Transformers

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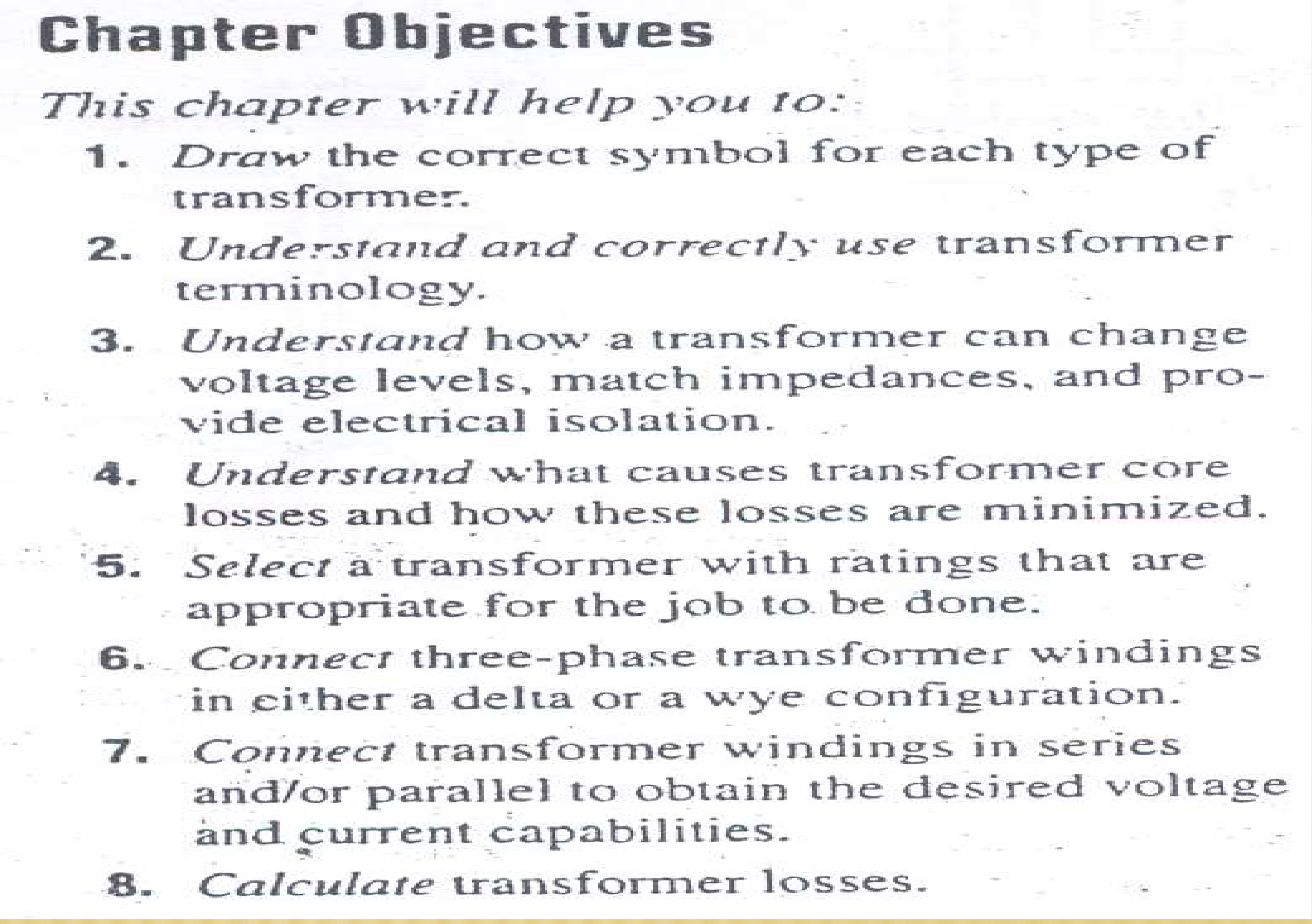
Transformers



Chapter Objectives

This chapter will help you to:

1. *Draw* the correct symbol for each type of transformer.
2. *Understand and correctly use* transformer terminology.
3. *Understand* how a transformer can change voltage levels, match impedances, and provide electrical isolation.
4. *Understand* what causes transformer core losses and how these losses are minimized.
5. *Select* a transformer with ratings that are appropriate for the job to be done.
6. *Connect* three-phase transformer windings in either a delta or a wye configuration.
7. *Connect* transformer windings in series and/or parallel to obtain the desired voltage and current capabilities.
8. *Calculate* transformer losses.

