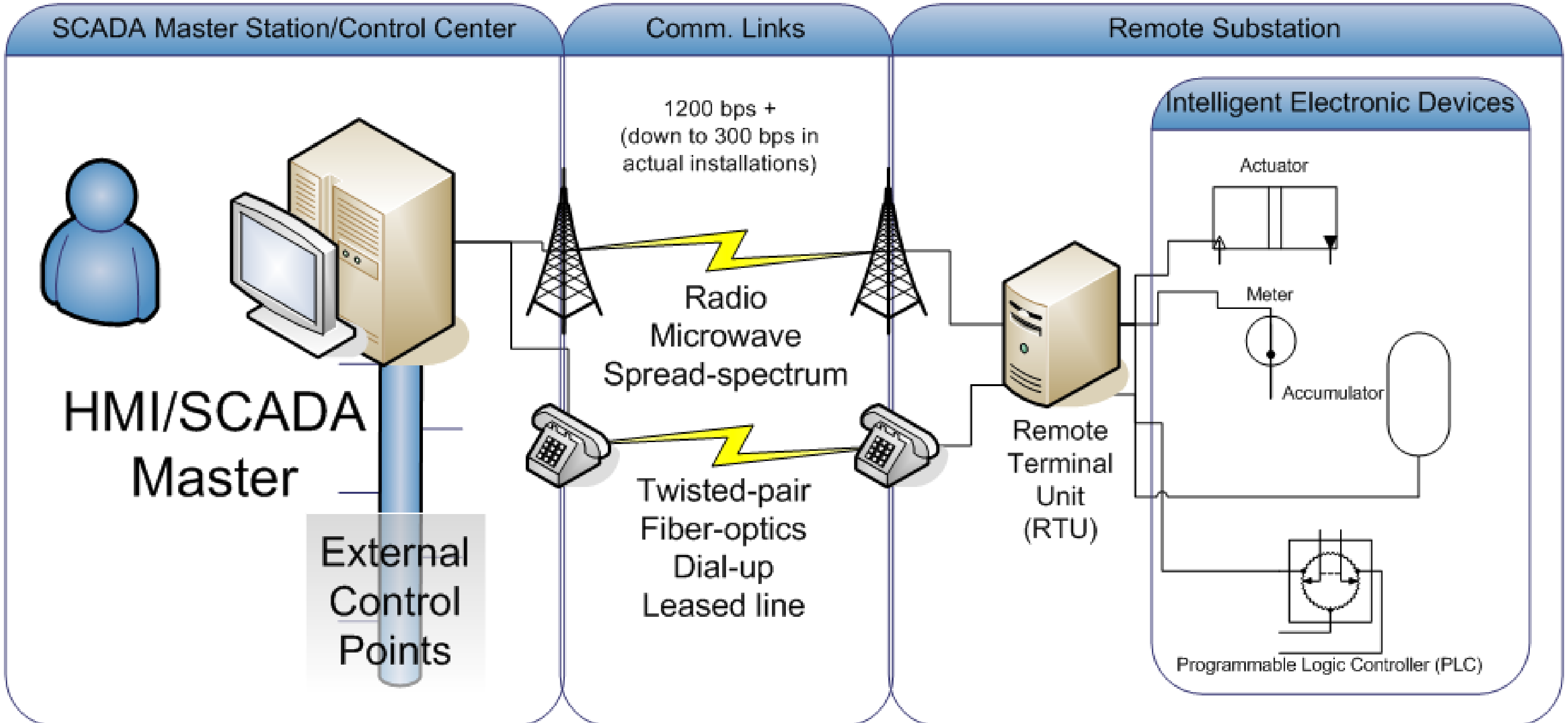
Introduction to State Estimation of Power Systems

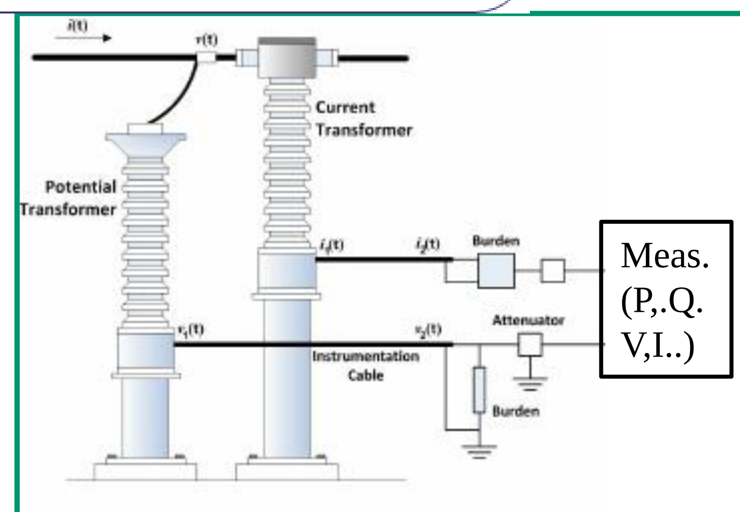
ECG 740

Introduction (cont.)

- Electric utilities have installed extensive supervisory control and data acquisition (SCADA) throughout the network to support computer-based systems.
- The data is used for numerous applications (e.g., system monitoring, economic system operation, security assessment, control of generation, etc…)
- Before any assessment is made or control action is taken, a reliable estimate of the existing state of the system must be determined.
- For this purpose, the number of physical measurements cannot be restricted to those quantities required to support power flow calculations.
- Moreover, errors in one or more of the input quantities can lead to useless results.

Utility SCADA





Introduction (cont.)

- In practice, other conveniently measured quantities (such as P&Q line flows) are available, but cannot be used in power flow calculations.
- The unavoidable errors in the measurements are assigned statistical properties.
- Such limitations are removed by state estimation based on weighted least-squares calculations.
- Gross errors detected in the course of state estimation are filtered out.
- A State Estimator allow the calculation of the variables of interest with high confidence despite:
  - measurements that are corrupted by noise.
  - measurements that may be missing or grossly inaccurate.

Introduction (cont.)

- The state (x) is defined as the voltage magnitude and angle at each bus

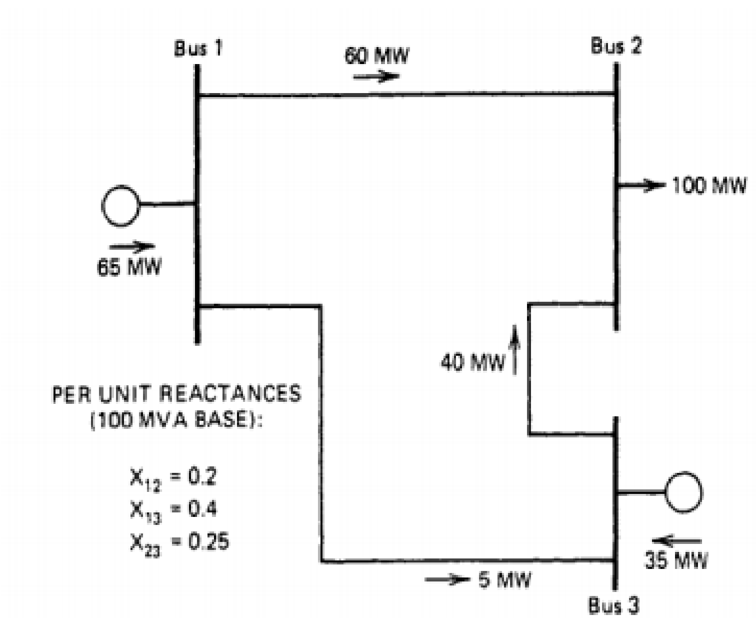
$$\tilde{V}_i = V_i e^{j\delta_i} \qquad x = [V_1, V_2, \ldots, V_n, \delta_1, \ldots, \delta_b]$$

