Simplified Power System Modeling

- Balanced three phase systems can be analyzed using per phase analysis
- A “per unit” normalization simplifies the analysis of systems with different voltage levels.
- To provide an introduction to power flow analysis, we need models for the different system devices:
  - Transformers and transmission lines, generators, and loads
- Transformers and transmission lines are modeled as a series impedances

Load Models

- Ultimate goal is to supply loads with electricity at constant frequency and voltage
- Electrical characteristics of individual loads matter, but usually they can only be estimated
  - Actual loads are constantly changing, consisting of a large number of individual devices
  - Only limited network observability of load characteristics
- Aggregate models are typically used for analysis
  - Two common models
    - Constant power: \( S_i = P_i + jQ_i \)
    - Constant impedance: \( S_i = |V|^2 / Z_i \)

Generator Models

- Engineering models depend upon application
- Generators are usually synchronous machines
- For generators, we will use two different models:
  - A steady-state model, treating the generator as a constant power source operating at a fixed voltage; this model will be used for power flow and economic analysis
  - This model works fairly well for type 3 and type 4 wind turbines
  - Other models include treating as constant real power with a fixed power factor.

Per Unit Calculations

- A key problem in analyzing power systems is the large number of transformers.
  - It would be very difficult to continually refer impedances to the different sides of the transformers
- This problem is avoided by a normalization of all variables.
  - This normalization is known as per unit analysis.

\[
\text{quantity in per unit} = \frac{\text{actual quantity}}{\text{base value of quantity}}
\]

Three Phase Per Unit

Procedure is very similar to 1-phase except we use a 3-phase VA base, and use line to line voltage bases

1. Pick a 3-phase VA base for the entire system, \( S_B^{3\phi} \)
2. Pick a voltage base for each different voltage level, \( V_B \). Voltages are line to line.
3. Calculate the impedance base:
   \[
   Z_B^{3\phi} = \frac{(\sqrt{3}V_B)^2}{S_B^{3\phi}}
   \]
4. Exactly the same impedance bases as with single phase!
Three Phase Per Unit, cont'd

4. Calculate the current base, \( I_B \)

\[
I_B = \frac{S_B^{\theta}}{\sqrt{3} V_{B,LI}^{\theta}} = \frac{3 \cdot S_B^{\theta}}{\sqrt{3} V_{B,LI}^{\theta}} = \frac{S_B^{\theta}}{V_{B,LI}^{\theta}} = I_0^{\theta}
\]

Exactly the same current bases as with single phase!

5. Convert actual values to per unit

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Power Flow Analysis

• We now have the necessary models to start to develop the power system analysis tools

• The most common power system analysis tool is the power flow (also known sometimes as the load flow)
  – power flow determines how the power flows in a network
  – also used to determine all bus voltages and all currents
  – because of constant power models, power flow is a nonlinear analysis technique
  – power flow is a steady-state analysis tool

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Bus Admittance Matrix or \( Y_{bus} \)

• First step in solving the power flow is to create what is known as the bus admittance matrix, often call the \( Y_{bus} \).  
• The \( Y_{bus} \) gives the relationships between all the bus current injections, \( I \), and all the bus voltages, \( V \),  
  \( I = Y_{bus} V \)
• The \( Y_{bus} \) is developed by applying KCL at each bus in the system to relate the bus current injections, the bus voltages, and the branch impedances and admittances

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Y\(_{bus}\) General Form

• The diagonal terms, \( Y_{ii} \), are the self admittance terms, equal to the sum of the admittances of all devices incident to bus \( i \).
• The off-diagonal terms, \( Y_{ij} \), are equal to the negative of the sum of the admittances joining the two buses.
• With large systems \( Y_{bus} \) is a sparse matrix (that is, most entries are zero)
• Shunt terms, such as with the \( \pi \) line model, only affect the diagonal terms.

