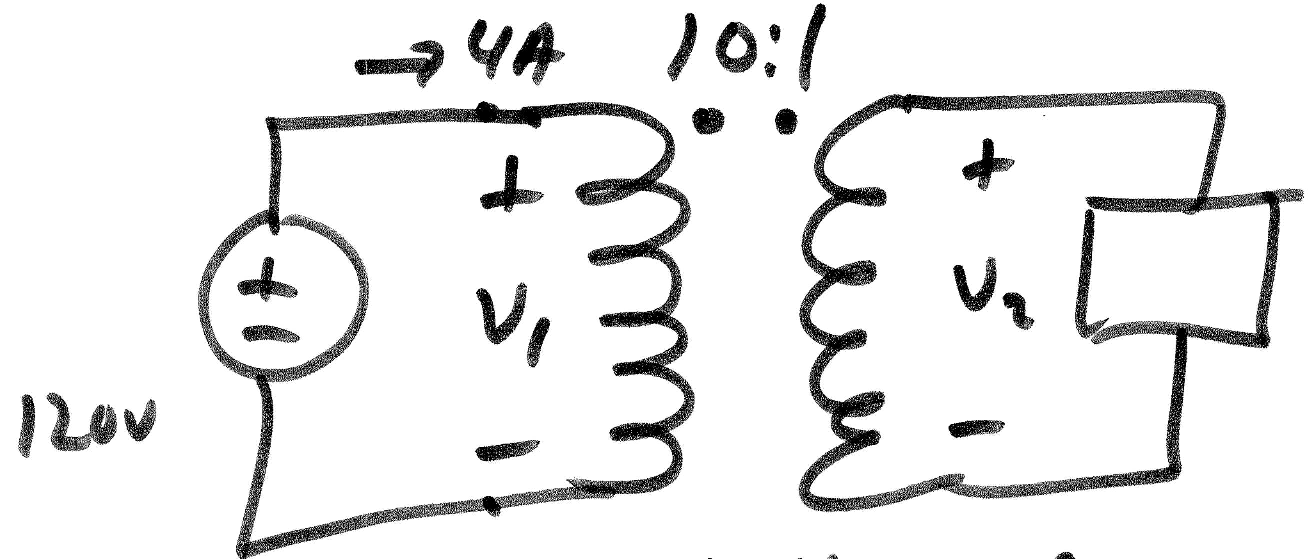
ECE 320 & ECE 329

ENERGY SYSTEMS I
BACKGROUND STUDY IN ENERGY SYSTEMS

SESSION no. 8

TRANSFORMER



FIND a) V AT PRIMARY AND SECONDARY

$V_1 = 120\angle 0^\circ$ V

$V_2 = \frac{1}{10} V_1 = 12\angle 0^\circ$ V

b) CURRENTS AT PRIMARY AND SECONDARY.

$$I_1 = 4A\angle\theta \text{ (GIVEN)}$$

$$I_2 = 10(I_1) = 10(4\angle\theta)$$

$$\underline{\underline{I_2 = 40\angle\theta \text{ A}}}$$

c) FIND POWER TO A LOAD THAT IS ALL RESISTANCE. → $\theta = 0$

$$R_L = \frac{V_2\angle 0°}{I_2\angle\theta} = \frac{120\angle 0}{40A\angle 0} = 0.30\angle 0°\,\Omega$$

$$= \underline{0.30\,\Omega}$$

$$P_L = \mathrm{Re}(V_2 I_2^*) = \mathrm{Re}[(12V\angle 0)(40A\angle 0)^*]$$

$$P_L = \underline{480\,W} \qquad Q_L = 0 \text{ VArs}$$

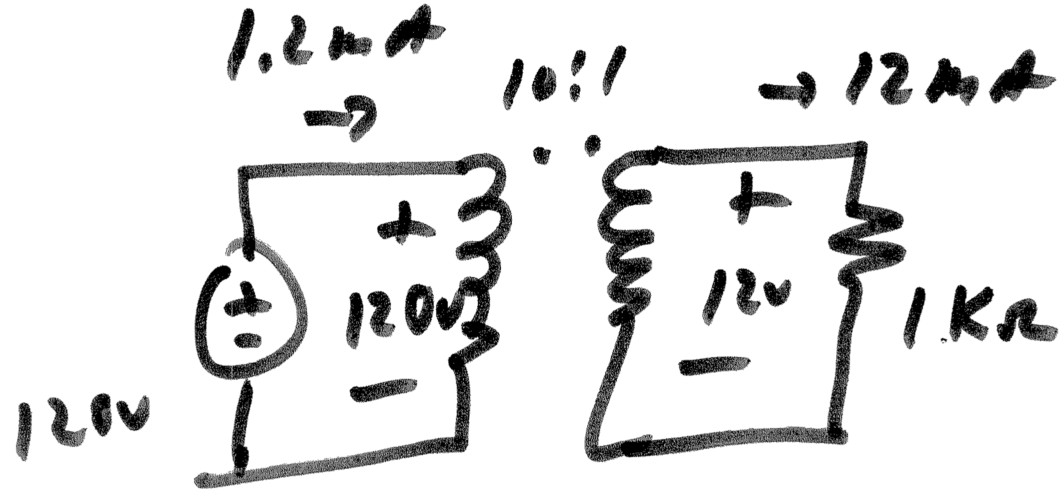
$$\frac{|V_2|^2}{R_L} = \frac{(12V)^2}{0.3\Omega} = \frac{144}{0.3} = \underline{\underline{480\,W}}$$

