7. Control of Power Flow

The following means are used to control power flow:

1. Prime mover and excitation control of generators.

   Prime mover $\downarrow$ P, δ excitation $\downarrow$ $Q, |V|$

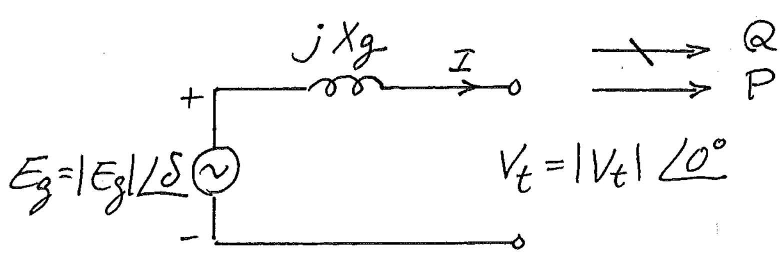
2. Shunt capacitor banks, shunt reactors, static var systems (SVS).

   $Q, \ |V|$

3. Tap-Changing and regulation transformers.

   Tap-Changing $\downarrow$ $Q, |V|$ regulation $\downarrow$ P, δ

1) Generator Control: Control of Power



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

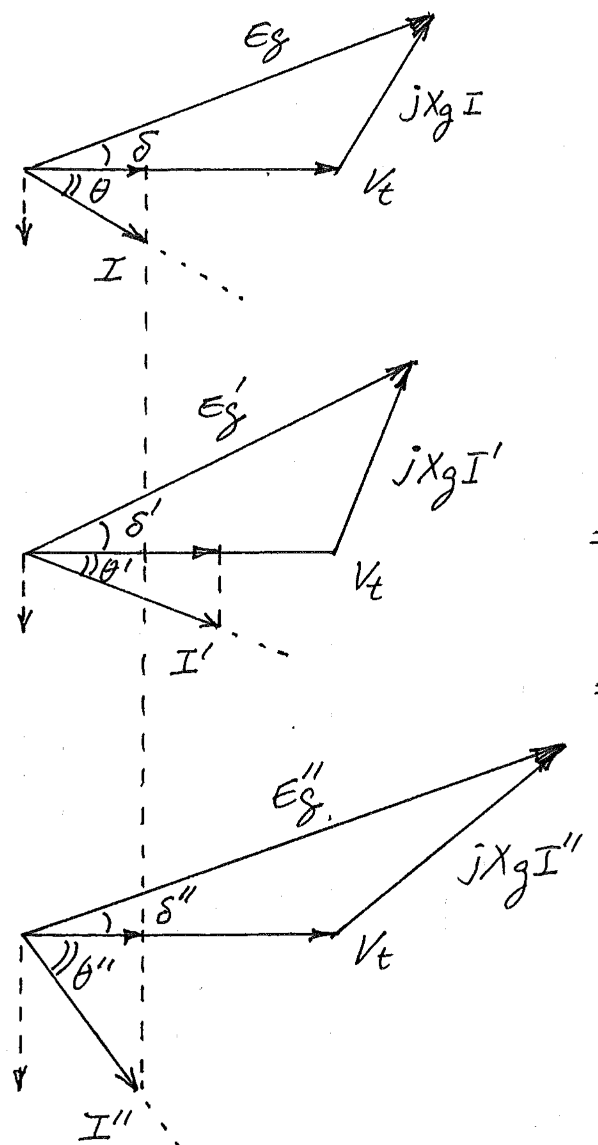
$$S = P + jQ = V_t I^* = |V_t| \left(\frac{|E_g| \angle -\delta - |V_t|}{-jX_g} \right)$$

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

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

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

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

Reactive Power Control:

