EEE 577
Power Systems Operation and Planning
G. T. Heydt
Fall 2011
Class meeting time: T Th 1:30 – 2:45
Location: BYAC 210
Additional overflow classroom: LL 148
Notes #1
Introduction to the course
Class policies, grades, homework, prerequisites, and other details

Power generation
Overview of the power industry in the US today
Fuels, heat rates
Generation types
Wind generation
Course objectives

- To provide to the students the basics of electric power system generation, operation, and control. The emphasis is on system operation and operating tools.
- The main points of the course are economic dispatch / optimal power flow studies (OPF), unit commitment, automatic generation control (AGC), and applications of dynamic programming (DP) and linear programming (LP). The role of voltage stability and stability limits in power exchange will be discussed. The various time frames in which these power systems infrastructural elements shall be discussed. Lagrangian relaxation and Mixed Integer Programming shall be described in the context of unit commitment software development.
- To describe the basic elements of renewable generation and their controls: wind, solar thermal, and solar photovoltaic.
- To include a few basic elements of power system planning: capacity outage tables, loss of load probability.
Course objectives

• The course contains an introduction to state estimation applications in power engineering.

• Because of the importance of the deregulation of the electric power industry in the United States, a section of the course is devoted to the topics of restructuring, auctions, and elements of the new deregulated power industry. The term deregulation means that competition has been augmented into power marketing, allowing generation companies and transmission companies to compete in a free market for business. The role of independent system operators, regional transmission organizations, and other newly formed sectors of deregulated power infrastructure shall be described.

• The role of power markets in power engineering shall be described.

• To provide an opportunity in technical writing practice.
Course objectives

- RENEWABLES
- DEREGULATION
- Planning / reliability
- State estimation
- Control / AGC
- Unit commitment
- Economic dispatch / OPF
Power System Operation and Control

Textbook


Reference texts


To contact Prof. Heydt:
Email at heydt@asu.edu
Telephone at 480 965 8307
Fax at 480 965 0745

The course web site

https://myasucourses.asu.edu
Office hours

Office hours will be posted. Dr. Heydt checks his email quite a bit ([heydt@asu.edu](mailto:heydt@asu.edu) – please put EEE577 in subject line). Dr. Heydt’s office telephone is 480 965 8307. Fax 480 965 0745. Ms. Nina Millmyn ([nina.millmyn@asu.edu](mailto:nina.millmyn@asu.edu)) in ERC 509 keeps his calendar.

How to turn in homework

- In class on due date
- As an email attachment to [heydt@asu.edu](mailto:heydt@asu.edu) (put EEE 577 in subject line)
- By fax 480 965 0745
- In my mailbox in ERC 507

Cyber students

Please send your homework by fax or attachment directly to Prof. Heydt – do not send this to CPD.
<table>
<thead>
<tr>
<th>Slide file / week</th>
<th>Topic</th>
<th>Reading</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 8/18-23</td>
<td>Introduction, course policies, generation basics, introduction to renewable generation</td>
<td>Text chapters 1 and 2</td>
</tr>
<tr>
<td>2 8/25-30</td>
<td>Heat rate, generating unit characteristics. Linear programming, Lagrange multipliers</td>
<td>Text chapter 2</td>
</tr>
<tr>
<td>3 9/01*-06</td>
<td>Economic dispatch, Lagrange multipliers, B-coefficients</td>
<td>Text chapter 3, the appendix for chapter 6</td>
</tr>
<tr>
<td>4 9/08-13</td>
<td>The equal incremental cost rule and the method of B-coefficients, Kuhn – Tucker, Dommel-Tinney method, reactive power</td>
<td>Text chapter 4</td>
</tr>
<tr>
<td>5 9/15-20</td>
<td>Dynamic programming, introduction to unit commitment</td>
<td>-</td>
</tr>
<tr>
<td>6 9/22-27</td>
<td>Unit commitment. Lagrangian relaxation. Mixed integer programming, multiobjective optimization, Pareto optimality</td>
<td>Text chapter 5</td>
</tr>
<tr>
<td>7 9/29-10/04</td>
<td>Review for midterm exam, discussion of term paper, practice with DP, take or pay contracts, EMSs.</td>
<td>-</td>
</tr>
<tr>
<td>8 10/06-11</td>
<td>Limited energy supply and hydroelectric energy sources, alarm processing, renewable resources.</td>
<td>Text chapter 6</td>
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</table>

