ECL 4340

POWER SYSTEMS

LECTURE 14

CONTROL OF POWER FLOWS, FAST POWER FLOW, INTEGRATION OF RENEWABLES

Professor Kwang Y. Lee
Department of Electrical and Computer Engineering

1

ANNOUNCEMENTS

- Be reading Chapter 6, also Chapter 2.4 (Network Equations).
- HW 8 is uploaded; Due date: October 28.

2

POWER SYSTEM CONTROL

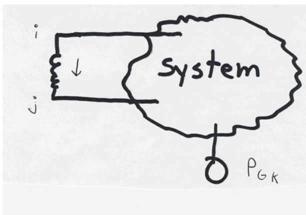
- A major issue with power system operation is the limited capacity of the transmission system
  - lines/transformers have limits (usually thermal)
  - no direct way of controlling flow down a transmission line (e.g., there are no valves to close to limit flow)
  - open transmission system access associated with industry restructuring is stressing the system in new ways
- We need to indirectly control transmission line flow by changing the generator outputs
- Similar control issues with voltage

3

3

Indirect Transmission Line Control

What we would like to determine is how a change in generation at bus k affects the power flow on a line from bus i to bus j.



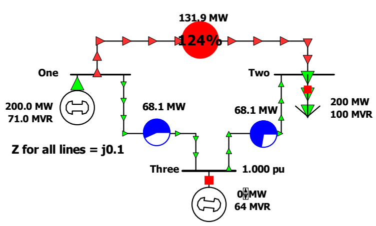
The assumption is that the change in generation is absorbed by the slack bus

4

4

Power Flow Simulation - Before

- One way to determine the impact of a generator change is to compare a before/after power flow.
- For example below is a three-bus case with an overload

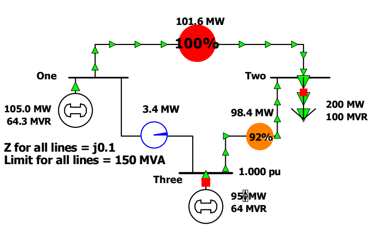


5

5

Power Flow Simulation - After

Increasing the generation at bus 3 by 95 MW (and hence decreasing it at bus 1 by a corresponding amount), results in
- 30.3 MW drop on the line from bus 1 to 2, and
- 64.7 MW drop on the flow from 1 to 3.



Expressed as a percent, 30.3/95 =32% and 64.7/95=68%

6

6

Control of Power Flow

7. Control of Power Flow

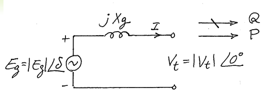
The following means are used to control power flow

1. Prime mover and excitation control of generators.
   - Prime mover → P, δ
   - excitation control → Q, $|V|$
2. Shunt capacitor banks, shunt reactors, static var systems (SVS).
   - Q, $|V|$
3. Tap-changing and regulation transformers.
   - Tap-changing → Q, $|V|$
   - regulation transformers → P, δ

7

Control of Power Flow

1) Generator Control: Control of Power



$$I = \frac{E_g - V_t}{jX_g}$$

$$S = P + jQ = V_t I^* = |V_t|\left(\frac{|E_g|\angle -\delta - |V_t|}{-jX_g}\right)$$

$$= \frac{|V_t||E_g|\angle 90^\circ - \delta - |V_t|^2\angle 90^\circ}{X_g}$$

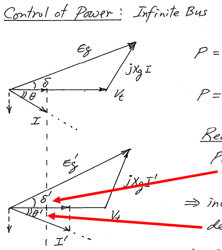
$$\Rightarrow \quad P = \frac{|V_t||E_g|}{X_g}\sin\delta \qquad \propto \delta$$

$$Q = \frac{|V_t|}{X_g}\left(|E_g|\cos\delta - |V_t|\right) \qquad \propto |E_g| - |V_t|$$

8

Control of Power Flow

Control of Power: Infinite Bus



$$P = \frac{V_t E_g}{X_g}\sin\delta$$

$$P = V_t I \cos\theta$$

Real Power Control:

Prime-mover increases power angle δ

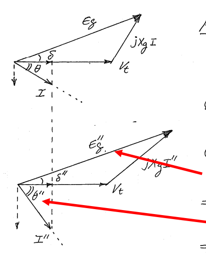
$\Rightarrow$ increases I and decreases θ