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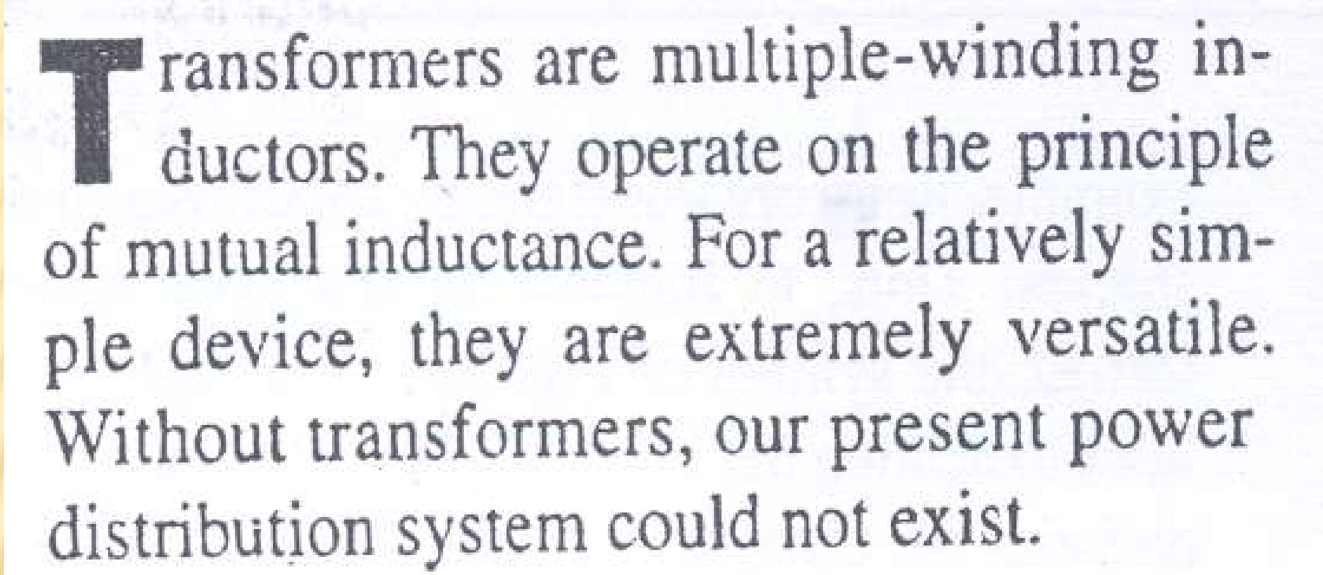

Transformers are multiple-winding inductors. They operate on the principle of mutual inductance. For a relatively simple device, they are extremely versatile. Without transformers, our present power distribution system could not exist.