*September 5, 2011 is Labor Day, a national holiday*
<table>
<thead>
<tr>
<th>Slide file / week beginning</th>
<th>Topic</th>
<th>Reading</th>
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<tbody>
<tr>
<td>9 10/13-18</td>
<td>Hydrothermal coordination, production costing, introduction to generation control. Midterm exam this week – 10/13/11.</td>
<td>Text chapters 7, 8, and 9</td>
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<tr>
<td>10 10/20-25</td>
<td>Generation control, PSSs, AGC, wind energy</td>
<td>Text chapter 9</td>
</tr>
<tr>
<td>11 10/27-11/01</td>
<td>Interchange of power, deregulation</td>
<td>Text chapter 10</td>
</tr>
<tr>
<td>12 11/03-08</td>
<td>Deregulation, power marketing, LMPs, E-tags, energy storage</td>
<td>Text chapter 10, papers on deregulation</td>
</tr>
<tr>
<td>14 11/17-22**</td>
<td>Capacity outage tables, combination with load duration curves</td>
<td>Text chapter 11</td>
</tr>
<tr>
<td>15/16 11/29</td>
<td>State estimation.</td>
<td>Text chapter 12</td>
</tr>
<tr>
<td>16 12/01-06</td>
<td>State estimation, term review (the last day of classes at ASU is 12/06/11). Final exam Tuesday 12/13/11 at 12:10 – 2:00 pm</td>
<td>Text chapter 12</td>
</tr>
</tbody>
</table>

*November 11, 2011 is observed as a holiday in AZ: Veterans’ Day

**November 24, 25, 2011 are national holidays: Thanksgiving
Final exam

The final exam is scheduled by the university, and all ASU final exam schedules appear at:
http://students.asu.edu/final-exam-schedule#fall

Our final is scheduled for Tuesday 12/13/11 at 12:10 – 2:00 pm.

Course grade

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight (%)</th>
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<tr>
<td>Project assignment (due 11/10/11)</td>
<td>8</td>
</tr>
<tr>
<td>Homeworks (about 7)</td>
<td>7</td>
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<tr>
<td>Midterm examination (10/13/11)</td>
<td>37</td>
</tr>
<tr>
<td>Final examination (12/13/11, 12:10 – 2:00 pm)</td>
<td>48</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
</tbody>
</table>
Term project assignment

• A computational project
• Relating to inclusion of renewable resources into the power system
• Involves ‘design’ – no single ‘correct answer’
• Different students will have different assigned parts of the assignment
• Grading will be based on accuracy of the solution; use of innovative design; credibility of the solution; documentation of the solution, good technical writing

Find the best power line Sasabe to Tempe
Why is technical writing important?

Read the *Technical Writing Notes* – could be on an exam – will be in homeworks – will be among the criteria for the grading of the term report - can be a career booster

Many students do not appreciate the importance of technical writing – *but consider*:

• Communication is how engineers deliver their work
• If your audience can not understand your engineering solutions, the value of your work is in question
• Years from now, you are likely to value your technical writing skills much more than your ability to use lagrangian relaxation to solve a problem (for example)
• There is a (very) high correlation between engineers who communicate well and those who are successful
Plagiarism and cheating

• You may work with a friend on homeworks, but the work you turn in must be your own – not copied in any way from another student.

• Cheating on exams will not be tolerated and instances shall be turned in to the Dean of Students – NO EXCEPTIONS.