$\Rightarrow$ increases P while Q remain constant

9

Control of Power Flow

Control of Power : Infinite Bus



Reactive Power Control:

Excitation control controls E_g

$$Q = \frac{V_t}{X_g}(E_g \cos\delta - V_t)$$

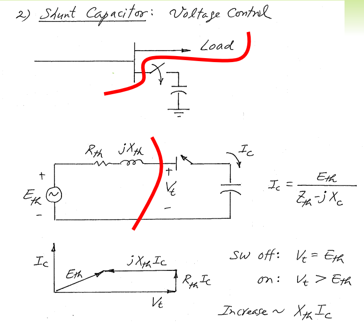
$$Q = V_t I \sin\theta$$

Increased E_g
⇒ increases I and increases θ
⇒ increases Q while P remain constant.

10

Control of Power Flow

2) *Shunt Capacitor:* Voltage Control



11

Control of Power Flow

Thus, by adding a capacitor bank at a bus, the bus voltage V_t is increased considerably, by $X_{th}I_c$, from the initial voltage (E_{th}).

Similarly, the addition of shunt reactor corresponds to the addition of a positive reactive load, causing the decrease in voltage. This is the practice in the power system for high voltage lines when the load is very light in evening hours.

12

Control of Power Flow

3) Tap-Changing Transformers: Chapter 3

Magnitude-regulating transformer:

Change voltage magnitude at a bus as well as reactive power flows on lines.

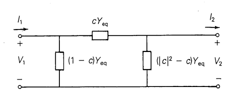
Phase-angle regulating transformer:

Change bus voltage angle as well as real power flows on lines.

13

Control of Power Flow

Both tap-changing and regulating transformers are modeled by a transformer with an off-nominal turns ratio "c".



(d) π circuit representation for real c
(Per-unit admittances are shown; $Y_{eq} = \frac{1}{Z_{eq}}$)

Power-flow program computes the changes in Y_{bus} corresponding to changes in "c", resulting in changes in bus voltage magnitude and angles, and branch flows.

14

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

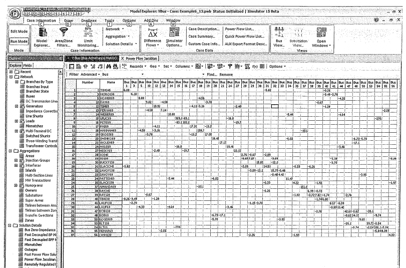
15

15

Fast Power Flow

EXAMPLE 6.16 Sparsity in a 37-bus system

To see a visualization of the sparsity of the power-flow Ybus and Jacobian matrices in a 37-bus system, open PowerWorld Simulator case Example 6_13.



Y_{bus}: 37x37 = 1369 entries, only 10% nonzero.

16

Dishonest Newton-Raphson

- Since most of the time in the Newton-Raphson iteration is spend calculating the inverse of the Jacobian, one way to speed up the iterations is to only calculate/inverse the Jacobian occasionally
  - known as the "Dishonest" Newton-Raphson
  - an extreme example is to only calculate the Jacobian for the first iteration

Honest: $\mathbf{x}^{(v+1)} = \mathbf{x}^{(v)} - \mathbf{J}(\mathbf{x}^{(v)})^{-1}\mathbf{f}(\mathbf{x}^{(v)})$

Dishonest: $\mathbf{x}^{(v+1)} = \mathbf{x}^{(v)} - \mathbf{J}(\mathbf{x}^{(0)})^{-1}\mathbf{f}(\mathbf{x}^{(v)})$

Both require $\left\|\mathbf{f}(\mathbf{x}^{(v)})\right\| < \varepsilon$ for a solution

17

17

Dishonest Newton-Raphson Example

Use the Dishonest Newton-Raphson to solve

$$f(x) = x^2 - 2 = 0$$

$$\Delta x^{(v)} = -\left[\frac{df(x^{(0)})}{dx}\right]^{-1} f(x^{(v)})$$

$$\Delta x^{(v)} = -\left[\frac{1}{2x^{(0)}}\right]((x^{(v)})^2 - 2)$$

$$x^{(v+1)} = x^{(v)} - \left[\frac{1}{2x^{(0)}}\right]((x^{(v)})^2 - 2)$$

18

18

Dishonest N-R Example, cont'd

$$x^{(v+1)} = x^{(v)} - \left[\frac{1}{2x^{(0)}}\right]((x^{(v)})^2 - 2)$$

Guess $x^{(0)} = 1$. Iteratively solving we get

v	$x^{(v)}$(honest)	$x^{(v)}$(dishonest)
0	1	1
1	1.5	1.5
2	1.41667	1.375
3	1.41422	1.429
4	1.41422	1.408

