Exercises

3.1 Verify that Re{$X\angle\theta$} in (3.1) is equal to $X\cos(\theta)$ and Im{$X\angle\theta$} in (3.2) is equal to $X\sin(\theta)$. Note that X is the phasor magnitude in RMS value.

3.2 Use (3.1) and (3.2) to obtain voltage phasor $V\angle\theta$ corresponding to the voltage wave in file `E3-2.csv`. Use a sampling rate of $N = 512$ samples per cycle; and a reporting rate of 60 fps, i.e., one phasor reading per cycle.

3.3 Repeat Exercise 3.2 for the voltage measurements in file `E3-3.csv`. Explain how the results here are different from the results in Exercise 3.2.

3.4 Repeat Exercise 3.2 for the voltage measurements in file `E3-4.csv`. Explain how the results here are different from the results in Exercise 3.2.

3.5 Consider the phase angle measurements in file `E3-5.csv`, which are given in the -180° to 180° range. The time stamps are in milliseconds in UTC.
(a) Present the measurements in the 0° to 360° range.
(b) Present the time stamps in year/month/day hour:minute:second.

3.6 Consider the measurements in Table 3.5 that are recorded by a PMU.
(a) What is the reporting rate of this PMU?
(b) Use (3.6) to estimate the frequency at each measurement.

Table 3.5 Voltage synchrophasor measurements in Exercise 3.6

UTC Time (millisecond)	Magnitude (V)	Phase Angle (°)
1286210900930	39830.183	359.7297
1286210900980	39831.177	359.8871
1286210901030	39832.088	0.0464
1286210901080	39833.174	0.1979

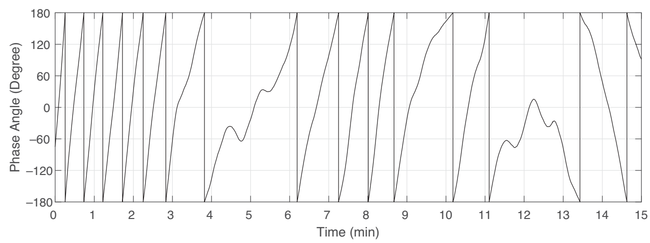

Figure 3.37 Voltage phase angle measurements in Exercise 3.7.

3.7 Consider the voltage phase angle measurements in Figure 3.37.
(a) How many times does frequency cross 60 Hz, the nominal frequency?
(b) Is the frequency mostly above 60 Hz, or below 60 Hz?

3.8 Consider the voltage phase angle measurements in file `E3-8.csv`.
(a) Estimate frequency using the linear model in (3.6).
(b) Apply the noise reduction command `smoothdata` in MATLAB [198] to the estimated frequency signal that is obtained in Part (a). Use the smoothing method `movmedian` and set the length of the `window` to be five.
(c) Plot the second-by-second average of the estimated frequency; before noise reduction, as in Part (a); and also after noise reduction, as in Part (b).

3.9 Again, consider the voltage phase angle measurements in Exercise 3.8. Estimate the frequency by applying the quadratic model in (3.11) to measurement windows of length one second, i.e., parameter $N = 20$.

3.10 Consider the phase angle measurements from two PMUs in file `E3-10.csv`.
(a) Plot the RPAD between the two PMUs versus time.
(b) How many events do you identify?
(c) How large in degrees is the size of each event?

3.11 Suppose two PMUs are installed at two ends of a 69 kV transmission line. The reactance of the transmission line is 0.541Ω. The voltage synchrophasor reading of the first PMU, on Phase A, is as in the first row in Table 3.1 in Section 3.2.1. The voltage synchrophasor reading of the second PMU, on Phase A, is as in Table 3.6. Estimate the amount and the direction of real power flow on this line. Assume that the transmission line is balanced.

3.12 A D-PMU is installed at the secondary side of a 69 kV–12.47 kV transformer at a power distribution substation. The voltage magnitude and the current

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Table 3.6 Voltage synchrophasor reading at the second PMU in Exercise 3.11.

UTC Time (micro-second)	Magnitude (V)	Phase Angle (°)
1579101467916666	39821.487	183.318749

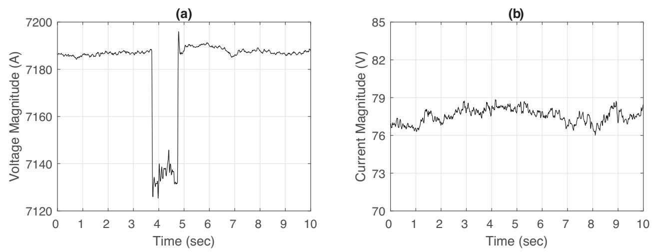

Figure 3.38 Measurements in Exercise 3.12: (a) voltage magnitude; (b) current magnitude.

magnitude that this D-PMU measures during a voltage event are shown in Figure 3.38. Explain the likely cause of the voltage event.