• Do not copy any material or diagram from the literature without full attribution as to where this has come from – with a clear reference and a statement that the material was taken from the literature.
Where these course notes come from

- G. T. Heydt and the course textbook
- Drs. R. Ayyanar and V. Vittal, ASU
- US DoE, Energy Information Agency, NERC, and FERC web sites
- Dr. P. K. Sen, Colorado School of Mines
- Suggestions from Areva T&D
- Dr. S. S. Venkata, KEMA
- Mr. Joseph Eto, Lawrence Berkeley National Laboratories (DoE)
- Prof. A. Dominguez-Garcia, Univ. of Illinois
Course prerequisites

- Basic AC circuits (phasors, impedance, three phase circuits, P, Q, power factor)
- Complex numbers and their manipulation
- Basic differential equations
- Laplace transforms
- Basic algebraic manipulation
- Basic concepts of optimization
- The per unit system
- Vectors, matrices
- Some sophistication in engineering mathematics
- Basic terminology of power engineering including units, energy vs. power, components, and a concept of the magnitudes involved in power systems

If you are unfamiliar with basic AC calculations, the per unit system, and basic three-phase circuits, it is advised that you take a more basic course than EEE 577 before attempting this course.
Overview of power systems

Basic Structure of the Electric System

- **Color Key:**
  - Blue: Transmission
  - Green: Distribution
  - Black: Generation

Consists of three major subsystems
- Generation subsystem
- Transmission subsystem
- Distribution subsystem
Overview of power systems-generation subsystems

• Electric power is produced at lower voltages (10,000 to 38,000 volts) at generators from various fuel sources, such as nuclear, coal, oil, natural gas, hydro power, geothermal, photovoltaic.
• Some generators are owned by the same electric utilities that serve the end-use customer.
• Some are owned by independent power producers (IPPs); and others are owned by customers themselves—particularly large industrial customers.
• Electricity from generators is "stepped up" to higher voltages for transportation in bulk over transmission lines.
• Operating the transmission lines at high voltage (i.e., 230,000 to 765,000 volts AC) reduces the losses of electricity from conductor heating and allows power to be shipped economically over long distances.
• Transmission lines are interconnected at switching stations and substations to form a network of lines and stations called a power "grid."
• Current flows through the interconnected network of transmission lines from the generators to the loads in accordance with the laws of physics—along "paths of least impedance".
Overview of power systems – distribution subsystem

• When the power arrives near a load center, it is "stepped down" to lower voltages for distribution to customers.

• The bulk power system is predominantly an alternating current (AC) system, as opposed to a direct current (DC) system, because of the ease and low cost with which voltages in AC systems can be converted from one level to another.

• Some larger industrial and commercial customers take service at intermediate voltage levels (12,000 to 115,000 volts), but most residential customers take their electrical service at 120 and 240 volts.
Overview of power systems

The North American Interconnection

– This electricity infrastructure represents more than $1 trillion (U.S.) in asset value
– More than 200,000 miles-or 320,000 kilometers (km) of transmission lines operating at 230,000 volts and greater
– 950,000 megawatts of generating capability
– Nearly 3,500 utility organizations serving well over 100 million customers and >300 million people.
Reliable operation of the grid

Reliable operation of the power grid is complex and demanding for two fundamental reasons:

• Electricity flows at close to the speed of light (186,000 miles per second or 297,600 km/s) and is not economically storable in large quantities. Therefore electric power must be produced (more or less) the instant it is used.

• Without the use of control devices too expensive for general use, the flow of alternating current cannot be easily controlled like a liquid or gas by opening or closing a valve in a pipe, or switched like calls over a long-distance telephone network.

• The foregoing implies that electric energy cannot be stored. This is not exactly true: there are storage technologies but they have largely had low impact due to high cost and other technological problems.
Reliable operation of the grid

Maintaining reliability is a complex enterprise that requires trained and skilled operators, sophisticated computers and communications, and careful planning and design.

There is a cost / benefit associated with power system reliability. Would you pay double your present electric bill if you were guaranteed zero outages? Or would you elect to pay half your bill if you could be interrupted for up to an hour per month? The issue is unresolved.

The North American Electric Reliability Corporation (NERC) and its ten Regional Reliability Councils / Corporations have developed system operating and planning standards for ensuring the reliability of a transmission grid that are based on seven key concepts:
Reliable operation of the grid

1. Balance power generation and demand continuously
2. Balance reactive power supply and demand to maintain scheduled voltages
3. Monitor flows over transmission lines and other facilities to ensure that thermal (heating) limits are not exceeded
4. Keep the system in a stable condition
5. Operate the system so that it remains in a reliable condition even if a contingency occurs, such as the loss of a key generator or transmission facility (the "N-1 criterion")
6. Plan, design, and maintain the system to operate reliably
7. Prepare for emergencies.