Excitation control controls E_g

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

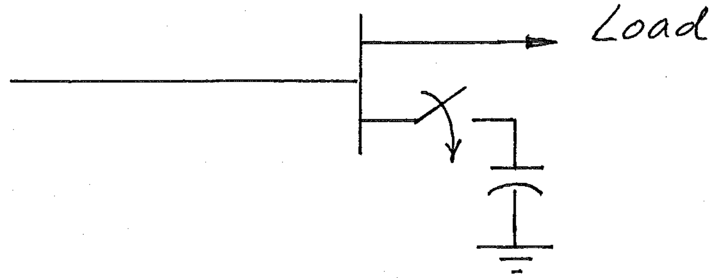
$$Q = V_t I \sin \theta$$

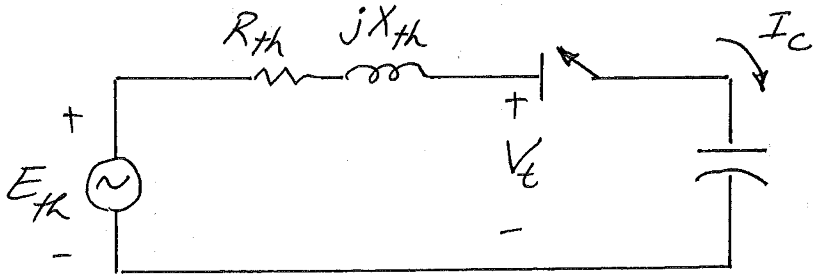
Increased E_g

$\Rightarrow$ increases I and increases θ

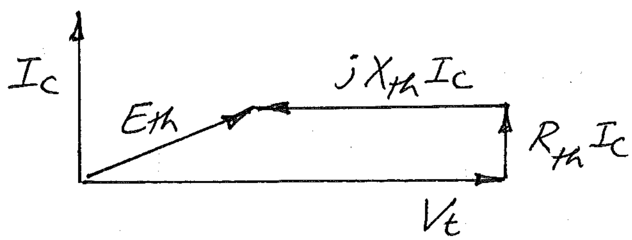
$\Rightarrow$ increases Q while P remain constant.

2) <u>Shunt Capacitor</u>: Voltage Control





$$I_c = \frac{E_{th}}{Z_{th} - jX_c}$$



SW off: $V_t = E_{th}$

on: $V_t > E_{th}$

Increase ~ $X_{th} I_c$

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.

TOPS. 35500

3) <u>Tap-Changing Transformers</u>: Chapter 3

Magnitude-regulating transformer:

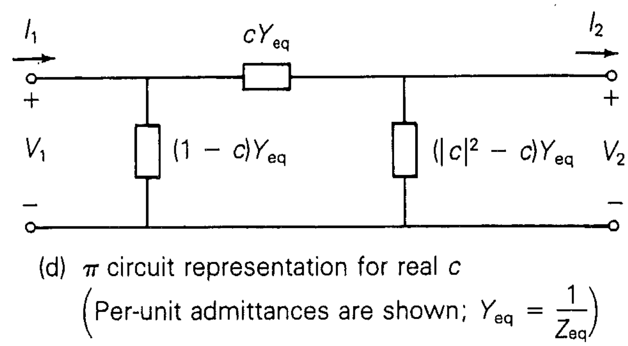
Change voltage magnitude at a bus as well as reactive power flows on lines.

Phase-angle regulating transformer:

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

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

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.



(d) π circuit representation for real c

(Per-unit admittances are shown; $Y_{eq} = \dfrac{1}{Z_{eq}}$)

8. Sparsity Techniques

A typical power system has an average of fewer than three lines connected to each bus. As such, each row of Y_{bus} has an average of fewer than four non-zero elements. Such a matrix, which has only a few nonzero elements, is said to be sparse.

Sparse matrix techniques: reduce computer storage and computation time.

- Compact storage of Y_{bus} and $J(i)$
- Reordering of buses to avoid fill-in of $J(i)$ during Gauss elimination steps.

1) Compact Storage: Consider the following matrix:

$$\mathbf{S} = \begin{bmatrix} 1.0 & -1.1 & -2.1 & -3.1 \\ -4.1 & 2.0 & 0 & -5.1 \\ -6.1 & 0 & 3.0 & 0 \\ -7.1 & 0 & 0 & 4.0 \end{bmatrix} \tag{6.8.1}$$

One method for compact storage of **S** consists of the following four vectors:

$$\mathbf{DIAG} = [1.0 \quad 2.0 \quad 3.0 \quad 4.0] \tag{6.8.2}$$

$$\mathbf{OFFDIAG} = [-1.1 \quad -2.1 \quad -3.1 \quad -4.1 \quad -5.1 \quad -6.1 \quad -7.1] \tag{6.8.3}$$

$$\mathbf{COL} = [2 \quad 3 \quad 4 \quad 1 \quad 4 \quad 1 \quad 1] \tag{6.8.4}$$

$$\mathbf{ROW} = [3 \quad 2 \quad 1 \quad 1] \tag{6.8.5}$$

DIAG: Diagonal elements
OFFDIAG: nonzero off-diagonals
COL: the column number of each off-diagonal element.
ROW: the number of off-diagonal elements in each row.