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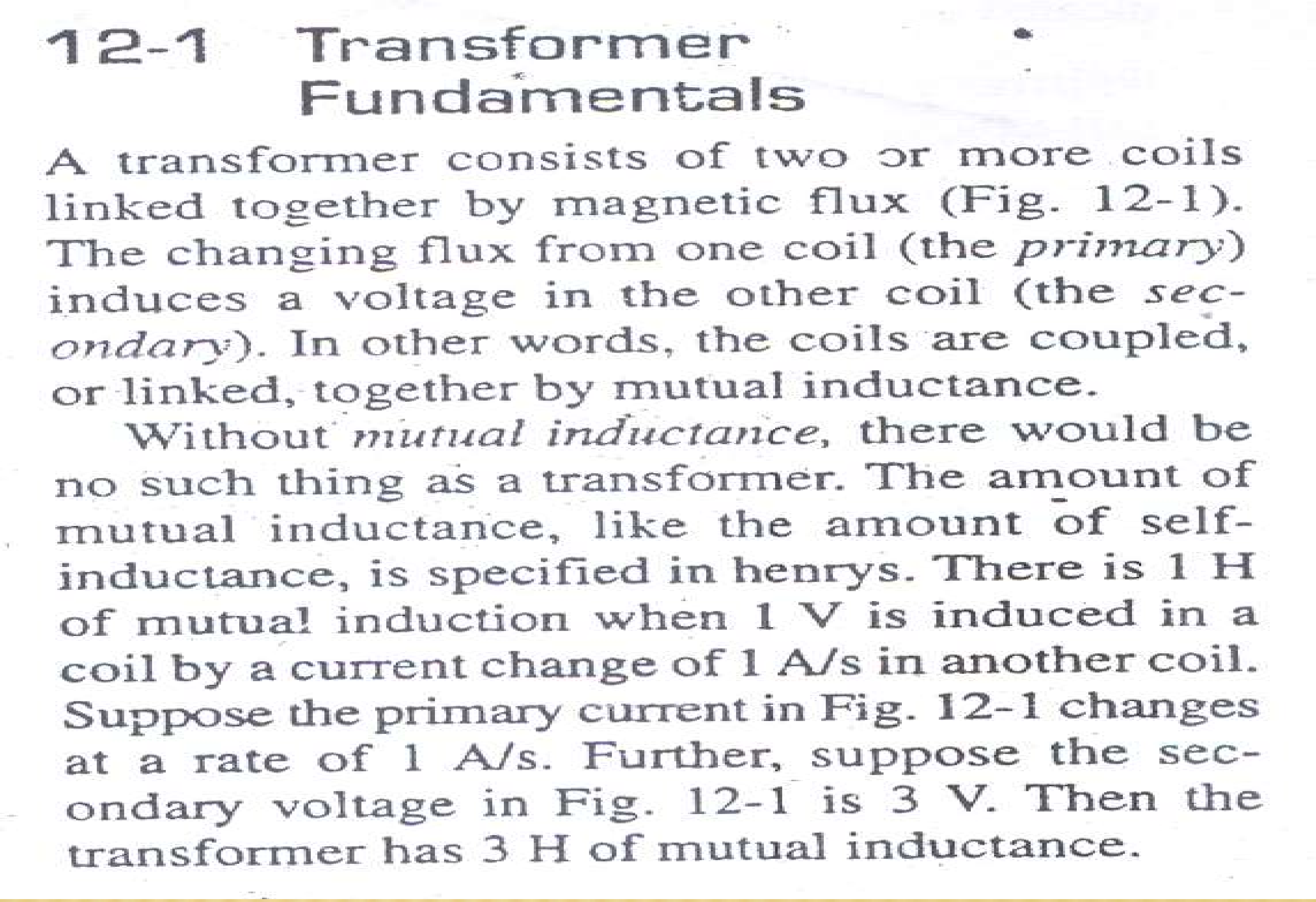

12-1 Transformer Fundamentals

A transformer consists of two or more coils linked together by magnetic flux (Fig. 12-1). The changing flux from one coil (the *primary*) induces a voltage in the other coil (the *secondary*). In other words, the coils are coupled, or linked, together by mutual inductance.

Without *mutual inductance*, there would be no such thing as a transformer. The amount of mutual inductance, like the amount of self-inductance, is specified in henrys. There is 1 H of mutual induction when 1 V is induced in a coil by a current change of 1 A/s in another coil. Suppose the primary current in Fig. 12-1 changes at a rate of 1 A/s. Further, suppose the secondary voltage in Fig. 12-1 is 3 V. Then the transformer has 3 H of mutual inductance.