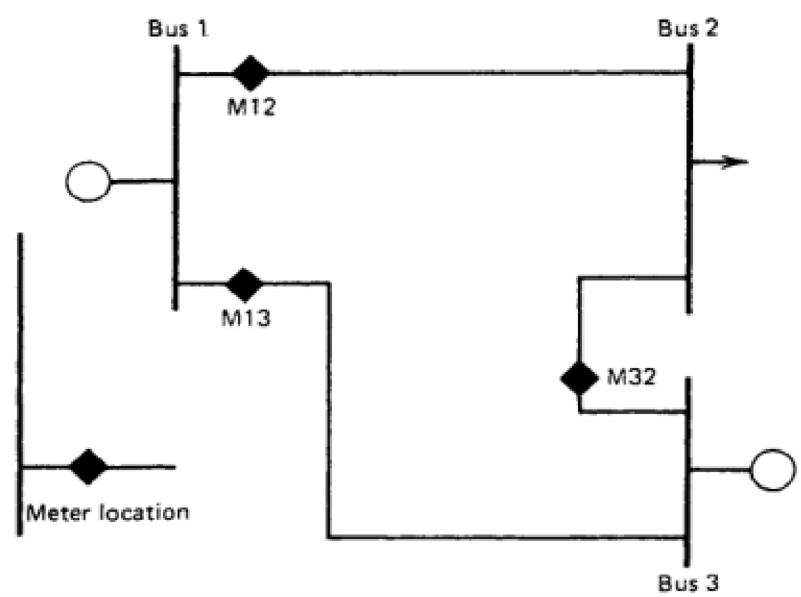
- All variables of interest can be calculated from the state and the measurement mode. z = h(x)
- We generally cannot directly observe the state
  - ✓ But we can infer it from measurements
  - ✓ The measurements are noisy (gross measurement errors, communication channels outage)

Illustration A: 3 –Bus DC Power Flow

Three-bus DC Load Flow

The only information we have about this system is provided by three MW power flow meters





- Only two of these meter readings are required to calculate the bus phase angles and all load and generation values fully

$$M_{13} = 5MW = 0.05pu$$

$$M_{32} = 40MW = 0.40pu$$

$$f_{13} = \frac{1}{x_{13}}(\theta_1 - \theta_3) = M_{13} = 0.05pu$$

$$f_{32} = \frac{1}{x_{23}}(\theta_3 - \theta_2) = M_{32} = 0.40pu$$

Now calculating the angles, considering third bus as swing bus we get

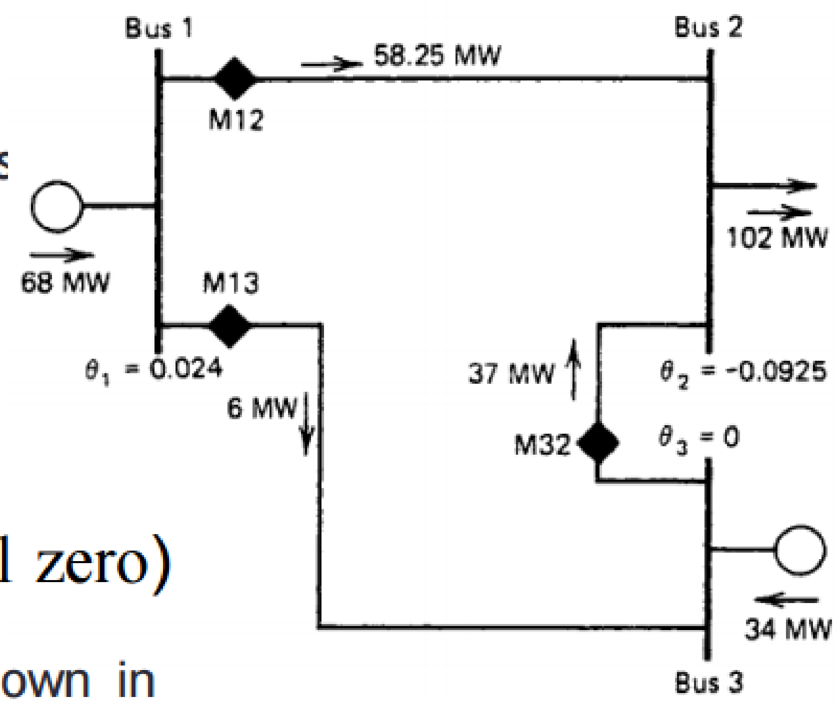
$$\theta_1 = 0.02rad$$

$$\theta_2 = -0.10rad$$

Case with all meters have small errors

$$M_{12} = 62MW = 0.62pu$$
$$M_{13} = 6MW = 0.06pu$$
$$M_{32} = 37MW = 0.37pu$$

If we use only the *M_{13} and M_{32} readings as before, then the phase* angles will be:



$$\theta_1 = 0.024rad$$
$$\theta_2 = -0.0925rad$$
$$\theta_3 = 0rad(\text{still assumed to equal zero})$$

This results in the system flows as shown in Figure . Note that the predicted flows match at *M_{13}, and M_{32} but the flow on line 1-2 does not match the* reading of 62 MW from M_{12}.

What we Need ?

- A procedure that uses the information available from all the three meters to produce the best estimate of the actual angles, line flows, and bus load and generation.
- We have three meters providing us with a set of redundant readings with which to estimate the two states θ_1 and $\theta_{2.}$
  - We say that the readings are redundant since, as we saw earlier, only two readings are necessary to calculate θ_1 and θ_2 the other reading is always “extra”.
  - The “extra” reading does carry useful information and ought not to be discarded.

Method of Least Squares

- The acquired data always contains inaccuracies during measurement and/or transmission. The best estimates are chosen as those which minimize the weighted sum of the squares of the measurement errors.
- Mathematically, let $Z = h(x) + e$

where,

Z = Measurement Vector

h = System model relating state vector to the measurement set

x = State vector (voltage magnitudes and angles)

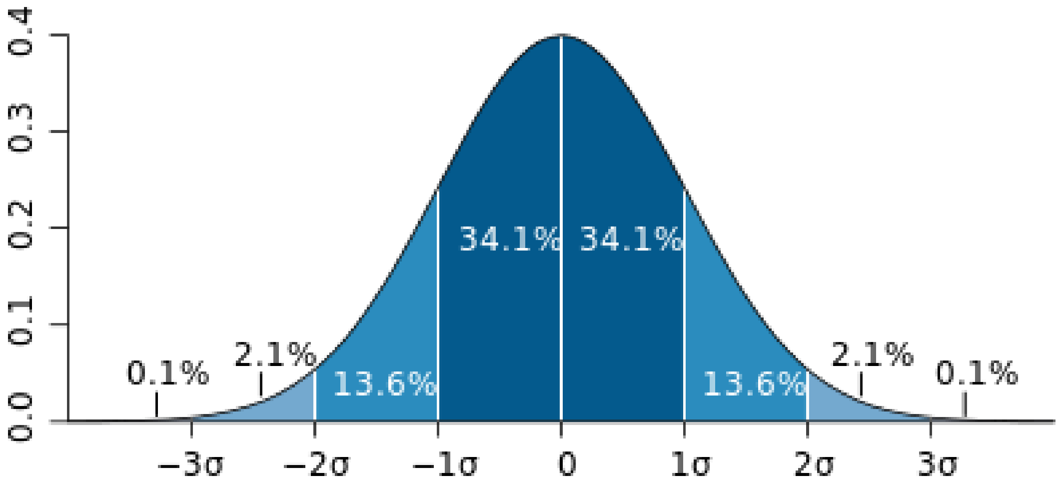
e = Error vector associated with the measurement set

Normal Gaussian distribution function

- If the measurement error is unbiased, the probability density function of η is usually chosen as a normal distribution with zero mean.

$$\mathrm{PDF}(\eta) = \frac{1}{\sigma\sqrt{2\pi}} \exp(-\eta^2 / 2\sigma^2)$$

- where, σ is called the standard deviation and σ^2 is called the variance of the random number.