Note: S can be completely reconstructed from these 4 vectors.

Y_{bus}: each element $Y_{ij} = |Y_{ij}| \angle \theta_{ij}$

Computer storage requirements:

4 bytes: for magnitude $|Y_{ij}|$

4 bytes: for phase θ_{ij}

3 nonzero off-diagonals (3 lines per bus)

DIAG: $(4+4)N = 8N$ bytes

OFFDIAG: $(4+4)\,3N = 24N$ bytes

2 bytes to store integers:

COL: $2 \times 3N = 6N$

ROW: $2N$

Total memory required: $(8+24+6+2)N = \underline{40N}$

cf. w/o compact memory: $(4+4)N^2 = \underline{8N^2}$

<u>Ex</u>: $N = 1000$ bus system.

$40 \times 1000 = 40$ kilobytes

vs. $8 \times (1000)^2 = 8000$ kilobytes

Further storage reduction could be obtained by storing only the <u>upper triangular portion</u> of the symmetric Y_{bus} matrix.

<u>Jacobian Marix</u> J is also sparse.

e.g., $Y_{kn} = 0$ (From Table 6.5)

$\Rightarrow J1_{kn} = J2_{kn} = J3_{kn} = J4_{kn} = 0.$

2) Re-ordering of bus numbers:

Consider again the sparse matrix

$$\mathbf{S} = \begin{bmatrix} 1.0 & -1.1 & -2.1 & -3.1 \\ -4.1 & 2.0 & 0 & -5.1 \\ -6.1 & 0 & 3.0 & 0 \\ -7.1 & 0 & 0 & 4.0 \end{bmatrix}$$

After one Gauss elimination step, we have

$$\mathbf{S}^{(1)} = \begin{bmatrix} 1.0 & -1.1 & -2.1 & -3.1 \\ 0 & -2.51 & -8.61 & -7.61 \\ 0 & -6.71 & -9.81 & -18.91 \\ 0 & -7.81 & -14.91 & -18.01 \end{bmatrix}$$

Thus, zeros in S are filled with non-zeros in $S^{(1)}$, and the original degree of sparsity is lost.

Re-ordering Method: Start with those buses having the fewest connected branches, and end with those having the most connected branches:

Bus 1: three branches connected $\longrightarrow$ bus 4
Bus 2: two branches connected $\longrightarrow$ bus 3
Bus 3: one branch connected $\longrightarrow$ bus 2
Bus 4: one branch connected $\longrightarrow$ bus 1

$$\mathbf{S}_{\text{reordered}} = \begin{bmatrix} 4.0 & 0 & 0 & -7.1 \\ 0 & 3.0 & 0 & -6.1 \\ -5.1 & 0 & 2.0 & -4.1 \\ -3.1 & -2.1 & -1.1 & 1.0 \end{bmatrix}$$

Now, after one Gauss elimination step,

$$\mathbf{S}^{(1)}_{\text{reordered}} = \begin{bmatrix} 4.0 & 0 & 0 & -7.1 \\ 0 & 3.0 & 0 & -6.1 \\ 0 & 0 & 2.0 & -13.15 \\ 0 & -2.1 & -1.1 & -4.5025 \end{bmatrix}$$