Balance of power

• Production by the generators must be scheduled or "dispatched" to meet constantly changing demands
• Typically on an hourly basis, and then fine-tuned throughout the hour.
• Automatic generation controls used to continuously match generation to actual demand.
• Demand is somewhat predictable (daily demand curve), highest during the afternoon and evening and lowest in the middle of the night, and higher on weekdays when most businesses are open.
The Regional Reliability Corporations and Councils

- ERCOT: Electric Reliability Council of Texas
- RFC: ReliabilityFirst Corporation
- MRO: Midwest Reliability Organization
- SPP: Southwest Power Pool, Incorporated
- FRCC: Florida Reliability Coordinating Council
- SERC: SERC Reliability Corporation
- NPCC: Northeast Power Coordinating Council, Inc.
- WECC: Western Electricity Coordinating Council

NERC INTERCONNECTIONS

QUEBEC INTERCONNECTION

WESTERN INTERCONNECTION

ERCC INTERCONNECTION

TRE

EASTERN INTERCONNECTION
Deregulation

- What does it mean?
- What is still regulated?
- Vertically integrated companies
- Horizontally integrated companies

- Genco
- Transco
- Disco
- Independent system operator (ISO)
- Regional transmission operator (RTO)
- Federal Energy Regulatory Commission (FERC)
Dollar figures

- $55.3B spent in the USA for transmission expansion in 2001-10 (about $5.5B/year)
- Expected to ‘invest’ $61.2B for transmission expansion in the US 2010 – 2021, about $5.1B per year
- About $18B spent for distribution system expansion annually, US
- ~$85B spent for all expansion in 2008, industry wide, US

Installed generation capacity

- The U.S. electric power industry total installed generating capacity was 1,122 GW (1000 MW = 1 GW) as of December, 2009 which is about 13.8 GW increase per year compared to 2004. The installed US capacity in 2010 is ~1,021 GW.
- In 2009, there were about 17876 generating units in the US
- The projected growth in installed generation (MW, US) over years 2006 – 2030 is about +0.9%/y.
- U.S. shareholder-owned installed generating capacity accounts for approximately 37 percent of total electric power industry installed capacity.

Source: Edison Electric Institute and the US Department of Energy

Useful source of statistical information: www.eia.gov (US DoE)
Customers, sales, and revenues
(US data)

- In 2005, the average number of ultimate customers served by electric utilities totaled 138,367,159 which is a 1.7 percent increase from 2004. In 2007, the number of customers in the US rose to 142,121,652. The growth in number of customers is about 2.6% per year.

- The average annual electricity use per customer was 26 MWh.

- In 2008, the total electric utility revenues from sales to ultimate customers equaled $365.4B which is a 6.3 percent increase from 2007.

- The average AZ revenue (2009) received cents/kWh sold was 9.51 (residential); 8.41 (commercial); 5.82 (industrial).

Source: Edison Electric Institute and US DoE
Some numbers

1/6 barrel of oil = 1 million BTU
1 BTU = 0.293071 watt hours
1 kWh = 3413 BTU

Oil costs ~67 $/bbl in August 2005; ~72 $/bbl in June 2007; 68 $/bbl in July 2009; all time historic high of 124 $/bbl in May 2008. On August 24 2010 oil was at ~74 $/bbl

Average heat content as measured by actual use in 2009: COAL 20.1 Mbtu/ton; OIL 6.1 Mbtu/bbl; NATURAL GAS 1.03 Mbtu/1000 ft³
Some numbers

Combustion of coal: 10,000 Btu energy in coal gives 1 kWh electrical energy

Cost of coal = about 41$ per short ton for 11,700 Btu coal, 1.2% SO$_2$ (in 2011)

Btu content of coal (typical) 14,500 Btu/lb = 31,900 Btu/kg

Mega = $10^6$

Giga = $10^9$

Tera = $10^{12}$

1 US billion = $10^9$

There is another (now archaic) ‘billion’ used in British English meaning $10^{12}$
Who produces electric power?