$$\frac{V_1}{I_1} = \left(\frac{N_1}{N_2}\right)^2 \frac{V_2}{I_2}$$

$$\frac{V_1}{I_1} = \left(\frac{10}{1}\right)^2 (0.30\Omega) = 30\Omega$$

$$I_1 = \frac{1}{10} I_2 = 4A \Rightarrow P_1 = (4A)^2 (30)\Omega$$

$$P_1 = 480\,W$$



P = 144 mW

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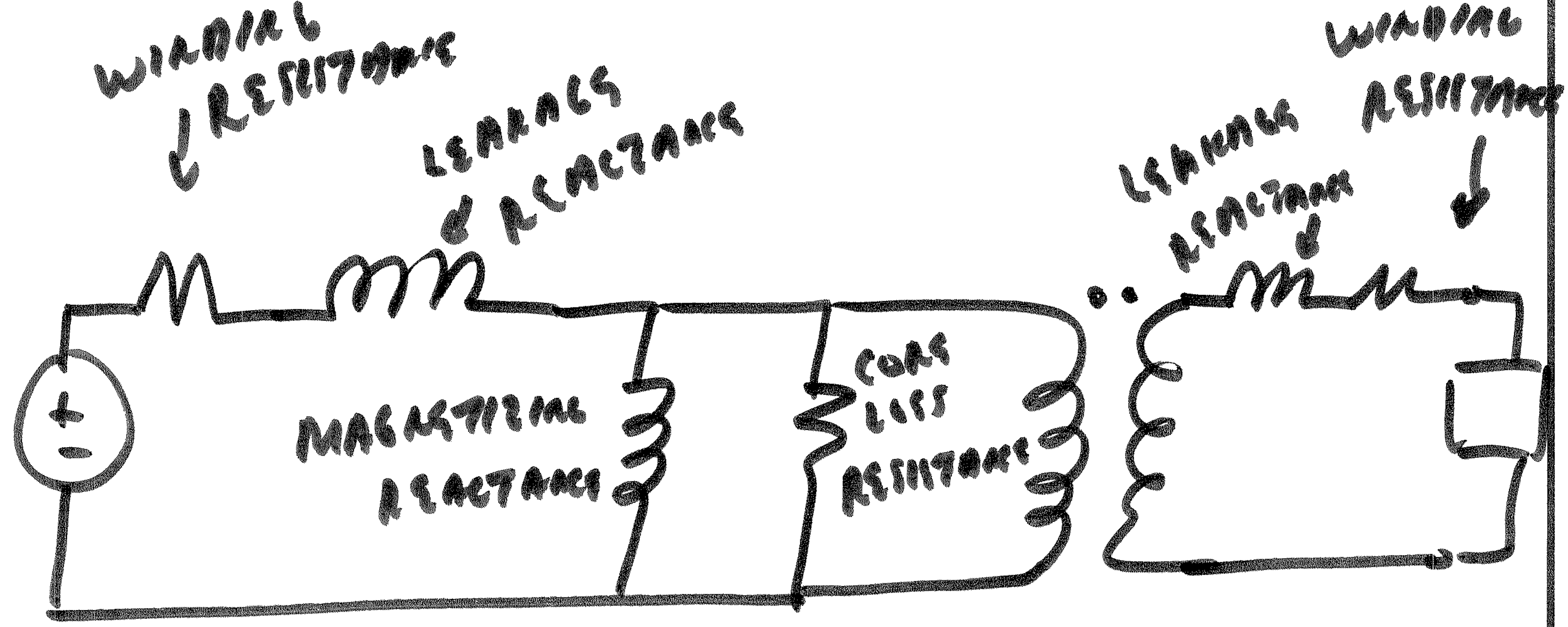