SE Problem Development

- Classical Approach: Weighted Least Squares…

$$\min\ J(x)=\sum_{i=1}^{m}\frac{(z_i-h_i(x))^2}{\sigma_i^2}$$

Minimize: $J(\mathbf{x}) = [\mathbf{z} - \mathbf{h}(\mathbf{x})]^{t}.\ \mathbf{W}.\ [\mathbf{z} - \mathbf{h}(\mathbf{x})]$

where,

J = Weighted least squares

W = Weighting matrix = reciprocal of error variances

- In case of a linear system, i.e., $h(x) = \mathbf{Hx}$, the weighted least square estimate of **x** is

$$\mathbf{x}^{est} = \mathbf{G}^{-1}\mathbf{H}^{T}\mathbf{W}\mathbf{z}$$

where the gain matrix $\mathbf{G} = \mathbf{H}^{T}\mathbf{W}\mathbf{H}$

Special Cases

- **Fully Determined Case**: When the number of measurements is equal to the number of state variables,

$$\mathbf{x}^{est} = \mathbf{H}^{-1}\mathbf{z}$$

- **Underdetermined case:** When the number of measurements is smaller than the number of state variables (unobservable case), minimize the sum of the squares of the solution values,

$$\mathbf{x}^{est} = [\mathbf{H}^T\mathbf{H}\mathbf{H}^T]^{-1}\,\mathbf{z}$$

Back to Illustration A

- Assume that all the three meters have the following characteristics:
  - Meter full scale value: 100 MW
  - Meter Accuracy: ± 3 MW
- This is interpreted to mean that the meters will give a reading within ± 3 MW of the true value being measured for approximately 99 % of time.
- Mathematically, we say that the errors are distributed according to a normal probability density function with a standard deviation ,σ, i.e., $3\sigma = \pm 3$ MW. Hence, the metering standard deviation $\sigma = 1$ MW = 0.01 pu.

Illustration A (cont.)

- To derive the H matrix , we need to write the measurements as a function of the state variables θ_1 and θ_2. These functions are written in per unit as
  - $M_{12} = f_{12} = 1/0.2\ x(\theta_1 - \theta_2) = 5\ \theta_1 - 5\theta_2$
  - $M_{13} = f_{13} = 1/0.4\ x(\theta_1 - \theta_3) = 2.5\ \theta_1$
  - $M_{32} = f_{32} = 1/0.25\ x(\theta_3 - \theta_2) = -4\ \theta_2$

$$[H] = \begin{bmatrix} 5 & -5 \\ 2.5 & 0 \\ 0 & -4 \end{bmatrix}, \quad x = \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}$$

- Error covariance matrix $W = \begin{bmatrix} .0001 & 0 & 0 \\ 0 & .0001 & 0 \\ 0 & 0 & .0001 \end{bmatrix}$

- Our least-squares "best" estimate of θ_1 and θ_2 is then calculated as

$$\begin{bmatrix}\theta_1^{est}\\ \theta_2^{est}\end{bmatrix}=\left[\begin{bmatrix}5 & 2.5 & 0\\ -5 & 0 & -4\end{bmatrix}\begin{pmatrix}0.0001 & & \\ & 0.0001 & \\ & & 0.0001\end{pmatrix}^{-1}\begin{pmatrix}5 & -5\\ 2.5 & 0\\ 0 & -4\end{pmatrix}\right]^{-1}$$

$$\times\begin{bmatrix}5 & 2.5 & 0\\ -5 & 0 & -4\end{bmatrix}\begin{pmatrix}0.0001 & & \\ & 0.0001 & \\ & & 0.0001\end{pmatrix}^{-1}\begin{bmatrix}0.62\\ 0.06\\ 0.37\end{bmatrix}$$

$$\begin{bmatrix}\theta_1^{est}\\ \theta_2^{est}\end{bmatrix}=\begin{bmatrix}0.028571\\ -0.094286\end{bmatrix}$$

- From the estimated phase angles, we can calculate the power flowing in each transmission line and the net generation or load at each bus.