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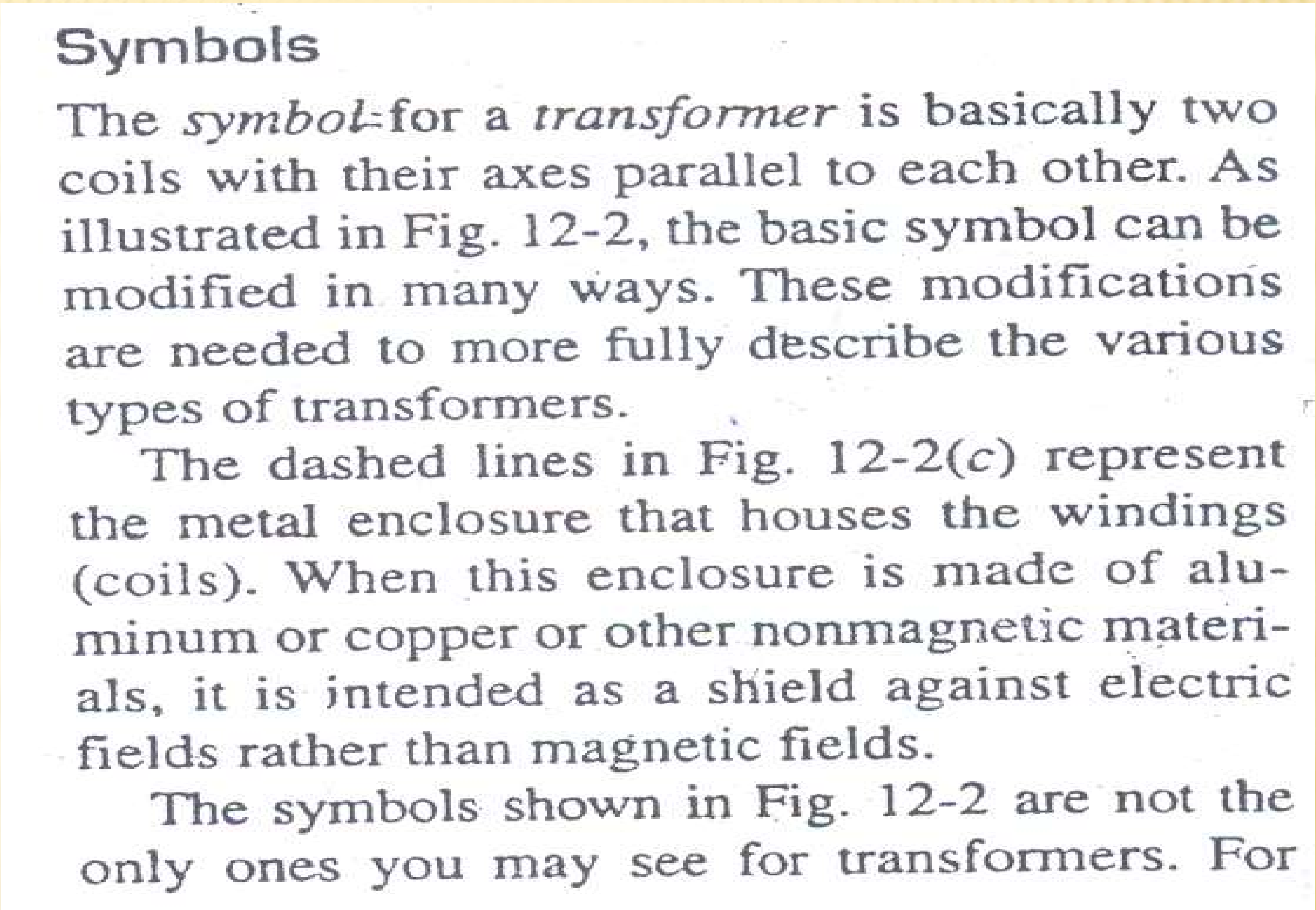

Symbols

The *symbol* for a *transformer* is basically two coils with their axes parallel to each other. As illustrated in Fig. 12-2, the basic symbol can be modified in many ways. These modifications are needed to more fully describe the various types of transformers.

The dashed lines in Fig. 12-2(*c*) represent the metal enclosure that houses the windings (coils). When this enclosure is made of aluminum or copper or other nonmagnetic materials, it is intended as a shield against electric fields rather than magnetic fields.