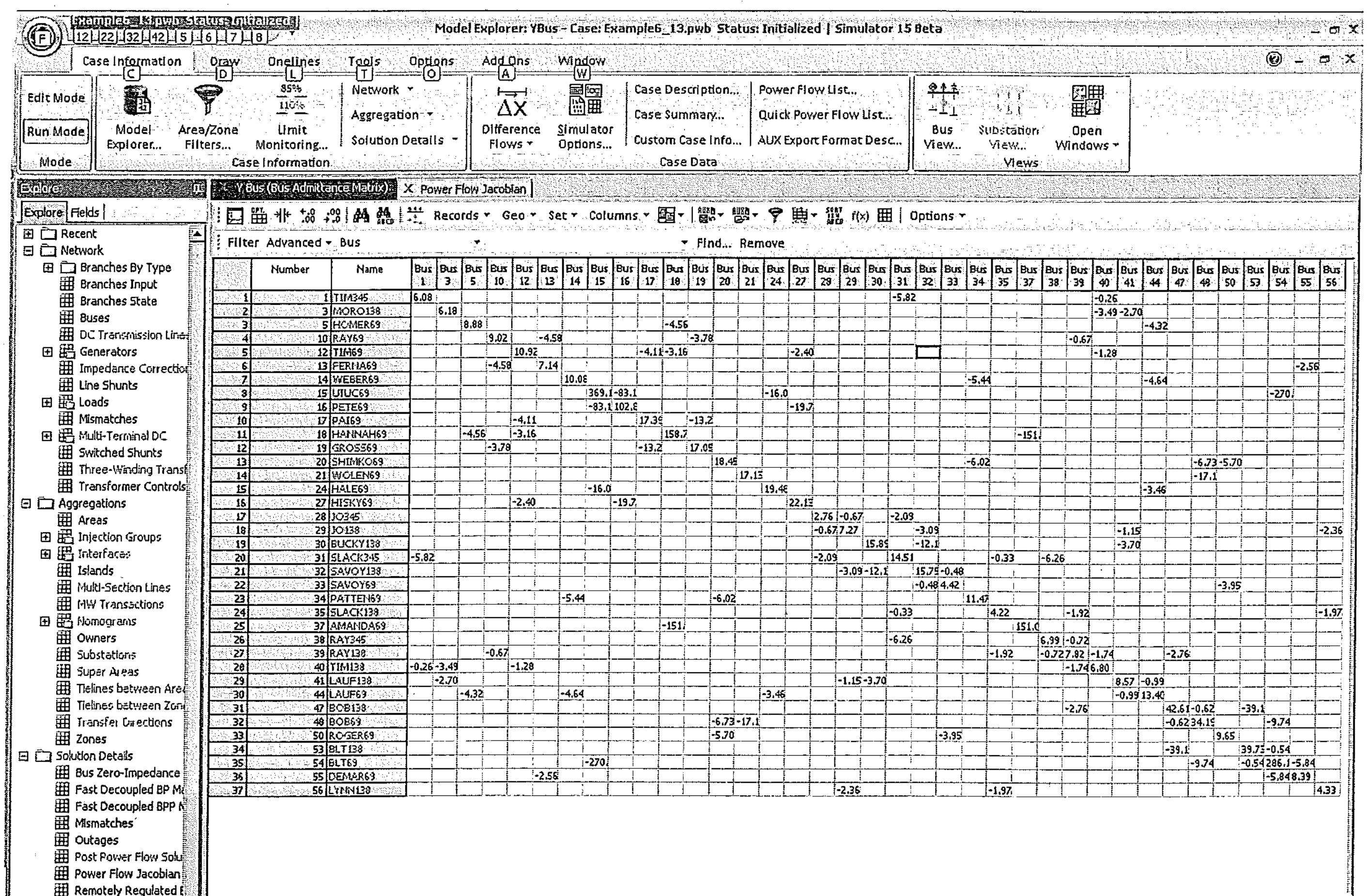
Note that the original degree of sparsity is not lost

Re-ordering buses can be peformed once, befor the Gauss elimination process begins. Alternatively, it can be performed during each Gauss elimination step.

Sparsity techniques are common in today's Newton-Raphson power-flow programs. As a result, typical 30,000-bus power-flow solutions require less than 10 megabyes of storage, less than one second per iteration of computer time, and less than 10 iterations to converge.

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.



Ybus: 37×37 = 1369 entries, only 10% nonzero.