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Power Flow Analysis

• When analyzing power systems we know neither the complex bus voltages nor the complex current injections
• Rather, we know the complex power being consumed by the load, and the power being injected by the generators plus their voltage magnitudes
• Therefore we can not directly use the \( Y_{bus} \) equations, but rather must use the power balance equations

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Power Flow Slack Bus

• We can not arbitrarily specify \( S \) at all buses because total generation must equal total load + total losses
• We also need an angle reference bus.
• To solve these problems we define one bus as the “slack” bus. This bus has a fixed voltage magnitude and angle, and a varying real/reactive power injection.
• A “slack bus” does not exist in the real power system.
Power Balance Equations
From KCL we know at each bus i in an n bus system the current injection, \( I_i \), must be equal to the current that flows into the network
\[
I_i = I_{Gi} - I_{Di} = \sum_{k=1}^{n} I_{ik}
\]
Since \( I = Y_{bus} V \) we also know
\[
I_i = I_{Gi} - I_{Di} = \sum_{k=1}^{n} Y_{ik} V_k
\]
The network power injection is then \( S_i = V_i I_i^* \)

Real Power Balance Equations
\[
S_i = P_i + jQ_i = V_i \sum_{k=1}^{n} Y_{ik} V_k^* = \sum_{k=1}^{n} |V_k|^2 e^{j\theta_k} (G_{ik} - jB_{ik})
\]
Resolving into the real and imaginary parts
\[
P_i = \sum_{k=1}^{n} |V_k|^2 (G_{ik} \cos \theta_k + B_{ik} \sin \theta_k) = P_{Gi} - P_{Di}
\]
\[
Q_i = \sum_{k=1}^{n} |V_k|^2 (G_{ik} \sin \theta_k - B_{ik} \cos \theta_k) = Q_{Gi} - Q_{Di}
\]

Newton-Raphson Method (scalar)
General form of problem: Find an \( x \) such that
\( f(x) = 0 \)
1. For each guess of \( x^{(v)} \), define
\[
\Delta x^{(v)} = x - x^{(v)}
\]
2. Represent \( f(x) \) by a Taylor series about \( x^{(v)} \)
\[
f(x) = f(x^{(v)}) + \frac{df(x^{(v)})}{dx} \Delta x^{(v)} + \frac{1}{2} \left( \frac{d^2 f(x^{(v)})}{dx^2} \right) (\Delta x^{(v)})^2 + \text{higher order terms}
\]
3. Approximate \( f(x) \) by neglecting all terms except the first two
\[
f(x) \approx f(x^{(v)}) + \frac{df(x^{(v)})}{dx} \Delta x^{(v)}
\]
4. Use this linear approximation to solve for \( \Delta x^{(v)} \)
\[
\Delta x^{(v)} = -\left( \frac{df(x^{(v)})}{dx} \right)^{-1} f(x^{(v)})
\]
5. Solve for a new estimate of \( x \)
\[
x^{(v+1)} = x^{(v)} + \Delta x^{(v)}
\]

Newton-Raphson Example
Use Newton-Raphson to solve \( f(x) = x^2 - 2 = 0 \)
The equation we must iteratively solve is
\[
\Delta x^{(v)} = -\frac{d^2 f(x^{(v)})}{dx^2} \left( \frac{d f(x^{(v)})}{dx} \right)^{-1} f(x^{(v)})
\]
\[
\Delta x^{(v)} = -\frac{1}{2x^{(v)}} \left( (x^{(v)})^2 - 2 \right)
\]
\[
x^{(v+1)} = x^{(v)} + \Delta x^{(v)}
\]
\[
x^{(v+1)} = x^{(v)} - \frac{1}{2x^{(v)}} \left( (x^{(v)})^2 - 2 \right)
\]