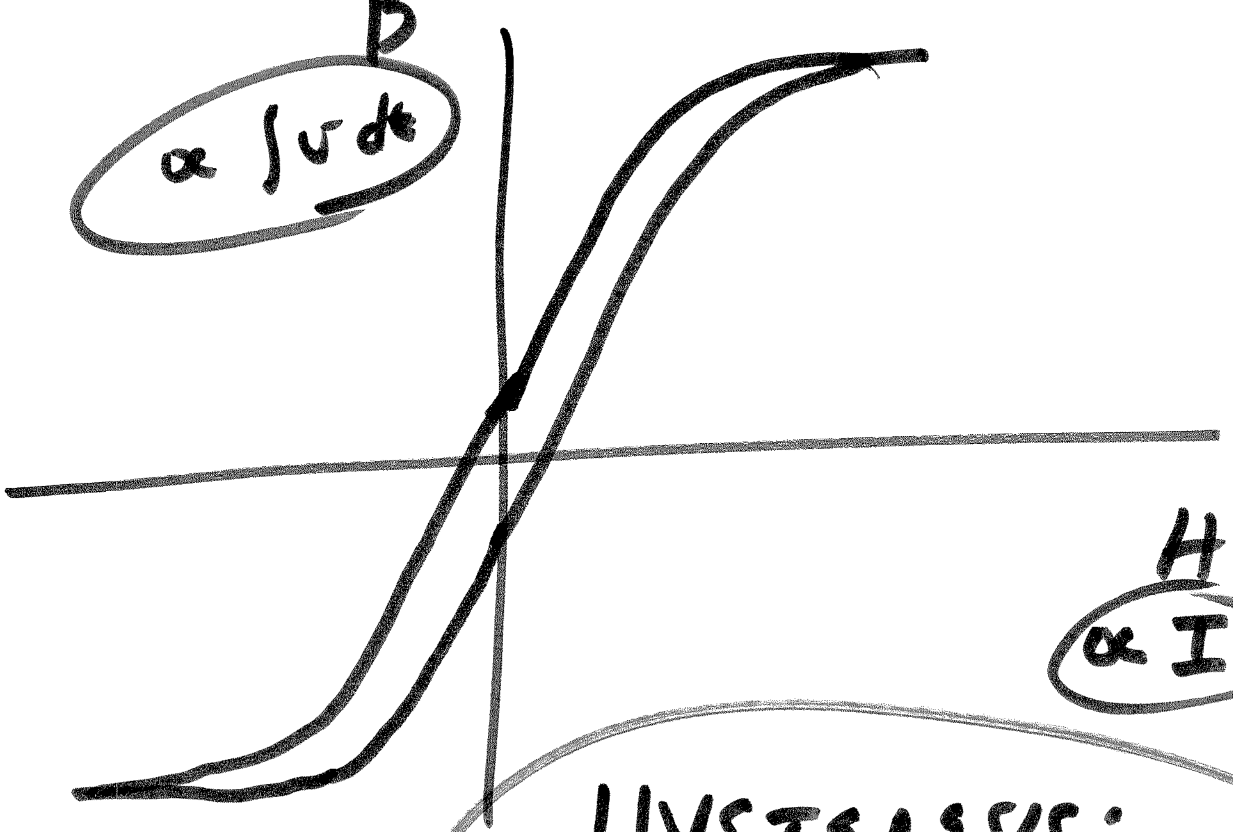

$W = \iiint \left[\int \bar{B} \cdot d\bar{H} \right] dVol$

HYSTERESIS: B LAGS H

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1 BOOTH

2 LYNOTT [redacted]

3 HAINES

4 ROUNDTREE

5 CONGER

6 TELLMAN

ECE 320 / ECE 329

Energy Systems I

Lesson 8

Transformers

Winding resistance

Leakage reactance

Magnetizing reactance

Core loss resistance

ECE 320 / ECE 329 NAME ____________________________

Quiz 2

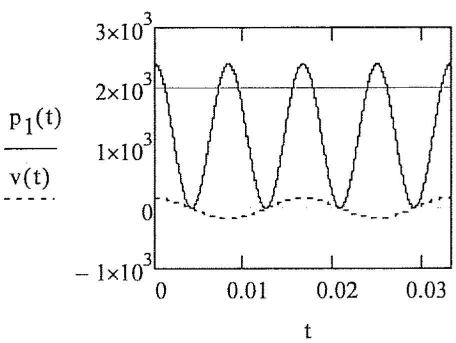
AC Circuits and Power

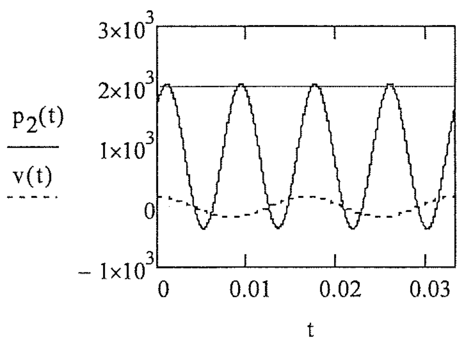
30 January 2012

1. (2 points) A load connected across a 120V AC rms line absorbs 1800 Watts and 480 VArs. Calculate its current.
   a. 15 Amps
   b. 4.0 Amps
   c. 15.5 Amps
   d. 64 mAmps
   e. Other _________

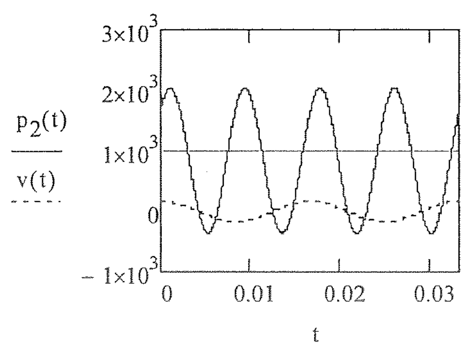
2. (1 point) A 120V AC rms voltage source supplies an electrical load that is entirely resistive. A typical hair dryer is often modeled as such a load. Such loads usually have a selector switch to allow the user to change the resistance value. If the user doubles the resistance value, the electrical power converted to heat
   a. doubles
   b. increases by a factor of four
   c. decreases by a factor of four
   d. is halved.
   e. Other ________________

3. (1 point) A 120V AC rms voltage source supplies an electrical load with a known power factor. At a certain time, the power and voltage waveforms are as shown in the left graph below. An hour later, the power and voltage waveforms have changed to the waveforms shown on the right. From these waveforms, we see that
   a. The power factor decreased
   b. The power factor increased
   c. The power factor merely changed from lagging to leading but has the same numerical value
   d. The power factor did not change





4. (1 point) For the plot of power vs. time as shown below (it's the same as the plot on the right in problem 2), the real power absorbed by the load is approximately
   a. 2000 Watts
   b. 800 Watts
   c. Zero
   d. -300 Watts
   e. Other ______________



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ECE 320 / ECE 329 NAME ______________________________

Quiz 2 30 January 2012

AC Circuits and Power

5. (1 point) A 120V AC rms voltage source with a (0.2+j1.0)Ohm source impedance supplies a certain load. The load impedance can be varied as we specify. At what impedance will the load absorb maximum real power?
   a. 0.02 Ohms
   b. j1.0 Ohms
   c. 1.020 $\angle -78.7°$Ohms
   d. 1.020 $\angle +78.7°$Ohms
   e. Other ________

6. (1 point) What is the maximum power that the load in problem 5 absorbs?
   a. 18kW
   b. 5.9 kW
   c. 12.7kW
   d. 6.02kW
   e. Other _________

7. (3 points) Two electrical loads absorb power from a single 480V AC rms voltage source. The first electrical load absorbs 20kW at a power factor of 0.92 lagging. The second electrical load draws a current of 40 Amps that lags the voltage by 20 degrees. Find the real and reactive power that the sum of the two loads draws.

