisis</td>
<td>2011 Fukushima</td>
</tr>
</tbody>
</table>

HE: Madrid, 1907
Iberduero: Bilbao, 1944
Endesa: Ponferrada, 1944
Introduction and basic concepts
The early history of electricity

• First systems date from 1870
  • Individual generators supplying arc lamps
• Thomas Edison invents incandescence lamp (1880)
  • The scale increases (one generator and many lamps)
• Local generation plus distribution systems (lightning)
• Invention of transformer
  • Allows to easily raise voltage (reduce losses)
• War of Currents: AC vs. DC
• Frequency is not homogenized: two groups
  • 60 Hz (EEUU, Canada, Center America, Brasil, North Japan)
    • The higher the frequency, the more compact equipment's are
    • But reactance in line increases
  • 50 Hz (South America, Europe, Africa, South Japan)
Evolution of voltage (kV)

TENSION DE SERVICIO (entre fases) kV

- USA
- URSS
- Brasil
- Mozambique
- Canada
- Inglaterra-Francia
- Suecia
- Nueva Zelanda

Year:
- 1900
- 1920
- 1940
- 1960
- 1980
- 2000
Standardization of electricity led to a constant increment of consumption.
Introduction and basic concepts
Evolution of production in Europe

Total Electricity Net Generation (TWh)

Fuente: http://www.eia.gov/
Elaboración propia
Introduction and basic concepts
How to organize the sector?

• Who takes the decisions involved by each activity?
• The answer has evolved with time, adapting to:
  • Technological developments
  • Prevailing economic theories in each time and place
Introduction and basic concepts
The vertically integrated company

• The concept of vertical integrated company naturally arises
  • That is, a company that generates, transports, distributes and commercializes electricity.

• Strong economies of scale lead to monopolies

• Essential good: the characteristic of essential good led to government intervention to ensure availability and affordability
  • Nationalization of the industry (Europe until the 90s)
  • Regulated monopoly

• The vertical integrated structure was not questioned
Introduction and basic concepts
Opening the sector to competition (Deregulation)

• Motivated by technical and economic reasons
  • Reduction of economies of scale
    • New generation technologies
    • Development of the network increases the relevant market
  • Prevailing economic theories

• In the early 80s it was put into question
  • The vertical integration
  • The monopolistic structure

• Unbundling of network business from generation
  • Network businesses (transmission and distribution) are regulated
  • Generation and retail are open to competition
Deregulation? Not everywhere

Image Source: www.deregulationofenergy.com
Anualidades Déficit Actividades reguladas: 2872 M€
Superávit actividades reguladas: -175 M€
Compensación Extrapeninsular: 741 M€
2º ciclo Combustible nuclear: 0,14 M€
Tasa CNMC: 21 M€
Prima Régimen Especial: 6.726 M€
Interrumpibilidad: 8,3 M€
Pagos por Capacidad: 512 M€

Transporte 1.764 M€
Distribución 5.024 M€
Gestión comercial del suministro 57 M€

Energía Mercado*
62,86 €/MWh
15.549 M€

CONSUMIDOR FINAL
33.274 M€
247.216 GWh
Energía (47%)
Regulados (53%)

Costes regulados/acceso
Mercado liberalizado
Pago cliente final

Fuente: CNMC - Liquidación Provisional 1/2016 del Sector Eléctrico (03/16)
*estimación según datos de OMIE para el año.
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Introduction and basic concepts
The economic weight of each activity

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Introduction and basic concepts

The electricity tariff

Electricity prices for household consumers, second half 2015 (¹) (EUR per kWh)

Data extracted in July 2016. Eurostat information.

¹ Annual consumption: 2 500 kWh < consumption < 5 000 kWh.
² Taxes and levies other than VAT are slightly negative and therefore the overall price is marginally lower than that shown by the bar.
Introduction and basic concepts

The electricity tariff

Electricity prices for industrial consumers, second half 2015 (¹) (EUR per kWh)

Data extracted in July 2016. Eurostat information.

(¹) Annual consumption: 500 MWh < consumption < 2 000 MWh. Excluding VAT.
Introduction and basic concepts
The future of power systems

• Some of the major challenges:
  • Demand participation
  • Regional markets
  • Decarbonize the sector
    • Integration of Renewable Energy Sources (RES)
  • Integration of distributed generation
    • Smart grids
  • Right to energy
    • Off-grid rural electrification
    • Universal access
    • Fight against energy poverty (in Spain 8-9 % of households)
Introduction and basic concepts
Energy and Poverty

• Energy poverty causes
  • Low income levels (poverty without adjectives)
  • Households low efficiency levels
  • High impact of energy costs on domestic budget (high energy prices)

• Energy poverty measurement
  • Difficult, need for a set of indicators an correlation among them
  • Self-reported (surveys) or data based
  • Arrears on utility bills, energy household expenditures, share of energy expenditure on income, inability to keep home adequately warm
  • EPOV (EU Energy Poverty Observatory)

• Solutions to energy poverty
  • Multidisciplinary approach (technical, economic, legal, social...)
  • Need for a contact with the real problem (NGOs)
  • Structural measures (UN sustainable development goal #7)
  • Palliative short-term measures (Spain: “bono social”)