2009 data

58.8% Central station, genco or electric utilities

41.2% IPPs

Increasing very slowly

Annual US electric energy production in terawatt hours

(1 TWh = 10^{12} Wh = 10^6 MWh)

Rolling year 03/09 4064 TWh

2008 4170 TWh

2007 4157 TWh

2006 4064 TWh

2005 4055 TWh

2004 3970 TWh

2003 3883 TWh

Approximate US growth rate in energy production: +0.3 %/y 2007 - 08

The net generation (MWh) in the United States dropped by +4.3 percent from March 2008 to March 2009. This was the eighth consecutive month that net generation was down compared to the same calendar month in the prior year.
Generation (MWh) mix in the US (2005 vs. 2009)

Coal = 49.7 (44.6) %
Petroleum = 3.0 (1.0) %
Petroleum – coke = 0.2 (0.4) %
Natural gas = 18.7 (23.3) %
Other gas = 0.4 (0.3) %
Nuclear = 19.3 (20.2) %
Hydro = 6.5 (6.9) %
Non-hydro renewables = 2.3 (3.9) %
Pumped storage = -0.2 (-0.1) %
Other = 0.1 (0.3) %

Source: Energy Information Administration / Annual Energy Outlook 2009
Ranked *energy generation* (MWh) sources – top five in the USA in 2005 and 2009

- **2005**
  - COAL
  - NUCLEAR
  - NATURAL GAS
  - HYDRO
  - PETROLEUM

- **2009**
  - COAL
  - NATURAL GAS
  - NUCLEAR
  - HYDRO
  - Non-HYDRO RENEWABLES

- Very close
- Fastest growing
Average US retail price of electricity (cents/kWh) to ultimate customers by end-use sector, year-to-date through March 2008-2009

Source: Energy Information Administration / Annual Energy Outlook 2009
- **Residential cost** in Phoenix metro area: about 7 cents / kWh off peak, 12 cents / kWh on peak
- This is **near the US national average**
- The US cost of electric energy is in the lower (cheaper) quartile of the nations of the world

**Example:** If the total production in the US is 4064 terawatt-hours annually, what is the fuel cost annually using coal at 41 $ per metric ton?

\[
(4064 \text{ TWh/y}) \times (1 \text{ kWh/10}^3 \text{ Wh}) \times (10^4 \text{ Btu of coal/ kWh}) \times (1 \text{ kg coal/31900 Btu}) \times (1 \text{ metric ton/10}^3 \text{ kg}) \times (41 \$/\text{metric ton}) = 4.08 \times 10^{10} \$/\text{year}
\]

= about **52.5 billion** US dollars per year
Retail US electric energy sales in 2008, by sector, in TWh

(1 TWh = 10^{12} Wh)

Residential 1380 TWh (37.0%)
Commercial 1336 TWh (35.8%)
Industrial 1009 TWh (27.0%)
Transportation 7 TWh (0.2%)
Total 3732 TWh

Source: U. S. Energy Information Administration, 2010
In 2009, US electric energy (MWh) generation was 70% fossil fuels, 20% nuclear, and 10% renewable.

2009 Total net generation: 3,953 billion kWh

2009 Non-hydro renewable net generation: 141 billion kWh

- Coal: 44.6%
- Natural gas: 23.3%
- Nuclear: 20.2%
- Conventional hydroelectric: 6.9%
- Other renewable: 3.6%
- Petroleum: 1.0%
- Other gases: 0.3%

Other renewable sources include:
- Wind: 1.8%
- Wood and wood-derived fuels: 0.9%
- Geothermal: 0.4%
- Other biomass: 0.5%
- Solar thermal and PV: <0.1%

