Exercises

4.1 Consider the following current wave at a nonlinear load:

$$i(t) = 5\cos(\omega t) + 2.8\cos(3\omega t) + 0.5\cos(5\omega t) + 0.7\cos(7\omega t). \quad (4.39)$$

Obtain the RMS value, THD, CF, and PHI for this current wave.

4.2 Obtain and plot the harmonic spectrum, up to the 25th harmonic, for both voltage and current waveform measurements in file `E4-2.csv`.

4.3 A periodic signal with period $T = 2\pi/\omega$ is *half-wave symmetric* if the second half of its waveform at each period is exactly the opposite of the first half, i.e., $x(t + T/2) = -x(t)$ at any time t. Show that a half-waved symmetric signal comprises only the odd-numbered harmonics.

4.4 The voltage and current measurements at a power electronics load are as in Figure 4.35 [265]. The RMS value of the current wave is 9.062 A, 9.350 A, and 10.283 A on Phases A, B, and C, respectively. The fundamental component of the current wave is 5.339 A, 5.536 A, and 6.267 A on Phases A, B, and C,

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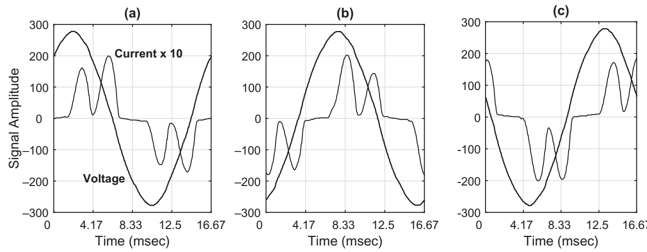

Figure 4.35 Voltage and current waveforms at a three-phase power electronics load in Exercise 4.4: (a) Phase A; (b) Phase B; (c) Phase C.

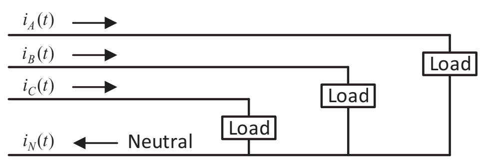

Figure 4.36 Voltage and current waveforms at a three-phase power electronics load in Exercise 4.8: (a) Phase A; (b) Phase B; (c) Phase C.

respectively. Obtain the THD and CF for each phase of the current wave. Note that you do *not* need the raw measurements to answer this question.

4.5 Calculate the *per-cycle* RMS values of the voltage signal in Example 4.3. Each cycle takes 16.667 msec, as in the fundamental component.

4.6 Consider the distorted voltage waveform in Figure 4.6(b) in Example 4.5. How many positive or negative zero-crossing points do you see in this waveform within the time period between 0.0733 seconds and 0.0767 seconds?

4.7 File `E4-7.csv` contains voltage waveform measurements for a voltage wave with notching. Obtain the notch depth, notch width, and notch area.

4.8 Consider a three-phase load, as in Figure 4.36. Suppose the load is *balanced*. That is, $i_B(t)$ is identical to $i_A(t)$, but it is 120° behind $i_A(t)$; and $i_C(t)$ is identical to $i_A(t)$, but it is 120° ahead of $i_A(t)$.

(a) Show that harmonic currents of orders which are *not* a multiple of *three* cancel each other out in the neutral current. As an example, plot the neutral current if the load current is as in Load Scenario 1 in file `E4-8.csv`.

(b) Show that harmonic currents of orders which *are* a multiple of *three* are added up arithmetically in the neutral current. As an example, plot the neutral current if the load current is as in Load Scenario 2 in file `E4-8.csv`.

4.9 Consider the voltage waveform measurements in file `E4-9.csv` [218].

(a) Obtain and plot the per-cycle RMS value profile.

(b) Obtain and plot the per-cycle THD profile.

(c) Capture and plot all waveform events when RMS value drops below 95% rated voltage or THD exceeds 5%. Let $C_{\text{before}} = 4$ and $C_{\text{after}} = 5$.

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4.10 File `E4-10.csv` contains the current waveform measurements at a single-phase load [218]. An event occurs during the period of measurements.
(a) Plot the differential waveform with a delay parameter of $N = 1$ cycle.
(b) Repeat Part (a) with $N = 2$ cycles and $N = 3$ cycles.
(c) At what cycle does the event take place?

4.11 File `E4-11.csv` contains the current waveform measurements at a three-phase load [218]. An event occurs during the period of measurements.
(a) Plot the neutral current waveform.
(b) At what cycle does the event occur?
(c) Is this a single-phase, a two-phase, or a three-phase event?

4.12 Consider the voltage waveform measurements in file `E4-12.csv` that are captured at one phase during a capacitor bank switching event [221].
(a) Does the capacitor bank switch on or switch off?
(b) Explain whether you identify any fault in this switching operation.

4.13 Obtain the angle, magnitude, and duration of the incipient fault that is captured by the current waveform measurements in file `E4-13.csv`.

4.14 File `E4-14.csv` contains the three-phase voltage and current waveform measurements during a fault [218]. The fault takes place only on one phase.
(a) Identify the faulted-phase, whether it is Phase A, Phase B, or Phase C.
(b) Obtain the fault impedance on the faulted phase at each fault cycle.

4.15 A Lissajous curve is a graph that is constructed by plotting the voltage waveform versus the current waveform; e.g., see [266, 267]. Plot the Lissajous curve for *each phase* for the three-phase voltage and current waveform measurements in Exercise 4.14. Use the Lissajous curves that you will plot to identify the faulted phase; whether it is Phase A, Phase B, or Phase C.