We pay a price in increased iterations, but with decreased computation per iteration

19

19

Decoupled Power Flow

- The completely Dishonest Newton-Raphson is not used for power flow analysis. However, several *approximations* of the Jacobian matrix are used.
- One common method is the Decoupled Power Flow. In this approach approximations are used to decouple the real and reactive power equations.

20

20

Decoupled Power Flow Formulation

General form of the power flow problem

$$-\begin{bmatrix} \frac{\partial \mathbf{P}^{(v)}}{\partial \boldsymbol{\theta}} & \frac{\partial \mathbf{P}}{\partial |\mathbf{V}|}^{(v)} \\ \frac{\partial \mathbf{Q}^{(v)}}{\partial \boldsymbol{\theta}} & \frac{\partial \mathbf{Q}}{\partial |\mathbf{V}|}^{(v)} \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{\theta}^{(v)} \\ \Delta |\mathbf{V}|^{(v)} \end{bmatrix} = \begin{bmatrix} \Delta \mathbf{P}(\mathbf{x}^{(v)}) \\ \Delta \mathbf{Q}(\mathbf{x}^{(v)}) \end{bmatrix} = \mathbf{f}(\mathbf{x}^{(v)})$$

where

$$\Delta \mathbf{P}(\mathbf{x}^{(v)}) = \begin{bmatrix} P_2(\mathbf{x}^{(v)}) + P_{D2} - P_{G2} \\ \vdots \\ P_n(\mathbf{x}^{(v)}) + P_{Dn} - P_{Gn} \end{bmatrix}$$

21

21

Decoupling Approximation

Usually the off-diagonal matrices, $\frac{\partial \mathbf{P}}{\partial |\mathbf{V}|}^{(v)}$ and $\frac{\partial \mathbf{Q}}{\partial \boldsymbol{\theta}}^{(v)}$ are small. Therefore we approximate them as zero:

$$-\begin{bmatrix} \frac{\partial \mathbf{P}}{\partial \boldsymbol{\theta}}^{(v)} & \mathbf{0} \\ \mathbf{0} & \frac{\partial \mathbf{Q}}{\partial |\mathbf{V}|}^{(v)} \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{\theta}^{(v)} \\ \Delta |\mathbf{V}|^{(v)} \end{bmatrix} = \begin{bmatrix} \Delta \mathbf{P}(\mathbf{x}^{(v)}) \\ \Delta \mathbf{Q}(\mathbf{x}^{(v)}) \end{bmatrix} = \mathbf{f}(\mathbf{x}^{(v)})$$

Then the problem can be decoupled

$$\Delta \boldsymbol{\theta}^{(v)} = -\left[\frac{\partial \mathbf{P}}{\partial \boldsymbol{\theta}}^{(v)} \right]^{-1} \Delta \mathbf{P}(\mathbf{x}^{(v)}) \quad \Delta |\mathbf{V}|^{(v)} = -\left[\frac{\partial \mathbf{Q}}{\partial |\mathbf{V}|}^{(v)} \right]^{-1} \Delta \mathbf{Q}(\mathbf{x}^{(v)})$$

22

22

Off-diagonal Jacobian Terms

Justification for Jacobian approximations:

1. Usually r ≪ x, therefore $|G_{ij}| \ll |B_{ij}|$
2. Usually θ_{ij} is small so $\sin\theta_{ij} \approx 0$

Therefore

$$\frac{\partial \mathbf{P}_i}{\partial |\mathbf{V}_j|} = |V_i|\left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) \approx 0$$

$$\frac{\partial \mathbf{Q}_i}{\partial \boldsymbol{\theta}_j} = -|V_i||V_j|\left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) \approx 0$$