There is more on the other side of this page.

ECE 320 / ECE 329 NAME ____________________

Quiz 2 30 January 2012

AC Circuits and Power

1. (2 points) A load connected across a 120V AC rms line absorbs 1800 Watts and 480 VArs. Calculate its current.
   a. 15 Amps
   b. 4.0 Amps
   c. 15.5 Amps
   d. 64 mAmps
   e. Other _________

C

$$j := \sqrt{-1}$$

$$I_1 := \frac{(1800 + j \cdot 480) \cdot V \cdot A}{120 \cdot V} = (15 + 4i)\,A \qquad |I_1| = 15.524\,A$$

2. (1 point) A 120V AC rms voltage source supplies an electrical load that is entirely resistive. A typical hair dryer is often modeled as such a load. Such loads usually have a selector switch to allow the user to change the resistance value. If the user doubles the resistance value, the electrical power converted to heat
   a. doubles
   b. increases by a factor of four
   c. decreases by a factor of four
   d. is halved.
   e. Other _________________

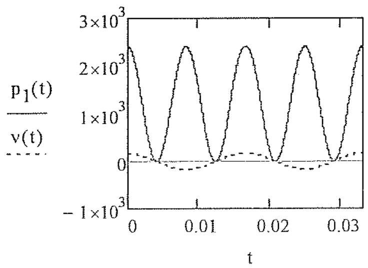
D

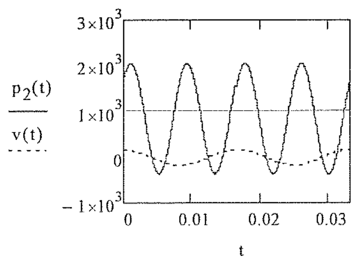
$$P = \frac{V^2}{R}$$

3. (1 point) A 120V AC rms voltage source supplies an electrical load with a known power factor. At a certain time, the power and voltage waveforms are as shown in the left graph below. An hour later, the power and voltage waveforms have changed to the waveforms shown on the right. From these waveforms, we see that
   a. The power factor decreased
   b. The power factor increased
   c. The power factor merely changed from lagging to leading but has the same numerical value
   d. The power factor did not change

A

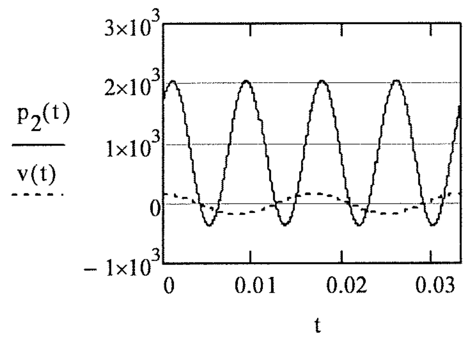
The average power decreases while the double frequency term retains the same amplitude.
This means that the power factor decreased.





4. (1 point) For the plot of power vs. time as shown below (it's the same as the plot on the right in problem 2), the real power absorbed by the load is approximately
   a. 2000 Watts
   b. 800 Watts
   c. Zero
   d. -300 Watts
   e. Other ______________

B



The average value of this power waveform is about 800 Watts.

5. (1 point) A 120V AC rms voltage source with a (0.2+j1.0)Ohm source impedance supplies a certain load. The load impedance can be varied as we specify. At what impedance will the load absorb maximum real power?
   a. 0.02 Ohms
   b. j1.0 Ohms
   c. $1.020\angle -78.7°$ Ohms
   d. $1.020\angle +78.7°$ Ohms
   e. Other ________

C

The impedance that gives maximum power transfer is the complex conjugate of the source impedance.

6. (1 point) What is the maximum power that the load in problem 5 absorbs?
   a. 18kW
   b. 5.9 kW
   c. 12.7kW
   d. 6.02kW
   e. Other _________

A

$$I_6 := \frac{(120 \cdot V)}{0.2\cdot\Omega + j\cdot 1\cdot\Omega + 0.2\cdot\Omega - j\cdot 1.0\cdot\Omega} = 300\ A \qquad P_6 := \left(\left|I_6\right|\right)^2\cdot(0.2\cdot\Omega) = 18\,kW$$

1. (3 points) Two electrical loads absorb power from a single 480V AC rms voltage source. The first electrical load absorbs 20kW at a power factor of 0.92 lagging. The second electrical load draws a current of 40 Amps that lags the voltage by 20 degrees. Find the real and reactive power that the sum of the two loads draws.

$$j := \sqrt{-1} \qquad lagging := 1 \qquad kVAr := kV\cdot A$$

$$V_7 := 480\cdot V \qquad P_{71} := 20\cdot kW \qquad pf_{71} := 0.92\cdot lagging \qquad I_{72} := 40\cdot e^{-j\cdot 20\cdot deg}\cdot A$$

$$S_{71} := \frac{P_{71}}{pf_{71}} = 21.739\,kV\cdot A \qquad \theta_{71} := acos\left(pf_{71}\right) = 23.074\,deg \qquad S_{71} := S_{71}\cdot e^{j\cdot\theta_{71}} = (20 + 8.52i)\,kV\cdot A$$

$$S_{72} := V_7\cdot\overline{I_{72}} = (18.042 + 6.567i)\,kV\cdot A \qquad S_7 := S_{71} + S_{72} = (38.042 + 15.087i)\,kV\cdot A$$

$$P_7 := Re\left(S_7\right) = 38.042\,kW \qquad Q_7 := Im\left(S_7\right) = 15.087\,kVAr$$