4.16 Revise (3.1) and (3.2) in Chapter 3 to estimate harmonic synchrophasors.

4.17 Consider the non-sinusoidal voltage wave in file `E4-17.csv`.
(a) Use the expressions in (3.1) and (3.2) to obtain the magnitude and phase angle for the phasor corresponding to the fundamental component.
(b) Use the expressions that result from Exercise 4.16 to obtain the harmonic synchrophasors for the 3rd, the 5th, and the 7th harmonics.
(c) Combine the results from Parts (a) and (b) to reconstruct the original voltage wave as a summation of its fundamental and harmonic components.

4.18 File `E4-18.csv` contains the three-phase voltage and current waveform measurements that are obtained at a three-phase load.
(a) Obtain and plot the instantaneous power at each phase.
(b) How much is the average power per cycle that is delivered to the load?

4.19 Suppose we want to remotely evaluate the tap changing operation of a transformer on a power distribution feeder to identify a potential incipient fault, similar to the type of incipient fault that we discussed in Example 4.12. Is it better to place a waveform sensor in the *upstream* of the transformer, i.e., at location 1 in Figure 4.37(a), or in the *downstream* of the transformer, i.e., at location 2 in Figure 4.37(a)? Justify your answer.

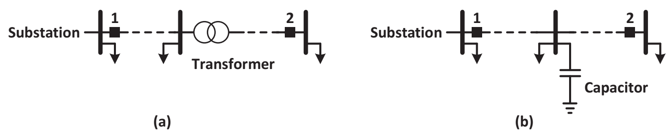

Figure 4.37 Sensor location for asset monitoring: (a) Exercise 4.19; (b) Exercise 4.20.

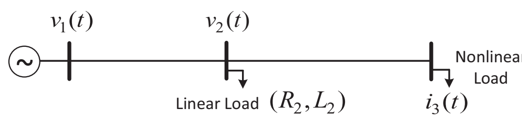

Figure 4.38 The network setup in Exercise 4.21.

4.20 Repeat Exercise 4.19 for the case of evaluating the operation of a capacitor bank, based on the two locations that are marked on Figure 4.37(b). Our goal here is to identify a potential incipient fault in the capacitor bank, similar to the type of incipient fault that we discussed in Example 4.13.

4.21 Two waveform sensors are installed at the 3-bus network in Figure 4.38 to measure voltage $v_1(t)$ and current $i_3(t)$. The measurements are given in file `E4-21.csv`. The linear load at bus 2 is a 70 Ω resistor in series with a 90 mH inductor. Each power line has 1 Ω resistance and 5 mH inductance. Estimate and plot the waveform for voltage $v_2(t)$. As a hint, you can first obtain the fundamental phasors and the dominant harmonic phasors of voltage $v_1(t)$ and current $i_3(t)$; then you can solve the circuit in frequendy domain at each frequency mode separately. After that, you can combine the results at different frequencies in order to reconstruct the voltage waveform $v_2(t)$.

4.22 Consider the power distribution network in Figure 4.39. The network includes six switches. Switches ①, ③, ④, and ⑤ are the normally closed switches. Switches ② and ⑥ are the normally open switches. There is one source of the 3rd harmonic and also one source of the 5th harmonic in this network. The locations of the harmonic sources are known. There are three H-PMUs at the beginning of each lateral, which are denoted by A, B, and C. They measure the harmonic current synchrophasors.

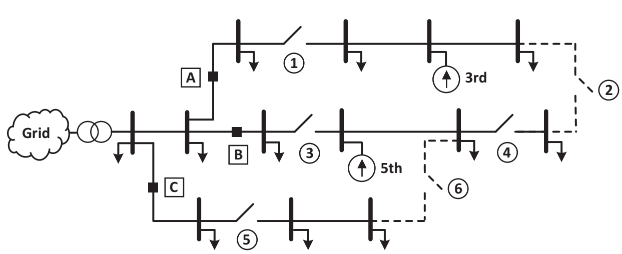

Figure 4.39 The power distribution network that is considered in Exercise 4.22.

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Table 4.4 The 5th harmonic synchrophasors in Exercise 4.23.

Bus #	Measured Voltage (p.u.)
3	$0.033122\angle 67.025117^{\circ}$
4	$0.033436\angle 66.278581^{\circ}$
Line #	**Measured Current (p.u.)**
1,2	$0.062529\angle 178.101217^{\circ}$
1,4	$0.017765\angle 31.562689^{\circ}$
2,4	$0.078087\angle 5.274117^{\circ}$
3,4	$0.009945\angle 112.685782^{\circ}$

(a) How many topology configurations are possible in this network that are *radial* and include *all* the buses in the network?

(b) Suppose H-PMU A records the presence of the 3rd harmonic, H-PMU B does not record any harmonic, and H-PMU C records the presence of the 5th harmonic. What are the possible radial topology configurations?

4.23 Consider the harmonic state estimation problem in Example 4.22. Suppose the 5th harmonic phasor measurements are as in Table 4.4. Identify the bus number for the location of the harmonic source.

4.24 File `E4-24.csv` contains the synchronized voltage waveform measurements from two WMUs. The measurements are in per unit.

(a) Obtain and plot RPAD between the two voltage waves.

(b) Obtain and plot RVWD between the two voltage waves.

(c) Obtain the RMS value of the RVWD signal. Is it equal to $\sqrt{2}$ RPAD?

4.25 Consider the current waveform in file `E4-25.csv`.

(a) Obtain the harmonic phasors up to the 30th harmonic.

(b) Use (4.1) to reconstruct the original current waveform based on the harmonic phasors that are estimated in Part (a). Try the first 10, the first 20, and all 30 estimated harmonic phasors, respectively.

(c) Use (4.38) to obtain the RMSE for each of the three current waveforms that are reconstructed in Part (b) to evaluate their reconstruction accuracy in comparison with the original current waveform in file `E4-25.csv`.