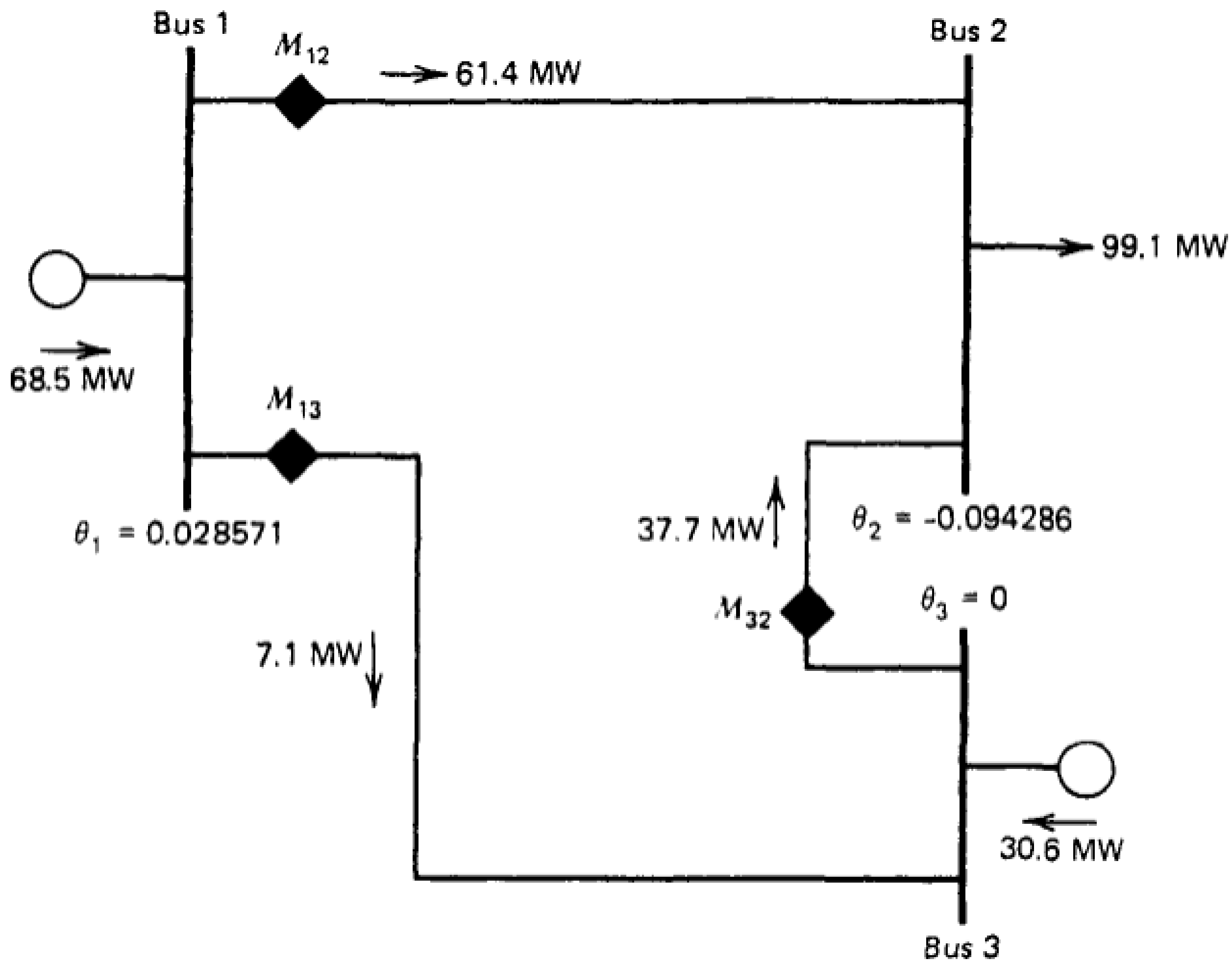
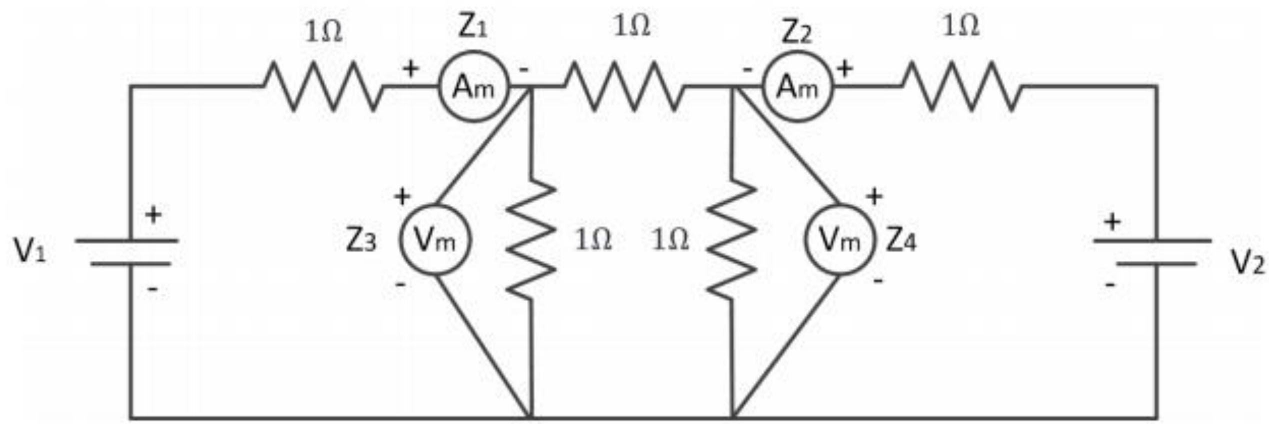


Illustration B

- Consider the following circuit which consists of two ammeters z_1, z_2 and two voltmeters z_3, z_4



- If the meter readings are $z_1 = 9.01A$, $z_2 = 3.02A$ $z_3 = 6.98V$, $z_4 = 5.01V$ and $w_1 = 100$, $w_2 = 100$, $w_3 = 50$, $w_4 = 50$ then we have to estimate the voltages and V_2.

Variance of amp-meters = 1/100, variance of volt-meters = 1/50

Solution

$$z_1 = \frac{5}{8}x_1 - \frac{1}{8}x_2 + e_1$$

$$z_2 = -\frac{1}{8}x_1 + \frac{8}{8}x_2 + e_2$$

$$z_3 = \frac{3}{8}x_1 + \frac{1}{8}x_2 + e_3$$

$$z_4 = \frac{1}{8}x_1 + \frac{3}{8}x_2 + e_4$$

$$H = \begin{pmatrix} 0.625 & -0.125 \\ -0.125 & 0.625 \\ 0.375 & 0.125 \\ 0.125 & 0.375 \end{pmatrix} \quad z = \begin{bmatrix} 9.01 \\ 3.02 \\ 6.98 \\ 5.01 \end{bmatrix} \quad W = \begin{bmatrix} 100 & 0 & 0 & 0 \\ 0 & 100 & 0 & 0 \\ 0 & 0 & 50 & 0 \\ 0 & 0 & 0 & 50 \end{bmatrix}$$

$$\begin{bmatrix} \hat{V}_1 \\ \hat{V}_2 \end{bmatrix} := \begin{bmatrix} 16.0072\text{V} \\ 8.0261\text{V} \end{bmatrix} \quad \begin{bmatrix} \hat{z}_1 \\ \hat{z}_2 \\ \hat{z}_3 \\ \hat{z}_4 \end{bmatrix} = \begin{bmatrix} 9.00123\text{A} \\ 3.01544\text{A} \\ 7.00596\text{V} \\ 5.01070\text{V} \end{bmatrix} \quad \begin{bmatrix} \hat{e}_1 \\ \hat{e}_2 \\ \hat{e}_3 \\ \hat{e}_4 \end{bmatrix} = \begin{bmatrix} 9.01 \\ 3.02 \\ 6.98 \\ 5.01 \end{bmatrix} - \begin{bmatrix} 9.00123 \\ 3.01544 \\ 7.00596 \\ 5.01070 \end{bmatrix} = \begin{bmatrix} 0.00877\text{A} \\ 0.00456\text{A} \\ -0.02596\text{V} \\ -0.00070\text{V} \end{bmatrix}$$

(^) represent estimated values

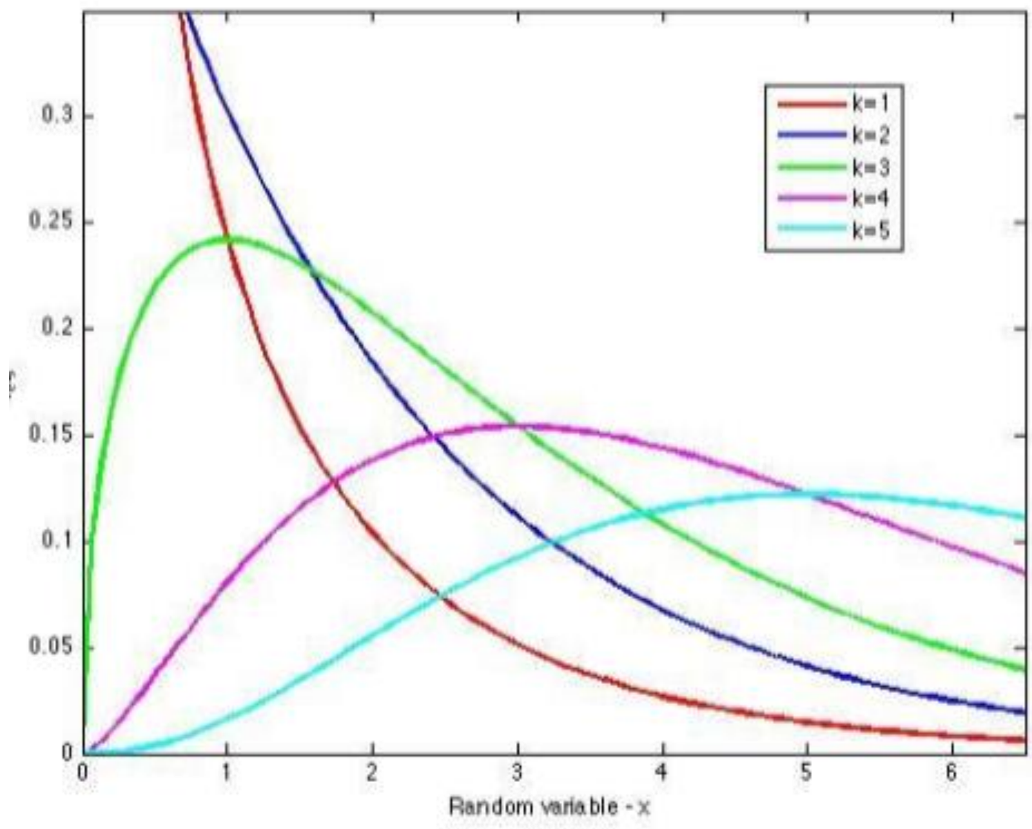
How Good are the Estimates?