Source: EIA Electric Power Monthly, October 2010
## Wind resources

### Table 3. Classes of Wind Power Density at Heights of 10 m and 50 m (a)

<table>
<thead>
<tr>
<th>Wind Power Class</th>
<th>10 m (33 ft)</th>
<th>Speed(b) m/s (mph)</th>
<th>50 m (164 ft)</th>
<th>Speed(b) m/s (mph)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Wind Power Density (W/m²)</td>
<td></td>
<td>Wind Power Density (W/m²)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>4.4 (9.8)</td>
<td>200</td>
<td>5.6 (12.5)</td>
</tr>
<tr>
<td>3</td>
<td>150</td>
<td>5.1 (11.5)</td>
<td>300</td>
<td>6.4 (14.3)</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>5.6 (12.5)</td>
<td>400</td>
<td>7.0 (15.7)</td>
</tr>
<tr>
<td>5</td>
<td>250</td>
<td>6.0 (13.4)</td>
<td>500</td>
<td>7.5 (16.8)</td>
</tr>
<tr>
<td>6</td>
<td>300</td>
<td>6.4 (14.3)</td>
<td>600</td>
<td>8.0 (17.9)</td>
</tr>
<tr>
<td>7</td>
<td>400</td>
<td>7.0 (15.7)</td>
<td>800</td>
<td>8.8 (19.7)</td>
</tr>
<tr>
<td></td>
<td>1,000</td>
<td>9.4 (21.1)</td>
<td>2,000</td>
<td>11.9 (26.6)</td>
</tr>
</tbody>
</table>

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 3%/1000 m (5%/5000 ft) elevation.

* Note: Each wind power class should span two power densities. For example, Wind Power Class = 3 represents the Wind Power Density range between 150 W/m² and 200 W/m². The offset cells in the first column attempt to illustrate this concept.

Source: U. S. Energy Information Administration, 2010

750 kW NEG Micon Turbine in Moorhead Minnesota.
Wind resource potential
All U.S. wind generators, capacity factors

Capacity factor = \( \frac{\text{energy obtained}}{\text{Energy that would have been obtained if run continuously at rating}} \)

Average of distribution = 29%
Central range = 25-35%

Source: 2005 data from Platts
The ‘uncertainty’ of wind generation

A frequently quoted phenomenon: wind generation is often available at night, and at a low level in the day. This is exactly opposite to the availability of solar generation.
Balancing generation and load in the presence of wind power

- Since wind power is not a constant, the system generation needs to be adjusted to accommodate increases and decreases in wind power.
- How? If wind penetration is small, accommodate $\Delta P$ by allowing cycling generators (i.e., generators that receive raise and lower signals from the automatic generation control (AGC) system). You can not raise generation instantaneously, and therefore $\Delta f$ will reflect excess or deficient generation.
- For example, if a deficiency of 40 MW in a given system results in a decrement of frequency of 1.0 mHz, and suddenly a windy condition results in 100 MW of excess generation, $f$ will change from 60 Hz before the event to $60 + 0.001 \times (100/40) = 60.0025$ Hz.
- LBA = load balancing authority – could be automatic, or a quasi-governmental authority
- This is important if wind penetration is high. In 2007, the installed MW of wind was about 1.6% of the total installed capacity. But this does not mean that 1.6% of the energy generated came from wind – the wind capacity factor is about 30% and therefore 1.6% installed capacity is equivalent (roughly) to $1.6 \times 0.30 = 0.48\%$ of the generated energy.
- Some people project that wind energy could go above 20% by 2025.
Reserve margin for systems with wind generation

• A **reserve margin** is available generators that are ready to generate on short notice (e.g., a few seconds to a few minutes). A discussion of the reserve margin calculation for ‘conventional’ systems, and also for systems with wind energy will appear later in the semester.

• **Ramp rates** – must be specified. These are verified periodically by the Independent System Operator (ISO).

• Reserve generation sold to the independent system operator as an **ancillary service**

• How do you set the **reserve margin requirement** for a system with wind generation? Traditionally, this is not an issue since wind penetration is very low (e.g., < 1%), but what happens if wind energy is in the 20% range – or more?
Wind generation: Betz’ law

Betz’ law is an expression that gives the maximum power generated by a wind turbine. Based on basic physics: \( \text{power} = \frac{d(\text{energy})}{dt} \), and kinetic energy in the wind is \((1/2)mv^2\)

\[
P = \frac{dE}{dt} = \frac{1}{2} \rho S v (v_1^2 - v_2^2)
\]

The basis of this is Bernoulli’s laws of fluid dynamics.