Newton-Raphson Example, cont’d
Guess \( x^{(0)} = 1 \). Iteratively solving we get
\[
V \quad x^{(v)} \quad f(x^{(v)}) \quad \Delta x^{(v)}
\]
\[
0 \quad 1 \quad -1 \quad 0.5
1 \quad 1.5 \quad 0.25 \quad -0.08333
2 \quad 1.41667 \quad 6.953 \times 10^{-3} \quad -2.454 \times 10^{-3}
3 \quad 1.41422 \quad 6.024 \times 10^{-6}
\]
Newton-Raphson Comments

• When close to the solution the error decreases quite quickly -- method has quadratic convergence
• \( f(x^{(n)}) \) is known as the mismatch, which we would like to drive to zero
• Stopping criteria is when \( \| f(x^{(n)}) \| < \varepsilon \)
• Results are dependent upon the initial guess. What if we had guessed \( x^{(0)} = 0 \), or \( x^{(0)} = -1 \)?
• A solution’s region of attraction (ROA) is the set of initial guesses that converge to the particular solution. The ROA is often hard to determine

Multi-Variable Newton-Raphson

Next we generalize to the case where \( x \) is an n-dimension vector, and \( f(x) \) is an n-dimension function

\[
\begin{align*}
x &= \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \\
f(x) &= \begin{bmatrix} f_1(x) \\ f_2(x) \\ \vdots \\ f_n(x) \end{bmatrix}
\end{align*}
\]

Again define the solution \( \hat{x} \) so \( f(\hat{x}) = 0 \) and \( \Delta x = \hat{x} - x \)

Multi-Variable Case, cont’d

The Taylor series expansion is written for each \( f_i(x) \)

\[
f_i(x) = f_i(x) + \frac{\partial f_i(x)}{\partial x_1} \Delta x_1 + \frac{\partial f_i(x)}{\partial x_2} \Delta x_2 + \ldots + \frac{\partial^2 f_i(x)}{\partial x_1 \partial x_n} \Delta x_1 \Delta x_n + \text{higher order terms}
\]

\[
f_i(x) = f_i(x) + \frac{\partial f_i(x)}{\partial x_1} \Delta x_1 + \frac{\partial f_i(x)}{\partial x_2} \Delta x_2 + \ldots + \frac{\partial^2 f_i(x)}{\partial x_1 \partial x_n} \Delta x_1 \Delta x_n + \text{higher order terms}
\]

Jacobian Matrix

The \( n \) by \( n \) matrix of partial derivatives is known as the Jacobian matrix, \( J(x) \)

\[
J(x) = \begin{bmatrix}
\frac{\partial^2 f_1(x)}{\partial x_1 \partial x_1} & \frac{\partial^2 f_1(x)}{\partial x_1 \partial x_2} & \ldots & \frac{\partial^2 f_1(x)}{\partial x_1 \partial x_n} \\
\frac{\partial^2 f_2(x)}{\partial x_2 \partial x_1} & \frac{\partial^2 f_2(x)}{\partial x_2 \partial x_2} & \ldots & \frac{\partial^2 f_2(x)}{\partial x_2 \partial x_n} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{\partial^2 f_n(x)}{\partial x_n \partial x_1} & \frac{\partial^2 f_n(x)}{\partial x_n \partial x_2} & \ldots & \frac{\partial^2 f_n(x)}{\partial x_n \partial x_n}
\end{bmatrix}
\]

Multi-Variable Case, cont’d

This can be written more compactly in matrix form

\[
f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ \vdots \\ f_n(x) \end{bmatrix} = \begin{bmatrix} \frac{\partial f_1(x)}{\partial x_1} & \frac{\partial f_1(x)}{\partial x_2} & \ldots & \frac{\partial f_1(x)}{\partial x_n} \\
\frac{\partial f_2(x)}{\partial x_1} & \frac{\partial f_2(x)}{\partial x_2} & \ldots & \frac{\partial f_2(x)}{\partial x_n} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{\partial f_n(x)}{\partial x_1} & \frac{\partial f_n(x)}{\partial x_2} & \ldots & \frac{\partial f_n(x)}{\partial x_n} \end{bmatrix} \begin{bmatrix} \Delta x_1 \\ \Delta x_2 \\ \vdots \\ \Delta x_n \end{bmatrix}
\]