23

23

Fast Decoupled Power Flow

- By continuing with our Jacobian approximations we can actually obtain a reasonable approximation that is *independent of the voltage magnitudes/angles*.
- The Jacobian need only be built/inverted once.
- This approach is known as the fast decoupled power flow (FDPF)
- FDPF uses the same mismatch equations as standard power flow so it should have same solution
- The FDPF is widely used, particularly when we only need an approximate solution such as in contingency analysis

24

24

FDPF Approximations

The FDPF makes the following approximations:

1. $|G_{ij}| = 0$
2. $|V_i| = 1$
3. $\sin\theta_{ij} = 0 \quad \cos\theta_{ij} = 1$

Then

$$\Delta\boldsymbol{\theta}^{(v)} = \mathbf{B}^{-1}\frac{\Delta\mathbf{P}(\mathbf{x}^{(v)})}{\mathbf{V}^{(v)}} \qquad \Delta|\mathbf{V}|^{(v)} = \mathbf{B}^{-1}\frac{\Delta\mathbf{Q}(\mathbf{x}^{(v)})}{\mathbf{V}^{(v)}}$$

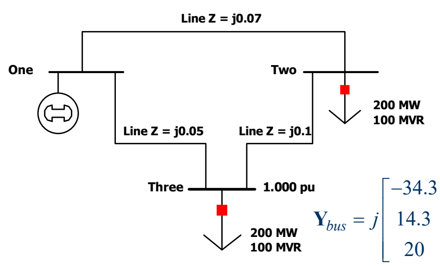
Where $\mathbf{B}$ is just the imaginary part of the $\mathbf{Y}_{\text{bus}} = \mathbf{G} + j\mathbf{B}$, except the slack bus row/column are omitted

25

25

FDPF Three Bus Example

Use the FDPF to solve the following three bus system



$$\mathbf{Y}_{bus} = j\begin{bmatrix} -34.3 & 14.3 & 20 \\ 14.3 & -24.3 & 10 \\ 20 & 10 & -30 \end{bmatrix}$$

26

26

FDPF Three Bus Example, cont'd

$$\mathbf{Y}_{bus} = j\begin{bmatrix} -34.3 & 14.3 & 20 \\ 14.3 & -24.3 & 10 \\ 20 & 10 & -30 \end{bmatrix} \rightarrow \mathbf{B} = \begin{bmatrix} -24.3 & 10 \\ 10 & -30 \end{bmatrix}$$

$$\mathbf{B}^{-1} = \begin{bmatrix} -0.0477 & -0.0159 \\ -0.0159 & -0.0389 \end{bmatrix}$$

Iteratively solve, starting with an initial voltage guess

$$\begin{bmatrix} \theta_2 \\ \theta_3 \end{bmatrix}^{(0)} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \qquad \begin{bmatrix} |V|_2 \\ |V|_3 \end{bmatrix}^{(0)} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} \theta_2 \\ \theta_3 \end{bmatrix}^{(1)} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} + \begin{bmatrix} -0.0477 & -0.0159 \\ -0.0159 & -0.0389 \end{bmatrix}\begin{bmatrix} 2 \\ 2 \end{bmatrix} = \begin{bmatrix} -0.1272 \\ -0.1091 \end{bmatrix}$$

27

27

FDPF Three Bus Example, cont'd

$$\begin{bmatrix} |V|_2 \\ |V|_3 \end{bmatrix}^{(1)} = \begin{bmatrix} 1 \\ 1 \end{bmatrix} + \begin{bmatrix} -0.0477 & -0.0159 \\ -0.0159 & -0.0389 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 0.9364 \\ 0.9455 \end{bmatrix}$$

$$\frac{\Delta P_i(\mathbf{x})}{|V_i|} = \sum_{k=1}^{n} |V_k| (G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik}) + \frac{P_{Di} - P_{Gi}}{|V_i|}$$

$$\begin{bmatrix} \theta_2 \\ \theta_3 \end{bmatrix}^{(2)} = \begin{bmatrix} -0.1272 \\ -0.1091 \end{bmatrix} + \begin{bmatrix} -0.0477 & -0.0159 \\ -0.0159 & -0.0389 \end{bmatrix} \begin{bmatrix} 0.151 \\ 0.107 \end{bmatrix} = \begin{bmatrix} -0.1361 \\ -0.1156 \end{bmatrix}$$

$$\begin{bmatrix} |V|_2 \\ |V|_3 \end{bmatrix}^{(2)} = \begin{bmatrix} 0.924 \\ 0.936 \end{bmatrix}$$