The symbols shown in Fig. 12-2 are not the only ones you may see for transformers. For

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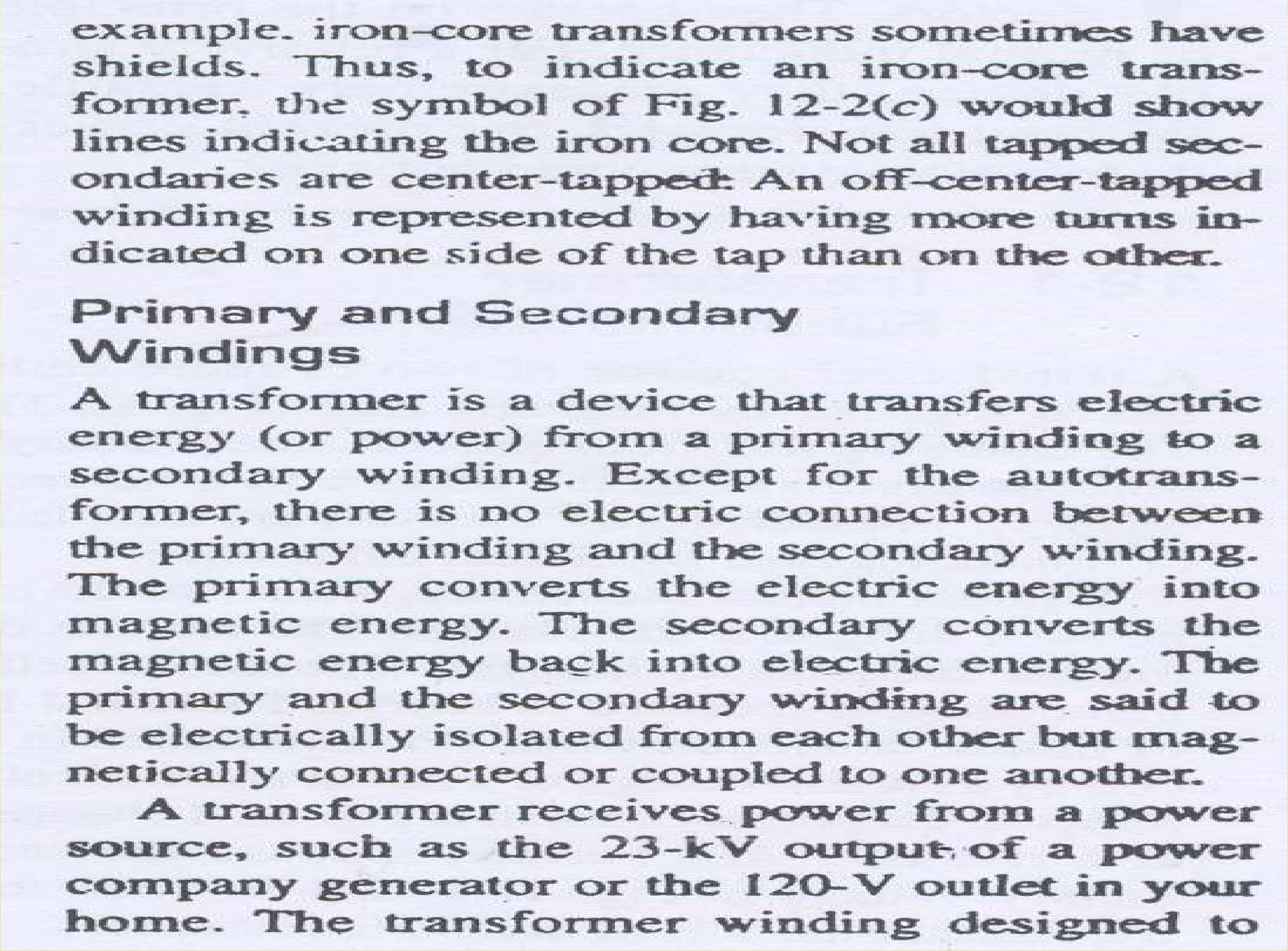

example. iron-core transformers sometimes have shields. Thus, to indicate an iron-core transformer, the symbol of Fig. 12-2(*c*) would show lines indicating the iron core. Not all tapped secondaries are center-tapped. An off-center-tapped winding is represented by having more turns indicated on one side of the tap than on the other.

Primary and Secondary Windings

A transformer is a device that transfers electric energy (or power) from a primary winding to a secondary winding. Except for the autotransformer, there is no electric connection between the primary winding and the secondary winding. The primary converts the electric energy into magnetic energy. The secondary converts the magnetic energy back into electric energy. The primary and the secondary winding are said to be electrically isolated from each other but magnetically connected or coupled to one another.