Multi-Variable N-R Procedure

Derivation of N-R method is similar to the scalar case

\[
\begin{align*}
f(\hat{x}) &= f(x) + J(x) \Delta x + \text{higher order terms} \\
f(\hat{x}) &= 0 = f(x) + J(x) \Delta x \\
\Delta x &= -J(x)^{-1}f(x) \\
x^{(n+1)} &= x^{(n)} + \Delta x^{(n)} \\
x^{(n+1)} &= x^{(n)} - J(x^{(n)})^{-1}f(x^{(n)})
\end{align*}
\]

Iterate until \( \| f(x^{(n)}) \| < \varepsilon \)
Multi-Variable Example

Solve for \( x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \) such that \( f(x) = 0 \) where

\[
\begin{align*}
  f_1(x) &= 2x_1^2 + x_2^2 - 8 = 0 \\
  f_2(x) &= x_1^2 - x_2^2 + x_1x_2 - 4 = 0
\end{align*}
\]

First symbolically determine the Jacobian

\[
J(x) = \begin{bmatrix}
  \frac{\partial f_1(x)}{\partial x_1} & \frac{\partial f_1(x)}{\partial x_2} \\
  \frac{\partial f_2(x)}{\partial x_1} & \frac{\partial f_2(x)}{\partial x_2}
\end{bmatrix}
\]

Multi-variable Example, cont’d

\[
x^{(2)} = \begin{bmatrix} 2.1 \\ 1.3 \end{bmatrix}
\]

Each iteration we check \( f(x^{(2)}) \) to see if it is below our specified tolerance \( \varepsilon \).

\[
f(x^{(2)}) = \begin{bmatrix} 0.1556 \\ 0.0900 \end{bmatrix}
\]

If \( \varepsilon = 0.2 \) then we would be done. Otherwise we'd continue iterating.

Real Power Balance Equations

\[
S_i = \mathbf{P}_i + j\mathbf{Q}_i = \mathbf{V}_i^* \mathbf{V}_i = \mathbf{P}_G + j\mathbf{Q}_G = (G_{ik} - jB_{ik})
\]

Resolving into the real and imaginary parts

\[
P_i = \sum_{k=1}^{n} \mathbf{V}_i^* G_{ik} \cos \theta_{ik} + B_{ik} \sin \theta_{ik} = P_G - P_D
\]

\[
Q_i = \sum_{k=1}^{n} \mathbf{V}_i^* G_{ik} \sin \theta_{ik} - B_{ik} \cos \theta_{ik} = Q_G - Q_D
\]

Power Flow Variables

Assume the slack bus is the first bus (with a fixed voltage angle/magnitude). We then need to determine the voltage angle/magnitude at the other buses.

\[
x = \begin{bmatrix} \theta_2 \\ \theta_3 \\ \vdots \\ \theta_n \\ \mathbf{P}_2 \\ \mathbf{P}_3 \\ \vdots \\ \mathbf{P}_n \\ \mathbf{Q}_2 \\ \mathbf{Q}_3 \\ \vdots \\ \mathbf{Q}_n \end{bmatrix}
\]
N-R Power Flow Solution

The power flow is solved using the same procedure discussed last time:

Set \( v = 0 \); make an initial guess of \( x, x^{(0)} \)

While \( |f(x^{(v)})| > \varepsilon \) Do

\[
x^{(v+1)} = x^{(v)} - J(x^{(v)})^{-1} f(x^{(v)})
\]

\( v = v + 1 \)