Actual solution: $\boldsymbol{\theta} = \begin{bmatrix} -0.1384 \\ -0.1171 \end{bmatrix}$ $\quad \mathbf{V} = \begin{bmatrix} 0.9224 \\ 0.9338 \end{bmatrix}$

28

28

"DC" Power Flow

- The "DC" power flow makes the most severe approximations:
  - completely *ignore reactive power*, assume all the voltages are always 1.0 per unit, ignore line conductance
- This makes the power flow a linear set of equations, which can be solved directly

$$\boldsymbol{\theta} = \mathbf{B}^{-1} \mathbf{P}$$

- The advantage is it is fast, and it has a guaranteed solution. The disadvantage is the degree of approximation. However, it is used sometimes.

29

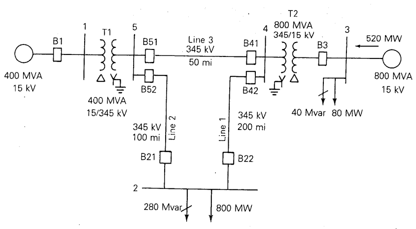
29

DC Power Flow Example

Example: 6.9

FIGURE 6.2

Single-line diagram for Example 6.9

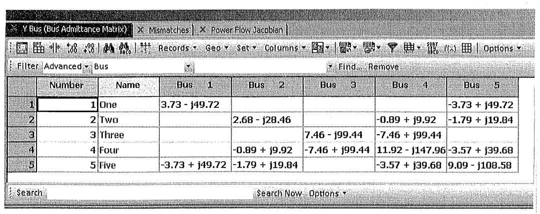


30

30

DC Power Flow Example

Y_{bus} matrix:



Y Bus (Bus Admittance Matrix) | Mismatches | Power Flow Jacobian

	Number	Name	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
1	1	One	3.73 - j49.72				-3.73 + j49.72
2	2	Two		2.68 - j28.46		-0.89 + j9.92	-1.79 + j19.84
3	3	Three			7.46 - j99.44	-7.46 + j99.44	
4	4	Four		-0.89 + j9.92	-7.46 + j99.44	11.92 - j147.96	-3.57 + j39.68
5	5	Five	-3.73 + j49.72	-1.79 + j19.84		-3.57 + j39.68	9.09 - j108.58

31

31

DC Power Flow Example

EXAMPLE 6.17

Determine the dc power-flow solution for the five bus system from Example 6.9.

SOLUTION With bus 1 as the system slack, the **B** matrix and **P** vector for this system are

$$\mathbf{B} = \begin{bmatrix} -30 & 0 & 10 & 20 \\ 0 & -100 & 100 & 0 \\ 10 & 100 & -150 & 40 \\ 20 & 0 & 40 & -110 \end{bmatrix} \qquad \mathbf{P} = \begin{bmatrix} -8.0 \\ 4.4 \\ 0 \\ 0 \end{bmatrix}$$

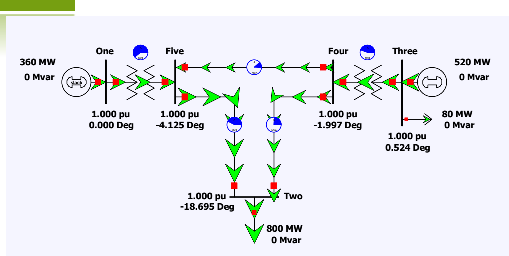
$$\delta = -\mathbf{B}^{-1}\mathbf{P} = \begin{bmatrix} -0.3263 \\ 0.0091 \\ -0.0349 \\ -0.0720 \end{bmatrix} \text{radians} = \begin{bmatrix} -18.70 \\ 0.5214 \\ -2.000 \\ -4.125 \end{bmatrix} \text{degrees}$$

To view this example in PowerWorld Simulator open case Example 6_17 which has this example solved using the DC power flow (see Figure 6.14). To view the DC power flow options select **Options, Simulator Options** to show the PowerWorld Simulator Options dialog. Then select the Power Flow Solution category, and the DC Options page.

32

32

DC Power Flow 5 Bus Example



Notice with the dc power flow all of the voltage magnitudes are 1 per unit.