- What criterion for acceptance is reasonable?
- If a grossly erroneous meter reading is present, can we detect that fact and identify the bad measurement?
- These questions can be answered within a quantifiable level of confidence by attaching a statistical meaning to the measurement errors in the least square calculations.

Test for Bad Data

- Each estimated error is a Gaussian variable with zero mean.
- The weighted sum of the squares of these has a Chi-square distribution χ_k^2 where k is the degree f freedom.
- Hypothesis Testing: **Probability that $J(x) > t_i = \alpha$**
- Where
- $J(x)$: measurement residual
- α: significance level

  (prob. of false alarm)
- t_j: test threshold



Hypothesis Testing Parameters

k

Percentage Points of the Chi-Square Distribution

Degrees of Freedom	Probability of a larger value of x^2								
	0.99	0.95	0.90	0.75	0.50	0.25	0.10	0.05	0.01
1	0.000	0.004	0.016	0.102	0.455	1.32	2.71	3.84	6.63
2	0.020	0.103	0.211	0.575	1.386	2.77	4.61	5.99	9.21
3	0.115	0.352	0.584	1.212	2.366	4.11	6.25	7.81	11.34
4	0.297	0.711	1.064	1.923	3.357	5.39	7.78	9.49	13.28
5	0.554	1.145	1.610	2.675	4.351	6.63	9.24	11.07	15.09
6	0.872	1.635	2.204	3.455	5.348	7.84	10.64	12.59	16.81
7	1.239	2.167	2.833	4.255	6.346	9.04	12.02	14.07	18.48
8	1.647	2.733	3.490	5.071	7.344	10.22	13.36	15.51	20.09
9	2.088	3.325	4.168	5.899	8.343	11.39	14.68	16.92	21.67
10	2.558	3.940	4.865	6.737	9.342	12.55	15.99	18.31	23.21
11	3.053	4.575	5.578	7.584	10.341	13.70	17.28	19.68	24.72
12	3.571	5.226	6.304	8.438	11.340	14.85	18.55	21.03	26.22
13	4.107	5.892	7.042	9.299	12.340	15.98	19.81	22.36	27.69
14	4.660	6.571	7.790	10.165	13.339	17.12	21.06	23.68	29.14
15	5.229	7.261	8.547	11.037	14.339	18.25	22.31	25.00	30.58
16	5.812	7.962	9.312	11.912	15.338	19.37	23.54	26.30	32.00
17	6.408	8.672	10.085	12.792	16.338	20.49	24.77	27.59	33.41
18	7.015	9.390	10.865	13.675	17.338	21.60	25.99	28.87	34.80
19	7.633	10.117	11.651	14.562	18.338	22.72	27.20	30.14	36.19
20	8.260	10.851	12.443	15.452	19.337	23.83	28.41	31.41	37.57
22	9.542	12.338	14.041	17.240	21.337	26.04	30.81	33.92	40.29
24	10.856	13.848	15.659	19.037	23.337	28.24	33.20	36.42	42.98
26	12.198	15.379	17.292	20.843	25.336	30.43	35.56	38.89	45.64
28	13.565	16.928	18.939	22.657	27.336	32.62	37.92	41.34	48.28
30	14.953	18.493	20.599	24.478	29.336	34.80	40.26	43.77	50.89
40	22.164	26.509	29.051	33.660	39.335	45.62	51.80	55.76	63.69
50	27.707	34.764	37.689	42.942	49.335	56.33	63.17	67.50	76.15
60	37.485	43.188	46.459	52.294	59.335	66.98	74.40	79.08	88.38

α

t_j

Continuing with Illustration B

- Assuming α =0.01, number of measurements are 4 and number of state variables are 2, then degree of freedom k=(4-2)=2
- From chi-square PDF we get χ_k^2=9.21
- Now evaluating the weighted sum of squares $\hat{f}$ we get

$$\hat{f} = \sum_{j=1}^{4} \hat{e}_i^2 / \sigma_i^2 = 100(0.00877)^2 + 100(0.00456)^2 + 50(0.02596)^2 + 50(0.00070)^2$$

$$= 0.043507$$

- Which is less than 9.21 Therefore we can conclude with 99% confidence that there is no bad data

- Now suppose the raw data measurement set as

$$[z_1\ z_2\ z_3\ z_4]^T = [9.01\text{A}\ 3.02\text{A}\ 6.98\text{V}\ 4.40\text{V}]^T$$

- Now calculating the estimated errors similar to above using the new measurement set we get

$$[\hat{e}_1\ \hat{e}_2\ \hat{e}_3\ \hat{e}_4]^T = [0.06228\ 0.15439\ 0.05965\ 0.49298]^T$$

- Now evaluating the weighted sum of squares f we get

$$\hat{f} = \sum_{j=1}^{4} \hat{e}_i^2 / \sigma_i^2 = 100(0.06228)^2 + 100(0.15439)^2 + 50(0.05965)^2 + 50(0.49298)^2$$

$$= 15.1009$$

- This value of f exceeds 9.21 and so it can be conclude that there is at-least one bad measurement.

Bad measurements can be identified by computing normalized residual errors and removing the largest ones > 3, one at a time.

Covariance matrix: $\mathbf{R' = W^{-1} - HG^{-1}H^T}$

- The normalized errors estimated values are calculated as

$$\frac{|e_1|}{\sqrt{R'_{11}}} = \frac{0.06228}{\sqrt{(1-0.807)\times 0.01}} = 1.4178$$

$$\frac{|e_2|}{\sqrt{R'_{22}}} = \frac{0.15439}{\sqrt{(1-0.807)\times 0.01}} = 3.5144$$

$$\frac{|e_3|}{\sqrt{R'_{33}}} = \frac{0.05965}{\sqrt{(1-0.193)\times 0.02}} = 0.4695$$

$$\frac{|e_4|}{\sqrt{R'_{44}}} = \frac{-0.49298}{\sqrt{(1-0.193)\times 0.02}} = -3.8804$$