3.13 Obtain the frequency of *oscillations* in the RPAD measurements in file `E3-13.csv` using Fourier analysis. Indicate the likely cause of oscillations.

3.14 File `E3-14.csv` contains the current phasor measurements during an event. Obtain I^{before}, I^{after}, and ΔI; both *without* and *with* taking into account the impact of an off-nominal frequency that we discussed in Section 3.5.2.

3.15 File `E3-15.csv` contains the synchronized voltage phasor measurements that are obtained by two different PMUs during the same event.

(a) Obtain the differential synchrophasors corresponding to this event.

(b) Obtain the RPAD during this event.

(c) Compare your observations in Parts (a) and (b).

3.16 Consider the event location identification problem in Example 3.11. Suppose a different event occurs on the same power distribution feeder; and the synchrophasor measurements are obtained as in Table 3.7.

(a) Obtain $\Phi_1, \Phi_2, \ldots, \Phi_5$ as defined in (3.34).

(b) What bus is the location of this switching event?

3.17 Use (1.32) and (1.33) in Chapter 1 and also the definition of symmetrical components in (3.40) to show that the zero sequence and the negative sequence are both zero for balanced three-phase phasor measurements.

3.18 Consider the three-phase voltage synchrophasor measurements in `E3-18.csv`.

(a) Plot V^+, V^-, and V^0.

(b) Plot UF and obtain the maximum UF.

(c) Plot PU and obtain the maximum PU.

3.19 File `E3-19.csv` contains the current phasor measurements during a three-phase event. Is the event in these measurements a balanced or unbalanced event?

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Table 3.7 Synchrophasor measurements in per unit in Example 3.16.

Phasor	Before	After
$V_1\angle\theta_1$	$0.9889\angle 28.796^\circ$	$0.9958\angle 28.763^\circ$
$I_{12}\angle\phi_{12}$	$3.1619\angle 1.354^\circ$	$2.9292\angle 18.458^\circ$
$V_5\angle\theta_5$	$0.9534\angle 27.138^\circ$	$0.9741\angle 26.663^\circ$
$I_{45}\angle\phi_{45}$	$0.7537\angle 8.703^\circ$	$0.7701\angle 8.228^\circ$

Elaborate your answer based on examining the magnitudes of the symmetrical components and also by examining the UF plot.

3.20 File `E3-20.csv` contains 10 minutes of synchrophasor voltage measurements at a three-phase reference location at a power distribution substation and also at a single-phase load location. All measurements are in per unit. The phase connection of the single-phase load is unknown. Identify the phase connection for the load by doing the following:

(a) Calculate the correlation coefficient between the voltage magnitudes, similar to the analysis in Section 2.8.3 in Chapter 2.

(b) Compare the voltage phase angles, as in Section 3.6.4.

3.21 File `E3-21.csv` contains phase angle measurements during an event.

(a) Plot the original phase angle measurements.

(b) Plot the unwrapped phase angle measurements.

(c) Plot the phase angle measurements after removing the impact of off-nominal frequency. Identify the reference line in your calculation.

3.22 File `E3-22.csv` contains the vector of quantitative features for a total of 50 events to train an SVM classifier. The events are already labeled to belong to Class I, Class II, or Class III. The number of features is two.

(a) Obtain three separating hyperplanes for this classification, where each separating hyperplane can separate one class from the rest of the classes.

(b) Suppose the two features are the magnitude of the voltage phasor differential ΔV and the magnitude of the current phasor differential ΔI corresponding to the event, respectively. Both features are presented in per unit. Use the separating hyperplanes in Part (a) to identify the class of an event that is characterized by the following PD measurements:

$$\begin{aligned} \Delta V &= 0.054 + j0.081 \\ \Delta I &= 0.52 + j0.65. \end{aligned} \tag{3.111}$$

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3.23 Consider the vector of features for the same 50 events in Exercise 3.22. Suppose we add the following five additional events to the training set:

$$\mathbf{x}_{51} = \begin{bmatrix} 0.0254 \\ 0.1009 \end{bmatrix}, \quad \mathbf{x}_{52} = \begin{bmatrix} 0.0288 \\ 0.0797 \end{bmatrix}, \quad \mathbf{x}_{53} = \begin{bmatrix} 0.0386 \\ 0.0843 \end{bmatrix},$$
$$\mathbf{x}_{54} = \begin{bmatrix} 0.0353 \\ 0.1101 \end{bmatrix}, \quad \mathbf{x}_{55} = \begin{bmatrix} 0.0319 \\ 0.0919 \end{bmatrix}. \tag{3.112}$$

Events 51 and 55 belong to Class I. Event 52 belongs to Class II. Events 53 and 54 belong to Class III. Obtain the three separating hyperplanes for this classification by taking into account all 55 sample events. Are the resulting separating hyperplanes different from those in Exercise 3.22?