33

33

Integration of Renewable Energy

34

Integration of Renewable Energy

11. Integration of Renewable Energy

Renewable Energy Sources:

- Wind energy
- Solar energy
- Geothermal energy
- Hydro energy
- Bio energy

35

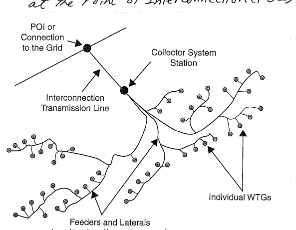
Integration of Renewable Energy

Typical Wind Turbine Generator (WTG)

1~3 MW, 600 V

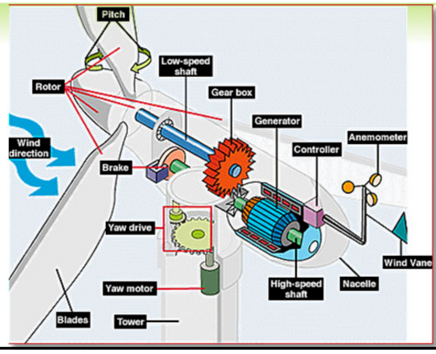
Voltage: Stepped-up to 34.5 kV, then to over 100 kV at the Point of Interconnection (POI):

FIGURE 6.15 Wind power plant collector system topology [14] (Figure 1 from WECC Wind Generation Modeling Group, "WECC Wind Power Plant Power Flow Model Guide," WECC, May 2008, p. 2)



36

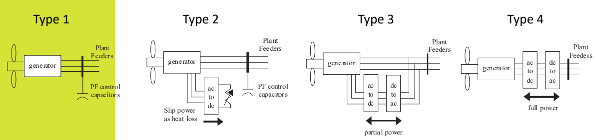
Wind Turbine Generators



37

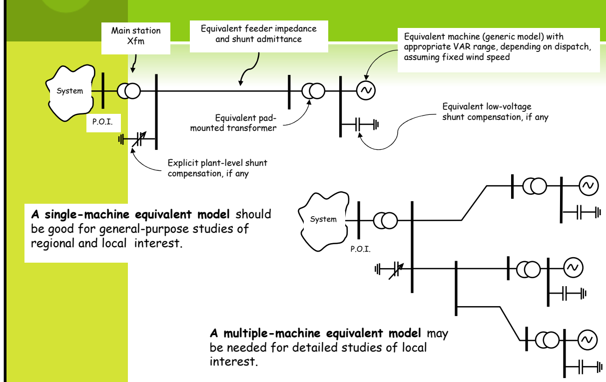
Wind Turbine Generators

- Based on characteristics of grid interface
  - Type 1 – conventional induction generator
  - Type 2 – wound rotor induction generator with variable rotor resistance
  - Type 3 – doubly-fed induction generator
  - Type 4 – full converter interface



38

Technical Challenges



39

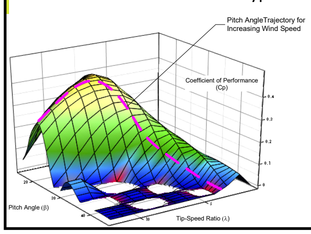
Technical Challenges

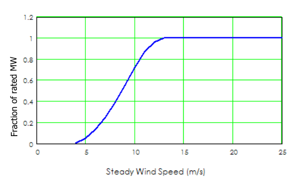
- Simplification of aerodynamic characteristics
- The mechanical power (*Pmech*) applied to the generator is a function of the performance factor (*Cp*)
  - *Pmech* = ½ × (air density) × (swept area) × *Cp* × (wind speed)^3
- *Cp* is a function of blade pitch and tip-speed ratio (or just rotor speed, if wind speed is assumed constant)
- During a typical dynamic simulation, blade pitch and tip speed ratio vary, thus *Cp* and *Pmech* will also vary
- *Cp* is modeled using a look-up table or *Cp* matrix specific to each WTG provided by the manufacturer usually on a confidentiality basis

40

Technical Challenges

- Example
  - Typical *Cp* curve (left) for a fixed-speed WTG (Type 1). The dashed magenta line shows operating points that correspond to the steady-state power curve (right)
  - Can a simplified model that captures the important performance characteristics of this type of WTG?





41

42