End While

Power Flow Jacobian Matrix

The most difficult part of the algorithm is determining and inverting the \( n \) by \( n \) Jacobian matrix, \( J(x) \):

\[
J(x) = \begin{bmatrix}
\frac{\partial f_1(x)}{\partial x_1} & \frac{\partial f_1(x)}{\partial x_2} & \cdots & \frac{\partial f_1(x)}{\partial x_n} \\
\frac{\partial f_2(x)}{\partial x_1} & \frac{\partial f_2(x)}{\partial x_2} & \cdots & \frac{\partial f_2(x)}{\partial x_n} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{\partial f_n(x)}{\partial x_1} & \frac{\partial f_n(x)}{\partial x_2} & \cdots & \frac{\partial f_n(x)}{\partial x_n}
\end{bmatrix}
\]

Power Flow Jacobian Matrix, cont’d

Jacobian elements are calculated by differentiating each function, \( f_i(x) \), with respect to each variable. For example, if \( f_i(x) \) is the bus \( i \) real power equation

\[
f_i(x) = \sum_{k=1}^{n} V_k' Y_{ik} (G_{ik} \cos \theta_k + B_{ik} \sin \theta_k) - P_{Gi} + P_{Di}
\]

\[
\frac{\partial f_i(x)}{\partial \theta_k} = \sum_{k=1}^{n} V_k' Y_{ik} (-G_{ik} \sin \theta_k + B_{ik} \cos \theta_k)
\]

\[
\frac{\partial f_i(x)}{\partial \theta_j} = V_j' Y_{ij} (G_{ij} \sin \theta_j - B_{ij} \cos \theta_j) \quad (j \neq i)
\]

Two Bus Newton-Raphson Example

For the two bus power system shown below, use the Newton-Raphson power flow to determine the voltage magnitude and angle at bus two. Assume that bus one is the slack and \( S_{Base} = 100 \) MVA.

Two Bus Example, cont’d

General power balance equations

\[
P_i = \sum_{k=1}^{n} V_k' Y_{ik} (G_{ik} \cos \theta_k + B_{ik} \sin \theta_k) = P_{Gi} - P_{Di}
\]

\[
Q_i = \sum_{k=1}^{n} V_k' Y_{ik} (G_{ik} \sin \theta_k - B_{ik} \cos \theta_k) = Q_{Gi} - Q_{Di}
\]

Bus two power balance equations

\[
V_2' P_2' \cos \theta_2 + 2.0 = 0
\]

\[
V_2' P_2' \sin \theta_2 + V_2' P_2' \cos \theta_2 + V_2' P_2' (10) + 1.0 = 0
\]

Two Bus Example, cont’d

Now calculate the power flow Jacobian

\[
J(x) = \begin{bmatrix}
\frac{\partial P_1(x)}{\partial \theta_2} & \frac{\partial Q_1(x)}{\partial \theta_2} \\
\frac{\partial P_2(x)}{\partial \theta_2} & \frac{\partial Q_2(x)}{\partial \theta_2} \\
\frac{\partial P_1(x)}{\partial \theta_2} & \frac{\partial Q_1(x)}{\partial \theta_2} \\
\frac{\partial P_2(x)}{\partial \theta_2} & \frac{\partial Q_2(x)}{\partial \theta_2}
\end{bmatrix}
\]

\[
= \begin{bmatrix}
10 P_1' \cos \theta_2 & -10 \sin \theta_2 \\
-10 \sin \theta_2 & -10 \cos \theta_2 + 20 P_2'
\end{bmatrix}
\]
Two Bus Example, First Iteration

Set $v = 0$, guess $x^{(0)} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$

Calculate

$$f(x^{(0)}) = \begin{bmatrix} |V_2| (10 \sin \theta_2) + 2.0 \\ |V_2| (-10 \cos \theta_2) + |V_2| (10) + 1.0 \end{bmatrix} = \begin{bmatrix} 2.0 \\ 1.0 \end{bmatrix}$$

$$J(x^{(0)}) = \begin{bmatrix} 10 |V_2| \cos \theta_2 & 10 |V_2| \sin \theta_2 \\ 10 |V_2| \sin \theta_2 & -10 \cos \theta_2 + 20 |V_2| \end{bmatrix} = \begin{bmatrix} 10 & 0 \\ 0 & 10 \end{bmatrix}$$