9. Fast Decoupled Power Flow

Recall that the power-flow problem is to solve

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix}$$

Since $\Delta P \propto \Delta\delta$

$\Delta Q \propto \Delta V$

Neglect $J_2 = \frac{\partial P}{\partial V}$ and $J_3 = \frac{\partial Q}{\partial \delta}$

$\Rightarrow$ Decoupled equations:

$$\Delta P = J_1 \Delta\delta$$

$$\Delta Q = J_4 \Delta V$$

Computer time required to solve these equations is significantly less than that required to solve the coupled equation.

Further Reduction in Computer Time:

$$V_k \simeq 1.0, \quad \delta_k \simeq \delta_n, \quad Y_{bus} \simeq -j B_{bus}$$

$\Rightarrow$ J_1, J_4 : constant,

$\Rightarrow$ There is no need to update Jacobians.

While the fast decoupled power flow takes more iterations to converge, it is usually faster than the Newton-Raphson algorithm.

10. The "DC" Power Flow

Simplify the fast decoupled power flow by

1. Neglecting the Q-V equation,
2. Assuming $V_k \simeq 1.0$

$\Rightarrow$ Power flow on the line from bus j to bus k:

$$P_{jk} = \frac{\delta_j - \delta_k}{X_{jk}}$$

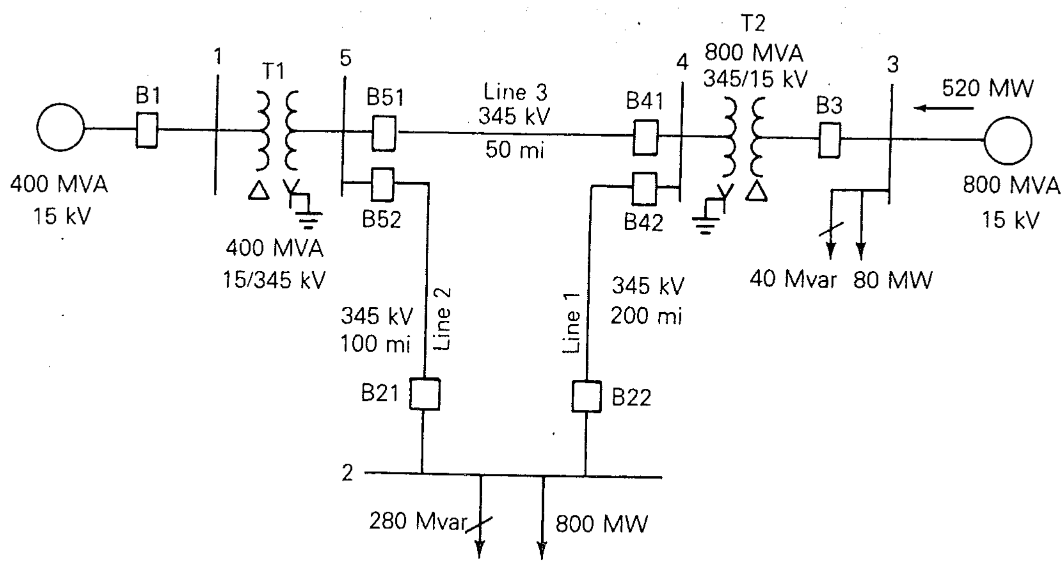
$\Rightarrow$

$$-B\,\delta = P, \qquad B = \mathrm{Im}(Y_{bus})$$

Example: 6.9

FIGURE 6.2

Single-line diagram for Example 6.9



Y_{bus} matrix:

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

Records ▾ Geo ▾ Set ▾ Columns ▾ Options ▾

Filter Advanced ▾ Bus ▾ Find... Remove

	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

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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

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

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

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.