Then take the derivative of \( P \) with respect to \((v_2/v_1)\) and set the derivative to zero to find the maximum \( P \). When this is done, find \( v_2/v_1 = 1/3 \) and

\[
P_{\text{max}} = \frac{16}{27} \frac{1}{2} \rho S v_1^3
\]

\[
P_{\text{max}} = \frac{1}{2} \rho S C_p v_1^3
\]

\( C_p = 16/27 = 0.593 \)
Example
Assuming that wind speed increases linearly with altitude ‘above ground level’ (AGL) as \( v = 15 + 0.9a \) meters/s \((a = \text{AGL distance in m})\), compare the heights of a wind turbine to obtain a 10% increase in maximum power output. Assume for this example that the original turbine is 20 m AGL.

Solution

\[
\frac{P_{\text{max-high}}}{P_{\text{max-low}}} = \frac{\frac{1}{2} \rho SC_p (15 + 0.9(a + \Delta a))^3}{\frac{1}{2} \rho SC_p (15 + 0.9a)^3}
\]

\[
\sqrt[3]{1.1} = 1.0322 = \frac{15 + 0.9a + 0.9\Delta a}{15 + 0.9a}
\]

Let \( a = 20 \) and solve for \( \Delta a = 1.181 \) m, therefore \( a + \Delta a = 21.181 \) m. In this case, a \( 1.181/20 = 5.9\% \) increase in tower height gives an increase of 10% in max power of the wind turbine.
Example
The maximum power generated by a wind farm is forecast utilizing wind forecasts. For every one percent error in wind forecasts, what is the percent error in maximum power generated?

Solution

\[ P_{\text{max}} = \frac{1}{2} \rho SC_p v_1^3 \]

Gather the constant coefficients ahead of \( v^3 \), and note that
\( (v(1+0.01))^3 \approx v^3 + 3v^3 (0.01) \). Therefore expect 3% deviation in \( P_{\text{max}} \) for every 1% deviation in forecast wind speed.
Types of wind generators

1. Based on an induction generator connected with a fixed-speed wind turbine, this design needs a soft-starter to decrease current transients during startup phase and a capacitor bank to compensate for reactive power. The generator can work closely to a zero value generation or consumption of reactive power. This type of compensation does not allow flexible reactive power control.

2. Introduced by Vestas, generator is designed to work with limited variable speed wind turbine. With the variable resistor in the rotor, it is possible to control power output. The capacitor bank and soft-starter role is analogous to type 1.
• This design uses two AC/DC converters with a capacitor between them to control the WECS. These converters are rated at 25% of total generator power.
• The wound rotor induction generator configuration is also known as a doubly fed induction generator (DFIG).
• The term “doubly” comes from the fact that the rotor winding is not short circuited (as in classical “singly-fed” induction machine), but a voltage is induced from the rotor-side converter.
• Depending on the operating scheme, a DFIG can keep a constant value of reactive power or keep the terminal voltage constant.
• The most widespread WECS.
Types of wind generators

The type D design uses a full-scale frequency converter with different types of generators.

- The most common one is the permanent magnet synchronous generator (PMSG).
- This design allows full control over active and reactive power production and has a high wind energy extraction value.
- Full power control improves power and frequency stability in the grid and reduces the short circuit power.
- Most type 4 designs do not need a gearbox, which is a great advantage.
Concentrated solar power (CSP)  
**Solar thermal technology**

The models used are basically *thermal* and *fluid* models. These have long time constants. The thermal energy is used via a heat exchanger and a steam turbine-generator. A standard synchronous machine model applies.
Basic design: concentrated solar power

Geometrical concentration ratio
\[ C_g = \frac{A_c}{A} \]

Collector area
Absorber area

Salts may be used in the oil loop to store energy (as molten salt). These are usually NaNO\(_3\) or KNO\(_3\). Thermal oils used: Caloria, Therminol