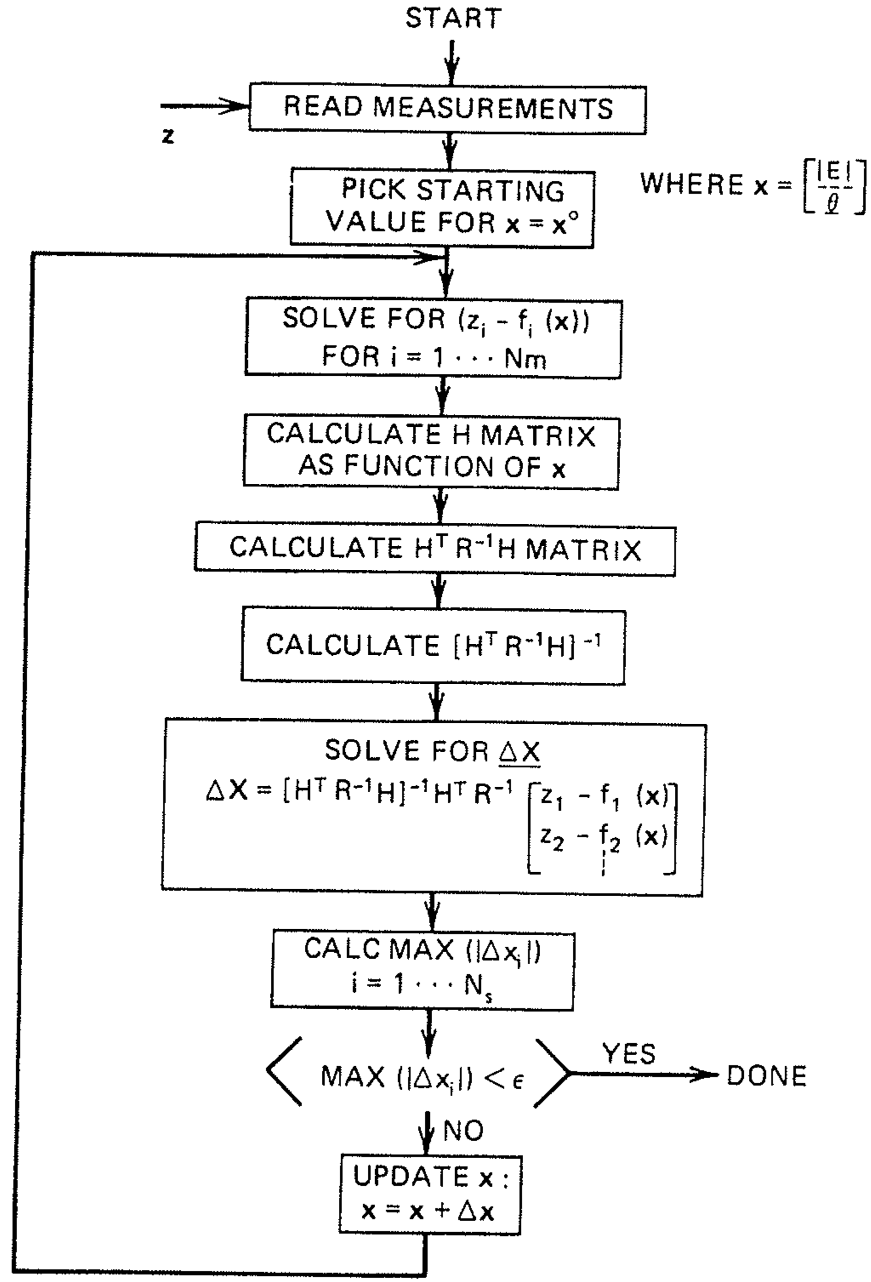
- It can be concluded from above that measurement z_4 as bad measurement.
- Then the measurement is removed from measurement set

With 3 measurements, $\hat{f}$ = .0435, and Chi-square value = 6.64.

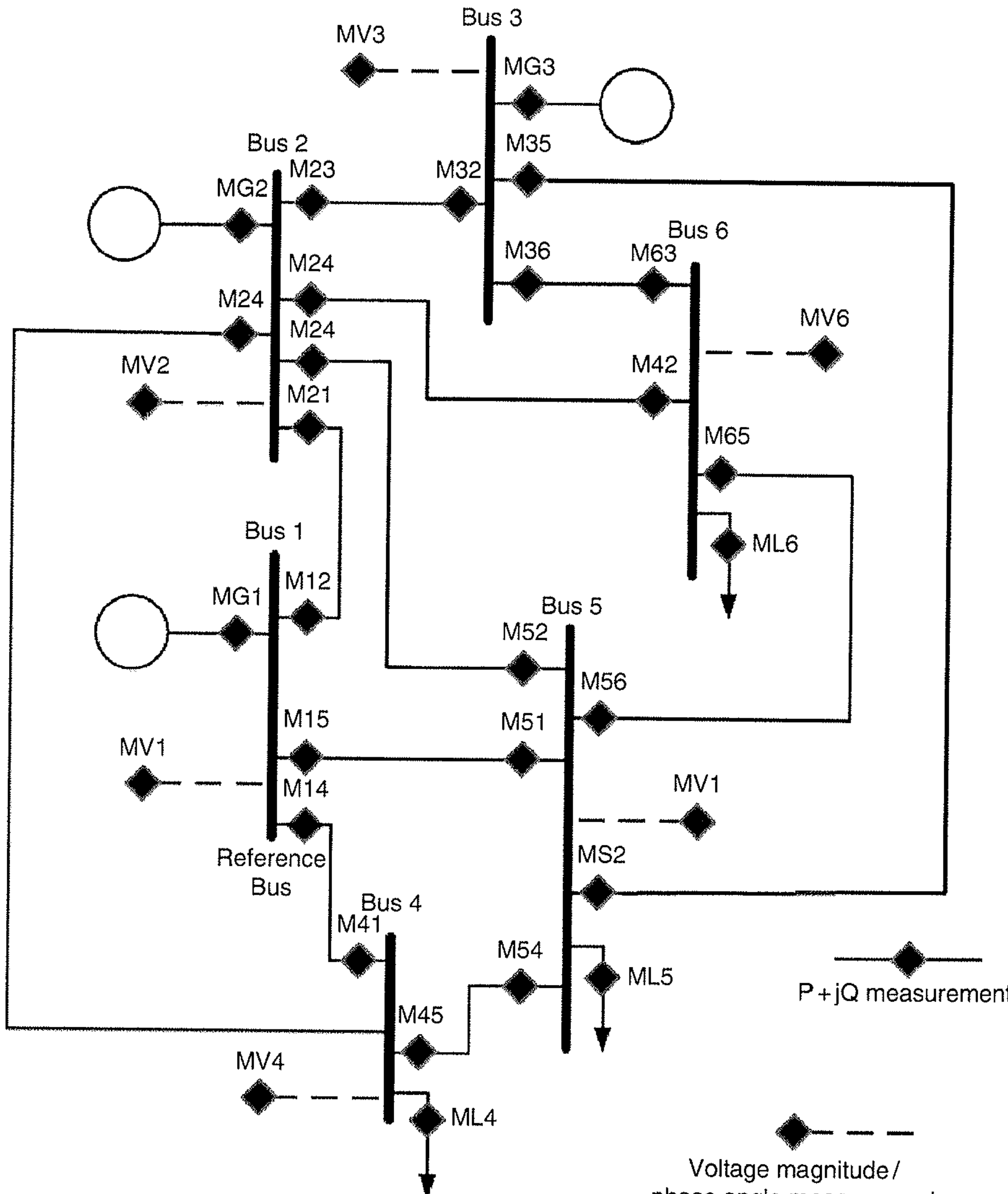
Power System State Estimation

- **State variables**: voltage magnitudes and their phase angles.
- **Two kinds of inputs:** data (e.g., P&Q measurements), and status information (e.g. on/off status of switching devices).
- Number of actual measurements is far greater than required.
- Unlike the earlier DC examples, the measurement equations h(**x**) are nonlinear.
- Common technique: calculate the gradient of J(x) and force it to zero using Newton's method.
- See algorithm in next slide

State Estimation Solution Algorithm



Example 6-Bus Power System



Assumption:
Base case is assumed true, but
Impossible to know in practice

PDF with zero mean, and the
Following standard deviations:
P&Q meters: σ = 3 MW/MVAR
V meters: σ = 3.83 kV

Random number generator was
to produces random errors which
are added to the base values.