3.24 Obtain matrix **A** for the state estimation problem in Example 3.20. What is the rank of matrix **A**? Is it full column ranked?

3.25 Consider the 5-bus power transmission network in Figure 3.39. Suppose we measure voltage synchrophasors at buses 1, 2, 3, and 5, as well as current synchrophasors at lines (2,3), (2,4), (4,1), and (4,5). The measurements are given in Table 3.8. Estimate all states of the system.

3.26 Repeat Exercise 3.25 but this time assume that the voltage measurement at bus 3 and the current measurement on transmission line (2,3) are not available. Explain the results based on the rank of matrix **A**, as defined in (3.76).

Table 3.8 Synchrophasor measurements in Exercise 3.25.

Bus #	Measured Voltage (p.u.)	Line #	Measured Current (p.u.)
1	$1.1008\angle 20.6212°$	2,3	$0.5846\angle 14.6320°$
2	$1.0734\angle 16.8138°$	2,4	$0.6162\angle -16.9375°$
3	$1.0640\angle 14.1337°$	4,1	$1.3218\angle 171.1914°$
5	$1.0806\angle 19.2546°$	4,5	$1.0475\angle 170.0581°$

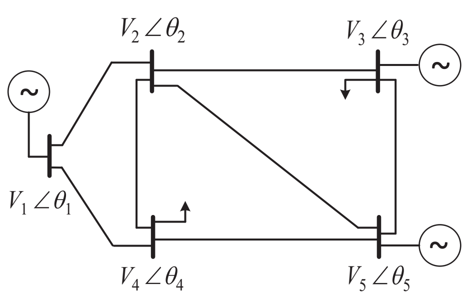

Figure 3.39 The 5-bus network in Exercise 3.25.

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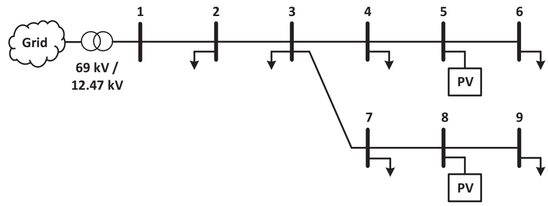

Figure 3.40 The balanced three-phase active distribution feeder in Exercise 3.27.

3.27 Consider a balanced three-phase power distribution system as shown in Figure 3.40. The per-phase impedance of each distribution line is $0.0412 + j0.0625\Omega$. Voltage phasors are measured (in volts) at selected buses:

$$\begin{aligned} V_1 &= 7200.0\angle 0^\circ, & V_2 &= 7173.4\angle -0.0736^\circ \\ V_4 &= 7141.7\angle -0.1357^\circ, & V_5 &= 7124.0\angle -0.1263^\circ \\ V_6 &= 7112.8\angle -0.1541^\circ, & V_7 &= 7133.9\angle -0.1327^\circ \\ V_9 &= 7121.6\angle -0.1269^\circ \end{aligned} \tag{3.113}$$

Current phasors are also measured (in amperes) at selected lines:

$$\begin{aligned} I_{21} &= 432.96\angle 139.9375^\circ, & I_{23} &= 346.30\angle -43.4090^\circ \\ I_{43} &= 160.31\angle 131.8792^\circ, & I_{45} &= 75.19\angle -68.8901^\circ \\ I_{65} &= 99.30\angle 150.5876^\circ, & I_{73} &= 137.31\angle 131.2470^\circ \\ I_{78} &= 55.64\angle -100.9283^\circ, & I_{98} &= 67.28\angle 148.7664^\circ. \end{aligned} \tag{3.114}$$

Estimate all the states of the system. Take bus 1 as the reference bus.

3.28 Verify the special case results for TVE in (3.100) and (3.101).

3.29 Two PMUs are installed at two ends of a transmission line. For both PMUs, TVE is limited to 1%, and it is solely due to potential error in measuring the phase angle. What is the maximum possible error, in degrees, in measuring RPAD between the voltage synchrophasors recorded by the two PMUs?

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