ECE 320 / ECE 329
Homework
Transformers

Recitation: Lesson 10
Due on campus: 6 February 2012

From the textbook, do the following problems:

1. 2.2
2. 2.3
3. 2.6
4. 2.7
5. 2.14
6. 2.17

2–17. What happens to a transformer when it is first connected to a power line? Can anything be done to mitigate this problem?

2–18. What is a potential transformer? How is it used?

2–19. What is a current transformer? How is it used?

2–20. A distribution transformer is rated at 18 kVA, 20,000/480 V, and 60 Hz. Can this transformer safely supply 15 kVA to a 415-V load at 50 Hz? Why or why not?

2–21. Why does one hear a hum when standing near a large power transformer?

PROBLEMS

2–1. A 100-kVA, 8000/277-V distribution transformer has the following resistances and reactances:

$$R_P = 5\ \Omega \qquad R_S = 0.005\ \Omega$$
$$X_P = 6\ \Omega \qquad X_S = 0.006\ \Omega$$
$$R_C = 50\ \text{k}\Omega \qquad X_M = 10\ \text{k}\Omega$$

The excitation branch impedances are given referred to the high-voltage side of the transformer.

(a) Find the equivalent circuit of this transformer referred to the low-voltage side.
(b) Find the per-unit equivalent circuit of this transformer.
(c) Assume that this transformer is supplying rated load at 277 V and 0.85 PF lagging. What is this transformer's input voltage? What is its voltage regulation?
(d) What are the copper losses and core losses in this transformer under the conditions of part *(c)*?
(e) What is the transformer's efficiency under the conditions of part *(c)*?

2–2. A single-phase power system is shown in Figure P2–1. The power source feeds a 100-kVA, 14/2.4-kV transformer through a feeder impedance of $38.2 + j140\ \Omega$. The transformer's equivalent series impedance referred to its low-voltage side is $0.10 + j0.40\ \Omega$. The load on the transformer is 90 kW at 0.80 PF lagging and 2300 V.

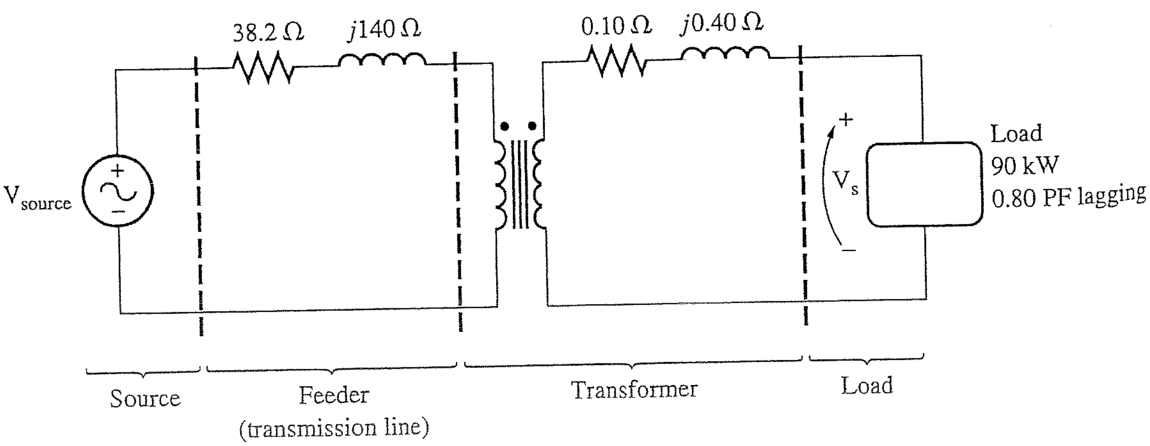


FIGURE P2–1
The circuit of Problem 2–2.

(a) What is the voltage at the power source of the system?
(b) What is the voltage regulation of the transformer?
(c) How efficient is the overall power system?

2–3. The secondary winding of an ideal transformer has a terminal voltage of $v_s(t) = 282.8 \sin 377t$ V. The turns ratio of the transformer is 100:200 ($a = 0.50$). If the secondary current of the transformer is $i_s(t) = 7.07 \sin (377t - 36.87°)$ A, what is the primary current of this transformer? What are its voltage regulation and efficiency?

2–4. The secondary winding of a real transformer has a terminal voltage of $v_s(t) = 282.8 \sin 377t$ V. The turns ratio of the transformer is 100:200 ($a = 0.50$). If the secondary current of the transformer is $i_s(t) = 7.07 \sin (377t - 36.87°)$ A, what is the primary current of this transformer? What are its voltage regulation and efficiency? The impedances of this transformer referred to the primary side are

$$R_{eq} = 0.20\ \Omega \qquad R_C = 300\ \Omega$$
$$X_{eq} = 0.80\ \Omega \qquad X_M = 100\ \Omega$$

2–5. When travelers from the USA and Canada visit Europe, they encounter a different power distribution system. Wall voltages in North America are 120 V rms at 60 Hz, while typical wall voltages in Europe are 230 V at 50 Hz. Many travelers carry small step-up/step-down transformers so that they can use their appliances in the countries that they are visiting. A typical transformer might be rated at 1 kVA and 115/230 V. It has 500 turns of wire on the 115-V side and 1000 turns of wire on the 230-V side. The magnetization curve for this transformer is shown in Figure P2–2, and can be found in file `p22.mag` at this book's website.