Solve $x^{(1)} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$

Two Bus Example, Next Iterations

$$f(x^{(1)}) = \begin{bmatrix} 0.9(10 \sin (-0.2)) + 2.0 \\ 0.9(-10 \cos (-0.2)) + 0.9^2 \times 10 + 1.0 \end{bmatrix} = \begin{bmatrix} 0.212 \\ 0.279 \end{bmatrix}$$

$$J(x^{(1)}) = \begin{bmatrix} 8.82 & -1.986 \\ -1.788 & 8.199 \end{bmatrix}$$

Solve $x^{(2)} = \begin{bmatrix} -0.2 \\ 8.82 \\ -1.986 \end{bmatrix}$

Three Bus Solved Values

Once the voltage angle and magnitude at bus 2 are known we can calculate all the other system values, such as the line flows and the generator reactive power output.

PV Buses

- Since the voltage magnitude at PV buses is fixed there is no need to explicitly include these voltages in $x$ or write the reactive power balance equations
- the reactive power output of the generator varies to maintain the fixed terminal voltage (within limits)
- optionally these variations/equations can be included by just writing the explicit voltage constraint for the generator bus

$$|V_i| - V_{	ext{setpoint}} = 0$$

Solving Large Power Systems

- The most difficult computational task is inverting the Jacobian matrix
  - inverting a full matrix is an order $n^3$ operation, meaning the amount of computation increases with the cube of the size
  - this amount of computation can be decreased substantially by recognizing that since the $Y_{bus}$ is a sparse matrix, the Jacobian is also a sparse matrix
  - using sparse matrix methods results in a computational order of about $n^{1.5}$
  - this is a substantial savings when solving systems with tens of thousands of buses
“DC” Power Flow

• The “DC” power flow makes some approximations to the power balance equations to simplify the problem
  – completely ignore reactive power, assume all the voltages are always 1.0 per unit, ignore line conductance, assumes
  angles across the lines are small.
  – Line flow is then approximated as $(\theta - \theta_j) X_j$
• This makes the power flow a linear set of equations, which can be solved directly $\mathbf{P} = \mathbf{B} \mathbf{V}$
• While the DC power flow is approximate, it is widely used to get a feel for power system MW flows.

DC Power Flow Example

• For the system shown in the previous slide with bus 1 as the system slack and with the below $\mathbf{B}$ matrix (100 MVA base) numbered from buses 2 to 5, determine the bus angles using the DC power flow approximation the and the flow on the line between bus 1 and 5, which has a pu $X$ of 0.02.

\[
\mathbf{B} = \begin{bmatrix}
-30 & 5 & 0 & 10 & 0 \\
5 & -100 & 100 & 0 & 0 \\
10 & -100 & -150 & 40 & 0 \\
0 & 10 & 40 & -110 & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

\[
\mathbf{V} = \begin{bmatrix}
4.4 \\
0 \\
0 \\
100 \\
0
\end{bmatrix}
\]

$\mathbf{P} = \mathbf{B} \mathbf{V} = \begin{bmatrix}
3.281 \\
6.601 \\
-0.0314 \\
-0.0729 \\
0
\end{bmatrix}$ radians $\begin{bmatrix}
-15.70 \\
0.5221 \\
-15.70 \\
5.690 \\
-4.125
\end{bmatrix}$ degrees

$P_{1j} = (\theta_1 - \theta_j) X_j = 0.072(0.02) = 3.6 \text{ pu} = 360 \text{ MW}$