Best guess cost in 2010: 6$ /kWe
Basic solar PV model

Current and voltage sensors

INVERTER

AC GRID

PV cell

\[ I = I_{PV} - I_d = I_{PV} - I_o \left( \frac{e(V + I_{d}R_s)}{n_kT_c} - 1 \right) \]

\[ k = \text{Boltzmann's gas constant} \]

\[ I_o = \text{saturation current (temperature dependent)} \]

\[ e = \text{charge on one electron} \]

\[ N = \text{factor for this PV cell} \]

\[ T_c = \text{cell temperature} \, ^\circ K \]
The fuel depletion curves

- Bell shaped, use per year vs. year
- As use rises, price rises, remaining resource falls, then use per year falls
- The integral of the curve is the amount of fuel used

Annual energy consumption in joules / year

- Coal peaks at $1500 \times 10^{18}$ joules / year in 2075
- Oil peaks at 2015 at $250 \times 10^{18}$ joules / year
What is the long term solution?

- Convert to renewables
- Conservation
- New energy sources
- Energy storage to levelize the demand
- Increase efficiency in end use, generation, transmission, distribution
- Fundamental change in energy generation – major breakthrough
- Lifestyle changes (especially in ‘first world nations’)
- Fundamental changes in population management

The term ‘sustainable’ has been promoted in power engineering – but what does this mean?

Many of these issues lie outside of traditional power engineering.
World energy consumption

World electric power consumption by ultimate source
The twentieth century saw a rapid twenty-fold increase in the use of fossil fuels. Between 1980 and 2004, the worldwide annual growth rate was 2%. According to the US Energy Information Administration's 2006 estimate, the estimated 15 TW total power consumption of 2004 was divided as follows: fossil fuels supplying 86% of the world's energy. Note: 1 zettajoule = $10^{21}$ J; 1 TW = $10^{12}$ W.

### World power and energy use

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Power in TW</th>
<th>Energy / year in ZJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>5.6</td>
<td>0.18</td>
</tr>
<tr>
<td>Gas</td>
<td>3.5</td>
<td>0.11</td>
</tr>
<tr>
<td>Coal</td>
<td>3.8</td>
<td>0.12</td>
</tr>
<tr>
<td>Hydroelectric</td>
<td>0.9</td>
<td>0.03</td>
</tr>
<tr>
<td>Nuclear</td>
<td>0.9</td>
<td>0.03</td>
</tr>
<tr>
<td>Geothermal, wind, solar, wood</td>
<td>0.13</td>
<td>0.004</td>
</tr>
<tr>
<td>Total</td>
<td>15</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Some other countries – the top three generating sources: 2009

**USA** 44.1% COAL; 21.6% NUCLEAR; 22.0% NATURAL GAS

**CANADA** 58% HYDRO; 28% COAL; 13% NUCLEAR

**INDIA** 60% COAL; 22% NATURAL GAS; 15% HYDRO

**CHINA** 78% COAL; 19% HYDRO; 2% NATURAL GAS

**FRANCE** 77% NUCLEAR; 14% HYDRO; 6% COAL

**RUSSIA** 45% COAL; 22% NATURAL GAS; 17% HYDRO

**GUATEMALA** 52% COAL; 35% HYDRO; 13% RENEWABLES
Energy *intensity* of different world economies
The graph shows the amount of energy it takes to produce one US $ of GNP for selected countries. GNP is based on 2004 purchasing power parity and 2000 dollars adjusted for inflation.
Load factor

\[ LF = \frac{\text{Total energy used}}{(\text{peak power demand}) \times (\text{time period})} \]

- The higher, the better – utilize all the installed capacity.
- Repair, downtime issues
- Typical annual LF is less than 50% in residential areas, can be 60 – 70% in industrial areas.
- Storage improves LF
- Could be daily LF, annual LF, seasonal LF

\[ LF = \frac{\text{area under curve}}{\text{area of box}} \]
Introduction: Optimal power flow studies

• Optimal power flow study
• What is the objective?
• Minimum fuel cost
• But that is zero – shut everything down
• Constrained optimum – find minimum fuel cost subject to serving the load

Description of this subject is postponed to after a presentation of optimization methods