TABLE 9.2 Base-Case Conditions

Measurement		Base Case Value			Measured Value		
Name	Status	kV	MW	MVAR	kV	MW	MVAR
		Bus 1					
MV1	1	246.1			246.1		
MA1	1	0.0			0.0		
M12	1		123.6	-35.6		123.2	-36.0
M14	1		179.9	23.9		180.4	23.8
M15	1		105.0	3.4		105.4	3.8
		Bus 2					
MV2	1	241.5			241.5		
MA2	0	0.0			0.0		
MG2	1		50.0	75.7		51.0	75.5
M21	1		-109.3	59.7		-110.6	60.5
M23	1		11.4	-5.4		11.7	-5.9
M24	1		93.1	17.2		94.1	16.4
M25	1		15.6	5.3		15.3	2.1
M26	1		39.2	-1.1		38.2	-1.3
		Bus 3					
MV3	1	241.5			241.5		
MA3	0	0.0			0.0		
MG3	1		50.0	24.2		49.8	24.9
M32	1		-11.3	-0.9		-12.2	-2.1
M35	1		8.9	7.5		8.4	7.3
M36	1		52.4	17.6		51.0	17.6
		Bus 4					
MV4	1	228.0			228.0		
MA4	0	0.0			0.0		
ML4	1		-100.0	-15.0		-99.4	-16.1
M41	1		-165.5	29.6		-164.5	28.7
M42	1		-89.0	-11.1		-89.2	-12.3
M45	1		-11.0	-3.9		-11.7	-5.5
		Bus 5					
MV5	1	233.3			233.3		
MA5	0	0.0			0.0		
ML5	1		-100.0	-15.0		-101.5	-16.1
M51	1		-97.3	19.1		-96.9	18.3
M52	1		-15.3	-8.7		-16.4	-10.2
M53	1		-8.7	-12.4		-10.3	-12.9
M54	1		11.2	-3.7		12.7	-1.6
M56	1		10.1	-9.2		10.2	-10.2
		Bus 6					
MV6	1	235.4			235.4		
MA6	0	0.0			0.0		
ML6	1		-100.0	-15.0		-101.4	-14.9
M62	1		-38.2	-1.5		-38.6	0.4
M63	1		-51.8	-16.9		-51.0	-16.5
M65	1		-9.9	3.4		-8.7	2.8

State Estimation algorithm results shown in right column.

Number of variables 11:

No. of degrees of freedom: 51

After 4 iterations, the residual converged to 56.3

Residual threshold with 99% Confidence: 63.4

→ No bad data detected

TABLE 9.4 State Estimation Solution

Measurement Name	Status	Base Case Value kV	MW	MVAR	Measured Value kV	MW	MVAR	Estimated Value kV	MW	MVAR
		Bus 1								
MV1	1	246.1			245.7			247.0		
MA1	1	0.0			0.0			0.0		
MG1	1		228.6	-32.2		225.4	-33.0		226.8	-31.7
M12	1		123.6	-35.6		126.7	-28.3		122.2	-35.2
M14	1		179.9	23.9		181.2	20.8		178.6	22.0
M15	1		105.0	3.4		107.4	0.8		104.6	3.5
		Bus 2								
MV2	1	241.5			246.6			242.3		
MA2	0	-14.5			0.0			-10.5		
MG2	1		50.0	75.7		49.7	71.3		49.7	72.3
M21	1		-109.3	59.7		-106.4	58.8		-108.3	58.5
M23	1		11.4	-5.4		10.4	-7.1		11.1	-5.1
M24	1		93.1	17.2		92.5	12.1		91.8	14.3
M25	1		15.6	5.3		17.7	6.1		16.1	5.2
M26	1		39.2	-1.1		36.2	-2.4		39.1	-0.6
		Bus 3								
MV3	1	241.5			238.5			242.1		
MA3	0	-16.0			0.0			-12.0		
MG3	1		50.0	24.2		50.6	21.7		51.2	23.1
M32	1		-11.3	-0.9		-14.4	-3.6		-11.0	-1.3
M35	1		8.9	7.5		8.1	11.3		9.6	6.9
M36	1		52.4	17.6		52.7	15.6		52.6	17.5
		Bus 4								
MV4	1	228.0			230.7			229.6		
MA4	0	-19.1			0.0			-15.1		
ML4	1		-100.0	-15.0		-100.3	-14.0		-98.2	-12.0
M41	1		-165.5	29.6		-159.9	32.4		-164.5	30.0
M42	1		-89.0	-11.1		-87.2	-11.5		-87.9	-8.6
M45	1		-11.0	-3.9		-8.5	-4.8		-10.4	-3.4
		Bus 5								
MV5	1	233.3			234.4			234.1		
MA5	0	-16.6			0.0			-12.7		
ML5	1		-100.0	-15.0		-102.7	-15.9		-102.1	-15.2
M51	1		-97.3	19.1		-96.3	17.4		-96.9	18.5
M52	1		-15.3	-8.7		-13.8	-13.2		-15.8	-8.6
M53	1		-8.7	-12.4		-7.3	-8.9		-9.4	-11.9
M54	1		11.2	-3.7		9.6	-4.6		10.6	-4.3
M56	1		10.1	-9.2		6.8	-10.7		9.5	-8.9
		Bus 6								
MV6	1	235.4			234.6			236.0		
MA6	0	-18.6			0.0			-14.6		
ML6	1		-100.0	-15.0		-98.9	-20.5		-99.5	-15.9
M62	1		-38.2	-1.5		-37.9	1.9		-38.1	-2.0
M63	1		-51.8	-16.9		-56.3	-16.4		-52.1	-16.9
M65	1		-9.9	3.4		-10.5	3.6		-9.4	3.0

Simulation of bad data:

Reverse the reading of M12

After 5 iterations, the residual
Converged to 6,455.

Recall threshold value: 63

→ Presence of bad data.