A transformer receives power from a power source, such as the 23-kV output of a power company generator or the 120-V outlet in your home. The transformer winding designed to

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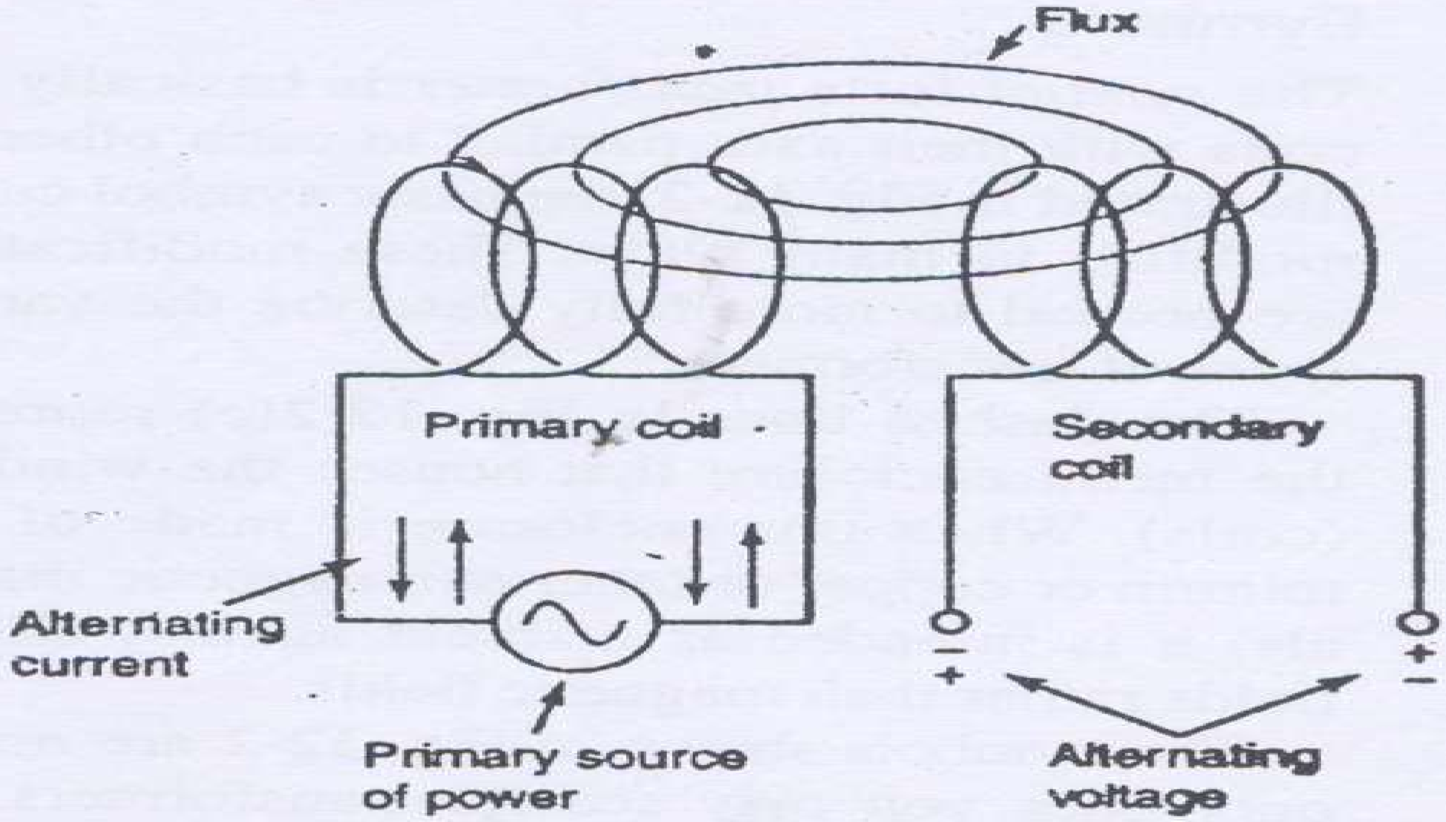

Fig. 12-1 Transformer action. The primary coil is linked to the secondary coil by magnetic flux.