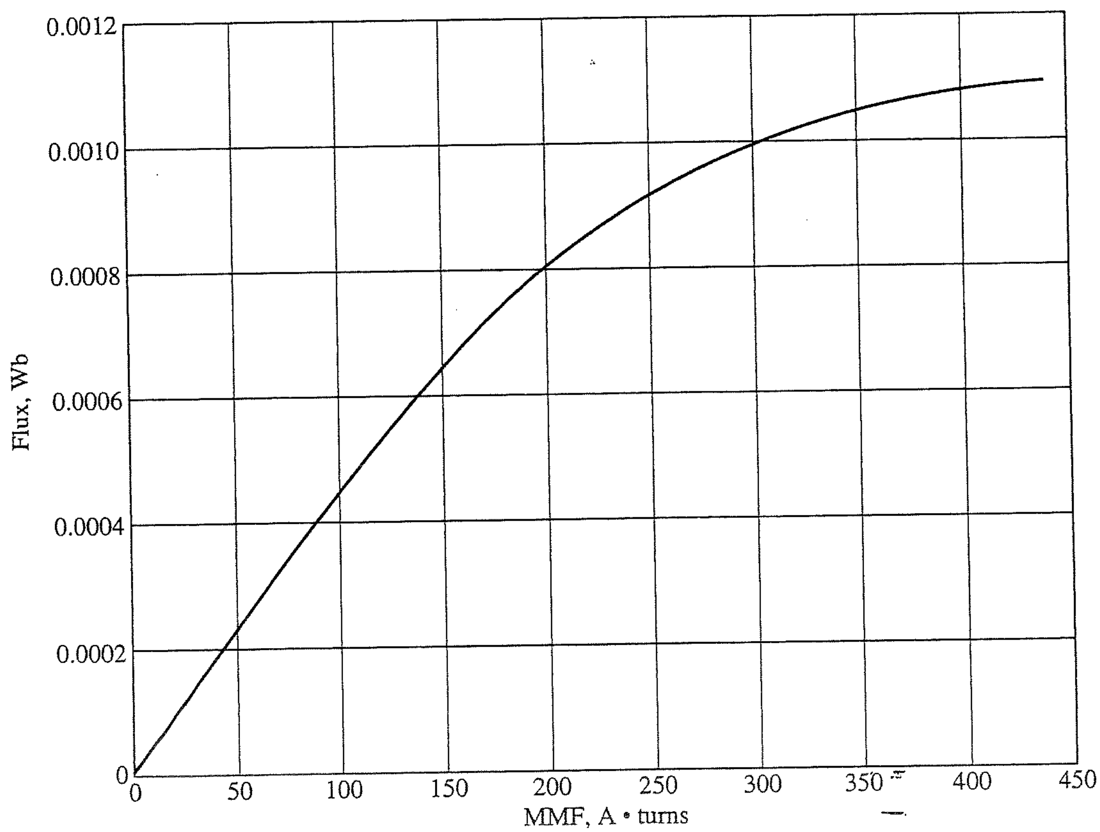


FIGURE P2–2
Magnetization curve for the transformer of Problem 2–5.

(a) Suppose that this transformer is connected to a 120-V, 60-Hz power source with no load connected to the 240-V side. Sketch the magnetization current that would flow in the transformer. (Use MATLAB to plot the current accurately, if it is available.) What is the rms amplitude of the magnetization current? What percentage of full-load current is the magnetization current?

(b) Now suppose that this transformer is connected to a 240-V, 50-Hz power source with no load connected to the 120-V side. Sketch the magnetization current that would flow in the transformer. (Use MATLAB to plot the current accurately, if it is available.) What is the rms amplitude of the magnetization current? What percentage of full-load current is the magnetization current?

(c) In which case is the magnetization current a higher percentage of full-load current? Why?

2–6. A 1000-VA, 230/115-V transformer has been tested to determine its equivalent circuit. The results of the tests are shown below.

Open-circuit test (on secondary side)	Short-circuit test (on primary side)
$V_{OC} = 115$ V	$V_{SC} = 17.1$ V
$I_{OC} = 0.11$ A	$I_{SC} = 8.7$ A
$P_{OC} = 3.9$ W	$P_{SC} = 38.1$ W

(a) Find the equivalent circuit of this transformer referred to the low-voltage side of the transformer.

(b) Find the transformer's voltage regulation at rated conditions and (1) 0.8 PF lagging, (2) 1.0 PF, (3) 0.8 PF leading.

(c) Determine the transformer's efficiency at rated conditions and 0.8 PF lagging.

2–7. A 30-kVA, 8000/230-V distribution transformer has an impedance referred to the primary of $20 + j100\ \Omega$. The components of the excitation branch referred to the primary side are $R_C = 100\ \text{k}\Omega$ and $X_M = 20\ \text{k}\Omega$.

(a) If the primary voltage is 7967 V and the load impedance is $Z_L = 2.0 + j0.7\ \Omega$, what is the secondary voltage of the transformer? What is the voltage regulation of the transformer?

(b) If the load is disconnected and a capacitor of $-j3.0\ \Omega$ is connected in its place, what is the secondary voltage of the transformer? What is its voltage regulation under these conditions?