Largest normalized residual
Occurred at meter M12 = 76.9

TABLE 9.6 State Estimation Solution with Measurement M12 Reversed

Measurement		Base Case Value			Measured Value			Estimated Value		
Name	Status	kV	MW	MVAR	kV	MW	MVAR	kV	MW	MVAR
		Bus 1								
MV1	1	246.1			245.9			247.6		
MA1	1	0.0			0.0			0.0		
MG1	1		228.6	-32.2		226.4	-30.6		179.9	-28.4
M12	1		123.6	-35.6		-125.2	38.7		92.4	-30.1
M14	1		179.9	23.9		184.5	23.8		148.5	20.0
M15	1		105.0	3.4		106.8	3.2		87.5	1.7
		Bus 2								
MV2	1	241.5			243.6			244.0		
MA2	0	-14.5			0.0			-8.5		
MG2	1		50.0	75.7		49.2	77.5		77.3	61.3
M21	1		-109.3	59.7		-108.1	57.5		-84.4	41.6
M23	1		11.4	-5.4		13.2	-5.6		9.4	-3.0
M24	1		93.1	17.2		93.8	14.2		95.1	17.4
M25	1		15.6	5.3		21.0	2.1		19.9	4.1
M26	1		39.2	-1.1		37.1	-2.9		37.3	1.1
		Bus 3								
MV3	1	241.5			241.9			242.9		
MA3	0	-16.0			0.0			-9.7		
MG3	1		50.0	24.2		51.8	17.6		57.3	15.2
M32	1		-11.3	-0.9		-14.6	-2.8		-9.3	-3.5
M35	1		8.9	7.5		9.8	6.4		14.4	3.1
M36	1		52.4	17.6		52.7	19.3		52.2	15.6
		Bus 4								
MV4	1	228.0			234.3			230.4		
MA4	0	-19.1			0.0			-13.1		
ML4	1		-100.0	-15.0		-104.0	-19.3		-99.8	-16.6
M41	1		-165.5	29.6		-160.6	28.3		-138.8	14.5
M42	1		-89.0	-11.1		-86.1	-13.0		-91.0	-11.2
M45	1		-11.0	-3.9		-8.7	-5.9		-8.9	-5.4
		Bus 5								
MV5	1	233.3			234.4			235.9		
MA5	0	-16.6			0.0			-11.3		
ML5	1		-100.0	-15.0		-98.8	-10.6		-102.1	-12.9
M51	1		-97.3	19.1		-103.3	16.1		-82.2	11.5
M52	1		-15.3	-8.7		-14.7	-13.3		-19.5	-7.3
M53	1		-8.7	-12.4		-6.3	-10.0		-14.2	-7.9
M54	1		11.2	-3.7		9.4	-3.1		9.0	-2.5
M56	1		10.1	-9.2		9.2	-9.6		4.7	-6.6
		Bus 6								
MV6	1	235.4			241.6			237.2		
MA6	0	-18.6			0.0			-12.2		
ML6	1		-100.0	-15.0		-101.0	-12.6		-92.7	-18.8
M62	1		-38.2	-1.5		-37.0	1.3		-36.4	-4.1
M63	1		-51.8	-16.9		-50.6	-19.9		-51.7	-15.1
M65	1		-9.9	3.4		-8.2	6.6		-4.7	0.4

State Estimation after removal of bad data:

No. degrees of freedom: k = 49

After 3 iterations, the residual Converged to 37.5

Bad data Threshold: 61

→ Bad data no longer present

TABLE 9.7 State Estimation Solution After Removal of Bad Data

Measurement		Base Case Value			Measured Value			Estimated Value		
Name	Status	kV	MW	MVAR	kV	MW	MVAR	kV	MW	MVAR
		Bus 1								
MV1	1	246.1			245.9			248.9		
MA1	1	0.0			0.0			0.0		
MG1	1		228.6	-32.2		226.4	-30.6		228.7	-32.4
M12	0		123.6	-35.6		-125.2	38.7		123.3	-35.3
M14	1		179.9	23.9		184.5	23.8		179.6	24.5
M15	1		105.0	3.4		106.8	3.2		105.4	3.0
		Bus 2								
MV2	1	241.5			243.6			244.1		
MA2	0	-14.5			0.0			-11.9		
MG2	1		50.0	75.7		49.2	77.5		50.4	75.7
M21	1		-109.3	59.7		-108.1	57.5		-109.4	58.6
M23	1		11.4	-5.4		13.2	-5.6		11.4	-4.8
M24	1		93.1	17.2		93.8	14.2		93.2	18.4
M25	1		15.6	5.3		21.0	2.1		15.9	4.7
M26	1		39.2	-1.1		37.1	-2.9		39.4	-1.2
		Bus 3								
MV3	1	241.5			241.9			243.7		
MA3	0	-16.0			0.0			-13.4		
MG3	1		50.0	24.2		51.8	17.6		50.1	20.2
M32	1		-11.3	-0.9		-14.6	-2.8		-11.3	-1.7
M35	1		8.9	7.5		9.8	6.4		9.0	6.2
M36	1		52.4	17.6		52.7	19.3		52.5	15.7
		Bus 4								
MV4	1	228.0			234.3			230.5		
MA4	0	-19.1			0.0			-16.4		
ML4	1		-100.0	-15.0		-104.0	-19.3		-100.1	-17.1
M41	1		-165.5	29.6		-160.6	28.3		-165.5	27.5
M42	1		-89.0	-11.1		-86.1	-13.0		-89.2	-12.4
M45	1		-11.0	-3.9		-8.7	-5.9		-10.9	-4.7
		Bus 5								
MV5	1	233.3			234.4			236.3		
MA5	0	-16.6			0.0			-14.0		
ML5	1		-100.0	-15.0		-98.8	-10.6		-101.1	-12.5
M51	1		-97.3	19.1		-103.3	16.1		-97.7	18.9
M52	1		-15.3	-8.7		-14.7	-13.3		-15.6	-8.2
M53	1		-8.7	-12.4		-6.3	-10.0		-8.8	-11.2
M54	1		11.2	-3.7		9.4	-3.1		11.2	-3.1
M56	1		10.1	-9.2		9.2	-9.6		9.9	-8.8
		Bus 6								
MV6	1	235.4			241.6			238.0		
MA6	0	-18.6			0.0			-15.9		
ML6	1		-100.0	-15.0		-101.0	-12.6		-100.2	-14.0
M62	1		-38.2	-1.5		-37.0	1.3		-38.4	-1.6
M63	1		-51.8	-16.9		-50.6	-19.9		-51.9	-15.2
M65	1		-9.9	3.4		-8.2	6.6		-9.8	2.8

Phasor Measurement Units (PMU)

- ❑Traditionally, input measurements have been provided by the SCADA system (Supervisory Control and Data Acquisition)

- ❑Synchronicity of the electrical measurements cannot be guaranteed when using the SCADA system. This means that during a dynamic event, the measurements provided to the state estimator by the SCADA system will not allow an accurate estimation of state variables. In actual operation, the snapshot is collected over a few seconds.

- ❑With the advent of real-time Phasor Measurement Units (PMU's), synchronised phasor measurements are possible which allows monitoring of dynamic phenomena. Also, the possibility of using PMUs for state estimation and the effect of using PMU measurements

➡ PMUs improve the accuracy of state estimation since they eliminate time differences and provide additional measurements of voltage magnitudes and their phases

Summary

- Real time monitoring and control of power systems is extremely important for an efficient and reliable operation of a power system.
- Sate estimation forms the backbone for the real time monitoring and control functions.
- In this environment, a real-time model is extracted at intervals from snapshots of real-time measurements.
- Estimate the nodal voltage magnitudes and phase angles together with the parameters of the lines.
- State estimation results can be improved by using accurate measurements like phasor measurement units.
- Traditional state estimation and bad data processing is reviewed.

References

1. Yih-Fang Huang, Stefan Werner, Jing Huang, Neelabh Kashyap, and Vijay Gupta, “State Estimation in Electric Power Grids”, *IEEE Signal Processing Magazine*, Sept. 2012.
2. G. Ortiz, D.G. Colome and J.J.Q. Puma, “State estimation of power system based on SCADA and PMU measurements”, *IEEE ANDESCON*, 2016

Assignment

- Solve Problem 9.4 of Chapter 9 (pp. 465-466)