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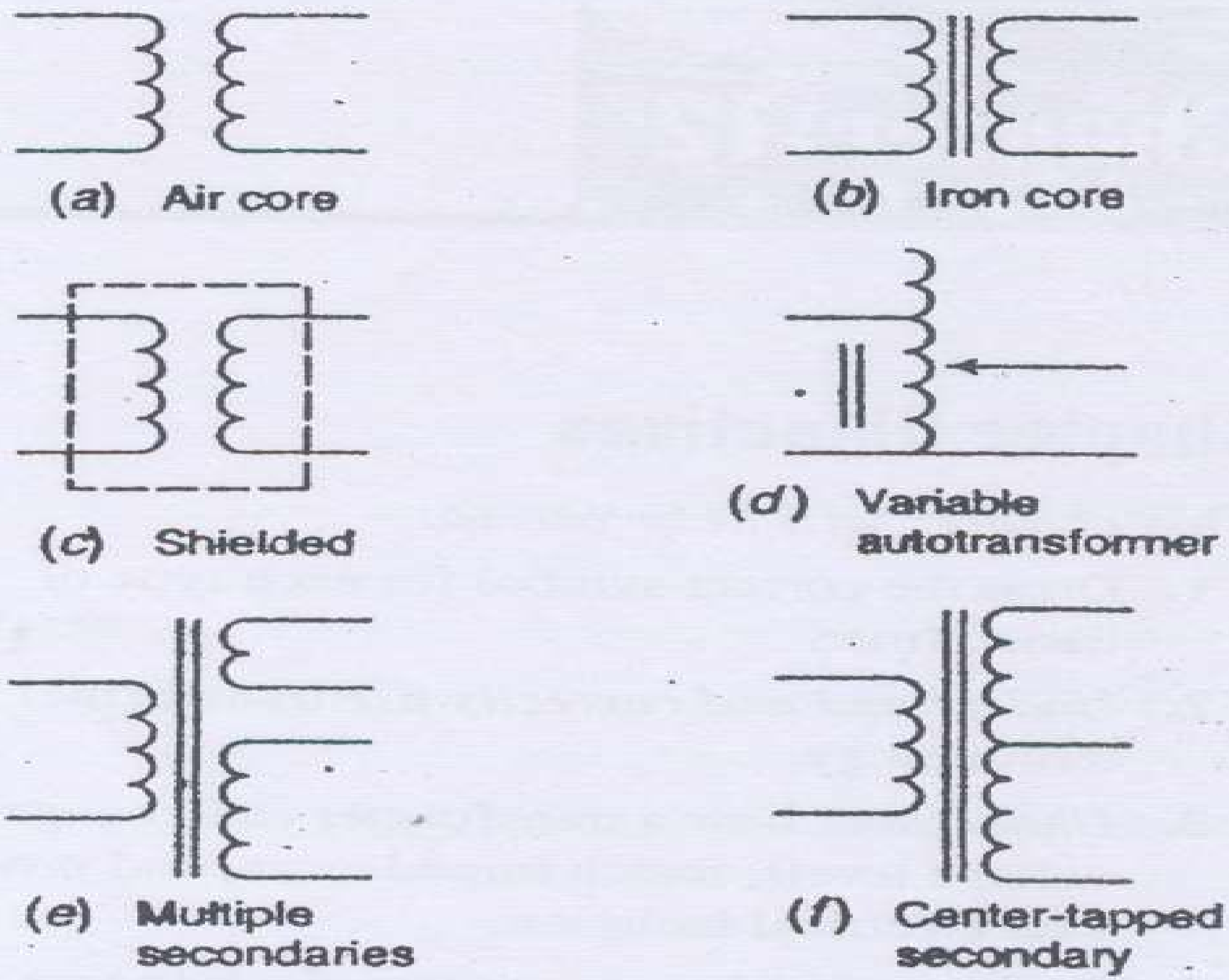
(a) Air core

(b) Iron core

(c) Shielded

(d) Variable autotransformer

(e) Multiple secondaries

(f) Center-tapped secondary

Fig. 12-2 Transformer symbols.