2–8. A 150-MVA, 15/200-kV, single-phase power transformer has a per-unit resistance of 1.2 percent and a per-unit reactance of 5 percent (data taken from the transformer's nameplate). The magnetizing impedance is $j80$ per unit.

(a) Find the equivalent circuit referred to the low-voltage side of this transformer.

(b) Calculate the voltage regulation of this transformer for a full-load current at power factor of 0.8 lagging.

(c) Calculate the copper and core losses in the transformer at the conditions in (b).

(d) Assume that the primary voltage of this transformer is a constant 15 kV, and plot the secondary voltage as a function of load current for currents from no-load to full-load. Repeat this process for power factors of 0.8 lagging, 1.0, and 0.8 leading.

2–9. A 5000-kVA, 230/13.8-kV, single-phase power transformer has a per-unit resistance of 1 percent and a per-unit reactance of 5 percent (data taken from the transformer's nameplate). The open-circuit test performed on the low-voltage side of the transformer yielded the following data:

$$V_{OC} = 13.8 \text{ kV} \qquad I_{OC} = 21.1 \text{ A} \qquad P_{OC} = 90.8 \text{ kW}$$

(*a*) Find the equivalent circuit referred to the low-voltage side of this transformer.
(*b*) If the voltage on the secondary side is 13.8 kV and the power supplied is 4000 kW at 0.8 PF lagging, find the voltage regulation of the transformer. Find its efficiency.

2–10. A three-phase transformer bank is to handle 500 kVA and have a 34.5/11-kV voltage ratio. Find the rating of each individual transformer in the bank (high voltage, low voltage, turns ratio, and apparent power) if the transformer bank is connected to (*a*) Y–Y, (*b*) Y–Δ, (*c*) Δ–Y, (*d*) Δ–Δ, (*e*) open–Δ, (*f*) open-Y–open-Δ.

2–11. A 100-MVA, 230/115-kV, Δ–Y three-phase power transformer has a per-unit resistance of 0.015 pu and a per-unit reactance of 0.06 pu. The excitation branch elements are $R_C = 100$ pu and $X_M = 20$ pu.
(*a*) If this transformer supplies a load of 80 MVA at 0.8 PF lagging, draw the phasor diagram of one phase of the transformer.
(*b*) What is the voltage regulation of the transformer bank under these conditions?
(*c*) Sketch the equivalent circuit referred to the low-voltage side of one phase of this transformer. Calculate all the transformer impedances referred to the low-voltage side.
(*d*) Determine the losses in the transformer and the efficiency of the transformer under the conditions of part (*b*).

2–12. Three 20-kVA, 24,000/277-V distribution transformers are connected in Δ–Y. The open-circuit test was performed on the low-voltage side of this transformer bank, and the following data were recorded:

$$V_{\text{line,OC}} = 480 \text{ V} \qquad I_{\text{line,OC}} = 4.10 \text{ A} \qquad P_{3\phi,\text{OC}} = 945 \text{ W}$$

The short-circuit test was performed on the high-voltage side of this transformer bank, and the following data were recorded:

$$V_{\text{line,SC}} = 1400 \text{ V} \qquad I_{\text{line,SC}} = 1.80 \text{ A} \qquad P_{3\phi,\text{SC}} = 912 \text{ W}$$

(*a*) Find the per-unit equivalent circuit of this transformer bank.
(*b*) Find the voltage regulation of this transformer bank at the rated load and 0.90 PF lagging.
(*c*) What is the transformer bank's efficiency under these conditions?

2–13. A 14,000/480-V, three-phase, Δ–Y-connected transformer bank consists of three identical 100-kVA, 8314/480-V transformers. It is supplied with power directly from a large constant-voltage bus. In the short-circuit test, the recorded values on the high-voltage side for one of these transformers are

$$V_{SC} = 510 \text{ V} \qquad I_{SC} = 12.6 \text{ A} \qquad P_{SC} = 3000 \text{ W}$$

(*a*) If this bank delivers a rated load at 0.8 PF lagging and rated voltage, what is the line-to-line voltage on the primary of the transformer bank?
(*b*) What is the voltage regulation under these conditions?
(*c*) Assume that the primary phase voltage of this transformer is a constant 8314 V, and plot the secondary voltage as a function of load current for currents from no-load to full-load. Repeat this process for power factors of 0.8 lagging, 1.0, and 0.8 leading.

(*d*) Plot the voltage regulation of this transformer as a function of load current for currents from no-load to full-load. Repeat this process for power factors of 0.8 lagging, 1.0, and 0.8 leading.

(*e*) Sketch the per-unit equivalent circuit of this transformer.

2–14. A 13.8-kV, single-phase generator supplies power to a load through a transmission line. The load's impedance is $Z_{load} = 500 \angle 36.87°\Omega$, and the transmission line's impedance is $Z_{line} = 60 \angle 60°\Omega$.