11. Integration of Renewable Energy

Renewable Energy Sources:

Wind energy
Solar energy
Geothermal energy
Hydro energy
Bio energy

Wind Energy:

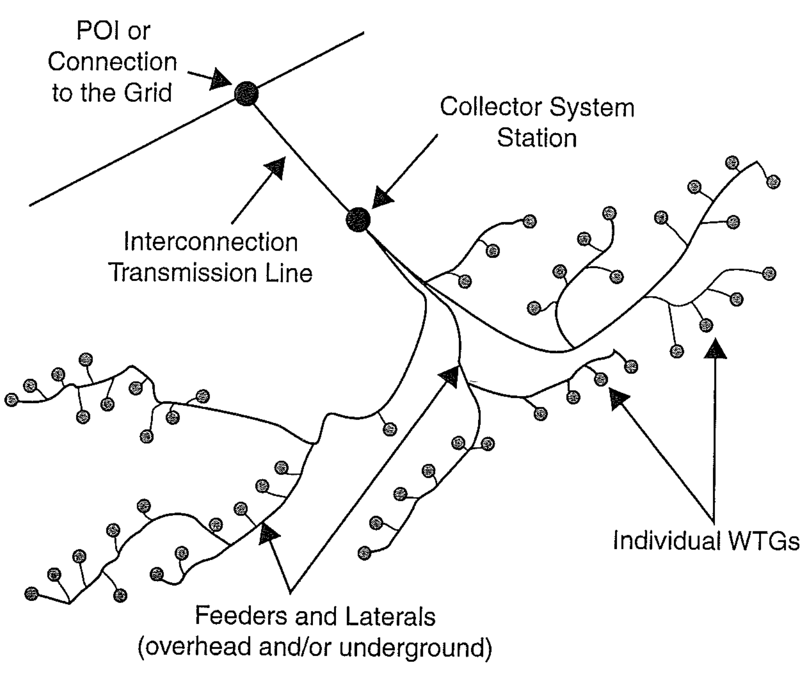
Denmark: 20% of total energy in 2008
Spain: 10% "
U.S.: 35 GW of 1000 GW in 2009

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)



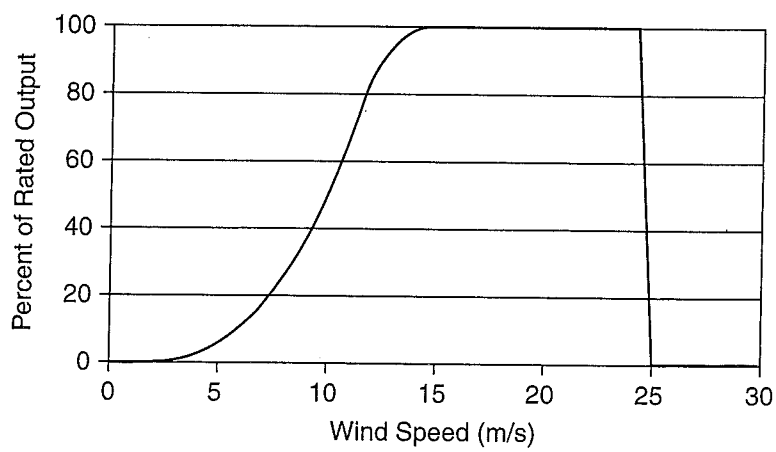
For power system analysis, the entire wind farm can be represented as a single equivalent generator connected at the POI through an equivalent impedance for the collector system and the step-up transformers.

The parameters for the equivalent generator are usually just scaled values of the parameters of the individual WTGs.

There are four main types of WTGs. As is the case with conventional synchronous generators, the real power outputs for all WTGs are considered to be constant in power-flow studies. How much real power a wind farm can actually produce at any moment depends upon the wind speed, as shown in Figure.

FIGURE 6.16

Typical wind speed versus power curve



Wind Turbine Generators

Type 1 WTGs: Squirrel-cage induction machines

Consume reactive power

Modeled as a constant powerfactor PQ bus under excited p.f. of 0.85 ~ 0.9.

Use capacitor banks at the POI to correct the wind farm power factor.

Type 2 WTGs: Wound-rotor induction machines

Rotor resistance can be controlled

Perform like Type 1 WTGs in power-flow.

Type 3 WTGs: Doubly-fed induction generators (DFIGs)

Rotor circuit is also connected to the AC network through an AC-DC-AC converter, allowing for much greater control.

Type 4 WTGs: Synchronous machines

Full power output is coupled to the AC network through an AC-DC-AC converter.

For power-flow perspective, both Type 3 & 4 are capable of full voltage control, between a p.f. of up to ± 0.9, like a traditional PV bus generator.