Good Power System Operation

• Good power system operation requires that there be no reliability violations for either the current condition or in the event of statistically likely contingencies
  • Reliability requires as a minimum that there be no transmission line/transformer limit violations and that bus voltages be within acceptable limits (perhaps 0.95 to 1.08)
  • Example contingencies are the loss of any single device. This is known as n-1 reliability.
• North American Electric Reliability Corporation now has legal authority to enforce reliability standards (and there are now lots of them). See http://www.nerc.com for details (click on Standards)

Looking at the Impact of Line Outages

Opening one line (Tim69-Hannah69) causes an overload. This would not be allowed (i.e., we can’t operate this way when line is in.
Contingency Analysis

Contingency analysis provides an automatic way of looking at all the statistically likely contingencies. In this example the contingency set is all the single line/transformer outages.

Generation Changes and The Slack Bus

- The power flow is a steady-state analysis tool, so the assumption is total load plus losses is always equal to total generation.
- Generation mismatch is made up at the slack bus.
- When doing generation change power flow studies one always needs to be cognizant of where the generation is being made up.
- Common options include system slack, distributed across multiple generators by participation factors or by economics.

Generation Change Example 1

Display shows “Difference Flows” between original 37 bus case, and case with a HLT138 generation outage; note all the power change is picked up at the slack.

Generation Change Example 2

Display repeats previous case except now the change in generation is picked up by other generators using a participation factor approach.

Sitting New Wind Generation Example

What does the Future Hold for Wind?

- Wind has experienced rapid growth over the last decade; but with a large drop in installations expected for 2010.
- Nuclear and renewal generation are running into strong “head winds” caused by low natural gas prices.
- Expiring tax credits is a continual concern.
- State renewable portfolio standards will help with growth.
Hurricanes Impact Energy Prices

- Many oil refineries and natural gas pipelines off the coast
- Need to be shut down and evacuated
- Takes time to get the systems back up and running afterwards

Hurricane Ike, Sept. 2008

http://home.eia.doe.gov/oep/special/hurricanes/gustav_091308.html

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What does the Future Hold for Wind?

Vestas to Cut 3000 Jobs (14%) (10/26/10)

Vestas Stock Price Over Last Five Years

Closed at 176 on Wednesday and 169.4 on Thursday!

Long-term the outlook for wind is probably good. On 9/1/10 EIA reduced their 2010 forecast for US capacity additions to 4.3 GW in 2010 and 6.5 GW in 2011; the totals for 2007 were 5.2 GW, 2008 8.4 GW and 2009 10.0GW

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Distributed Generation (DG)

- Small-scale, up to about 50 MW
- Includes renewable and non-renewable sources
- May be isolated from the grid or grid-connected
- Usually near the end user

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Integrated Generation, Transmission, Buildings, Vehicles

Pluggable Hybrid Electric Vehicles (PHEVs) as Distributed Generation

- Can charge at night when electricity is cheap
- Can provide services back to the grid

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DG Technologies, Excepting Solar

- Microturbines
- Reciprocating Internal Combustion Engines
- Biomass
- Micro-Hydro
- Fuel Cells (we’ll be skipping)
- Concentrated solar power is talked about in Chapter 4, but we’ll skip until after we cover Chapter 7.

Reasons for Distributed Generation

- Good for remote locations
- Renewable resources
- Reduced emissions
- Can use the waste heat
- Can sell power back to the grid

Terminology

- Cogeneration and Combined Heat and Power (CHP) – capturing and using waste heat while generating electricity
- When fuel is burned one product is water; if water vapor exits stack then its energy is lost (about 1060 Btu per pound of water vapor)
- Heat of Combustion for fuels
  - Higher Heating Value (HHV) – gross heat, accounts for latent heat in water vapor
  - Lower Heating Value (LHV) – net heat, assumes latent heat in water vapor is not recovered
- Both are used - Conversion factors (LHV/HHV) in Table 4.2

HHV and LHV Efficiency

- Find LHV efficiency or HHV efficiency from the heat rate:
  \[ \eta_{\text{HHV/LHV}} = \frac{3412 \text{ Btu/kWh}}{\text{Heat Rate (Btu/kWh)}_{\text{HHV/LHV}}} \]  