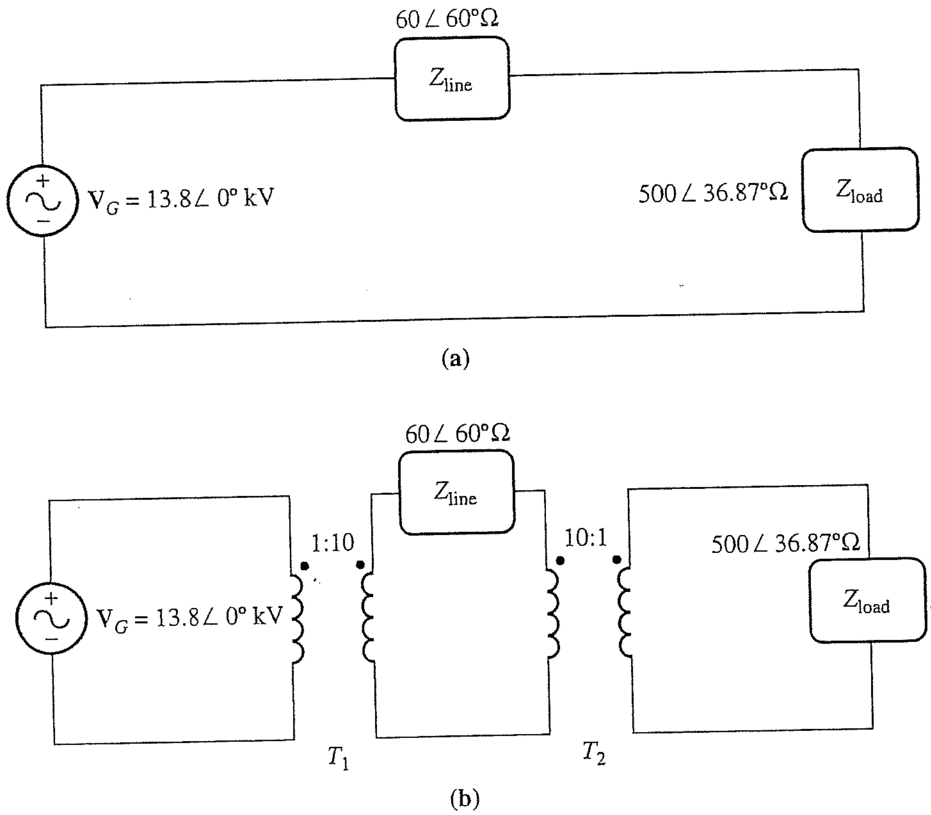


FIGURE P2–3
Circuits for Problem 2–14: (a) without transformers and (b) with transformers.

(*a*) If the generator is directly connected to the load (Figure P2–3a), what is the ratio of the load voltage to the generated voltage? What are the transmission losses of the system?

(*b*) What percentage of the power supplied by the source reaches the load (what is the efficiency of the transmission system)?

(*c*) If a 1:10 step-up transformer is placed at the output of the generator and a 10:1 transformer is placed at the load end of the transmission line, what is the new ratio of the load voltage to the generated voltage? What are the transmission losses of the system now? (*Note*: The transformers may be assumed to be ideal.)

(*d*) What percentage of the power supplied by the source reaches the load now?

(*e*) Compare the efficiencies of the transmission system with and without transformers.

2–15. An autotransformer is used to connect a 12.6-kV distribution line to a 13.8-kV distribution line. It must be capable of handling 2000 kVA. There are three phases, connected Y–Y with their neutrals solidly grounded.

(*a*) What must the N_C/N_{SE} turns ratio be to accomplish this connection?

(*b*) How much apparent power must the windings of each autotransformer handle?

(*c*) What is the power advantage of this autotransformer system?

(*d*) If one of the autotransformers were reconnected as an ordinary transformer, what would its ratings be?

2–16. Prove the following statement: If a transformer having a series impedance Z_{eq} is connected as an autotransformer, its per-unit series impedance Z'_{eq} as an autotransformer will be

$$Z'_{eq} = \frac{N_{SE}}{N_{SE} + N_C} Z_{eq}$$

Note that this expression is the reciprocal of the autotransformer power advantage.

2–17. A 10-kVA, 480/120-V conventional transformer is to be used to supply power from a 600-V source to a 120-V load. Consider the transformer to be ideal, and assume that all insulation can handle 600 V.

(*a*) Sketch the transformer connection that will do the required job.

(*b*) Find the kilovoltampere rating of the transformer in the configuration.

(*c*) Find the maximum primary and secondary currents under these conditions.

2–18. A 10-kVA, 480/120-V conventional transformer is to be used to supply power from a 600-V source to a 480-V load. Consider the transformer to be ideal, and assume that all insulation can handle 600 V.

(*a*) Sketch the transformer connection that will do the required job.

(*b*) Find the kilovoltampere rating of the transformer in the configuration.

(*c*) Find the maximum primary and secondary currents under these conditions.

(*d*) The transformer in Problem 2–18 is identical to the transformer in Problem 2–17, but there is a significant difference in the apparent power capability of the transformer in the two situations. Why? What does that say about the best circumstances in which to use an autotransformer?

2–19. Two phases of a 14.4-kV, three-phase distribution line serve a remote rural road (the neutral is also available). A farmer along the road has a 480 V feeder supplying 200 kW at 0.85 PF lagging of three-phase loads, plus 60 kW at 0.9 PF lagging of single-phase loads. The single-phase loads are distributed evenly among the three phases. Assuming that the open-Y–open-Δ connection is used to supply power to his farm, find the voltages and currents in each of the two transformers. Also find the real and reactive powers supplied by each transformer. Assume the transformers are ideal. What is the minimum required kVA rating of each transformer?

2–20. A 50-kVA, 20,000/480-V, 60-Hz, single-phase distribution transformer is tested with the following results:

Open-circuit test (measured from secondary side)	Short-circuit test (measured from primary side)
$V_{OC} = 480$ V	$V_{SC} = 1130$ V
$I_{OC} = 4.1$ A	$I_{SC} = 1.30$ A
$P_{OC} = 620$ W	$P_{SC} = 550$ W