- Convert to get the other efficiency:
  \[ \eta_{\text{LHV}} = \eta_{\text{HHV}} \]  

Note the LHV is less than the HHV

Microturbines

- Small natural gas turbines, 500 W to 100s kW
- Only one moving part
- Combined heat and power
- High overall efficiency

230 kW fuel
120 kW hot water output
65 kW electrical output
45 kW waste heat
Capstone 65 kW Microturbine
Source: http://www.capstoneturbine.com
**Microturbines**

1. Incoming air is compressed
2. Moves into cool side of recuperator & is heated
3. Mixes with fuel in combustion chamber
4. Expansion of hot gases spins shaft
5. Exhaust leaves

**Microturbines and Renewable Energy**

- Microturbines are not a renewable energy source since they ultimately use natural gas as their fuel. But when used for combined heat and electricity they can be quite efficient and emit significantly less CO2 than coal.
- A possible scenario: If natural gas prices remain low, commercial/industrial entities will increasingly go “off grid.” Hence they will not be subject to state renewable portfolio standards or utility taxes. This will mean renewable energy subsidies will increasingly be born by residential customers. Average residential price per therm is $0.57 in October in Illinois; with a heat rate of 8.5 this gives electricity at 4.8 cents/kWh.

**Biomass – Current Conditions**

- Biomass, including waste, currently provides about 4% of the US total energy, a value that is projected to grow to about 7% by 2030.
- In 2008 the 3.85 quad of biomass was split between biofuels such as ethanol (1.37 quad), waste such as landfill gas (0.436 quad) and wood (2.04 quad).
  - About 1/10 of the wood was used to produce electricity, primarily by the paper industry; total generation capacity in US is about 11.3 GW
  - We are not considering liquid fuels for non-electricity use in ECE 333; ethanol usage was growing at 30% per year
- Little to no fuel cost for wood waste but little growth

**Biomass – Future Possibilities for Electricity**

- Newer crops are being considered for future biomass, including various grasses (such as Miscanthus and Switch Grass) along with algae
- Potential uses include both fuel to create electricity (primarily the grasses), and conversion to liquid fuels such as ethanol.
  - On campus 320 acres in the South Farms are devoted to biofuel research
- A full consideration of biomass is beyond our scope of since it gets into agricultural economics issues
- Miscanthus can be harvested at rates of about 15 tons per acre in Illinois. Once established it does not need to be replanted. This allows the energy potential of about 225 Mbtu per acre; income depends on energy price, say $2/Mbtu = $450 per acre. For comparison corn can yield up to 200 bushels per acre at say $5.50/bushel = $1100 per acre
  - Energy yield is about 225/15 = 15 Mbtu/ton which is similar to coal
  - Not a native species so containment could be an issue

**Cofiring**

- Burn biomass and coal
- Modified conventional steam-cycle plants
- Allows use of biomass in plants with higher efficiencies
- Reduces overall emissions
Gas Turbines and Biomass

- Cannot run directly on biomass without causing damage
- Gassify the fuel first and clean the gas before combustion
- Coal-integrated gasifier/gas turbine (CIG/GT) systems
- Biomass-integrated gasifier/gas turbine (BIG/GT) systems

Biomass and Transportation

- A key issue associated with biomass is the transportation costs – these grasses are quite bulky.
- A rough estimate of the cost per ton for transportation is about $1 + 0.1 \times \text{round trip distance in miles} + \text{harvesting costs of about $22 per ton}. So if the power plant is 50 miles distant, total cost would be $33 per ton, or about $33/ton(15 \text{ Mbtu/ton}) = 2.2 \text{ per Mbtu}
- Total US corn planting is about 87 million acres, which if planted in grass could yield about 20 quad of energy.
  - Won’t meet all our needs but could play a major role

A Biomass plant