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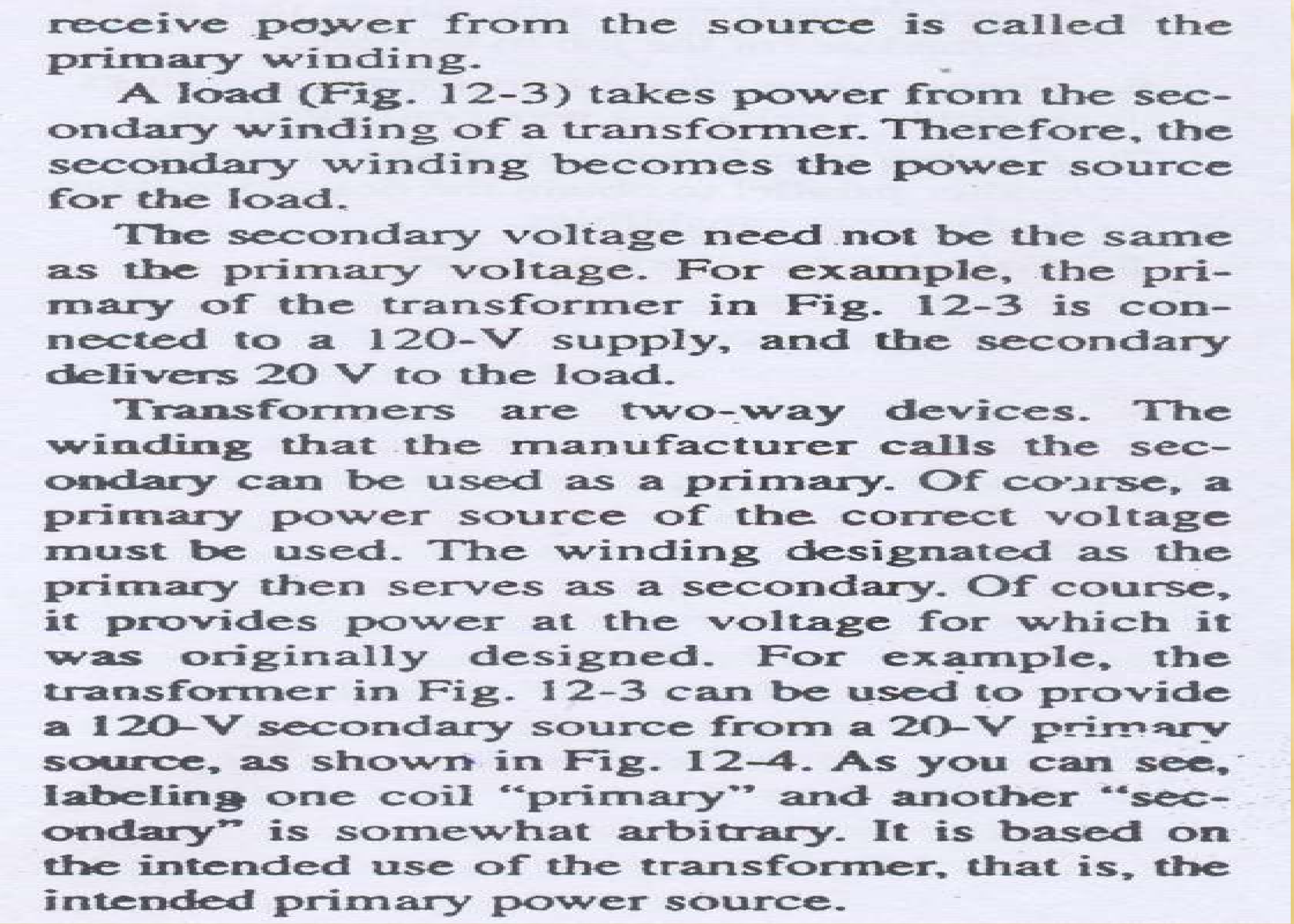

receive power from the source is called the primary winding.

A load (Fig. 12-3) takes power from the secondary winding of a transformer. Therefore, the secondary winding becomes the power source for the load.

The secondary voltage need not be the same as the primary voltage. For example, the primary of the transformer in Fig. 12-3 is connected to a 120-V supply, and the secondary delivers 20 V to the load.

Transformers are two-way devices. The winding that the manufacturer calls the secondary can be used as a primary. Of course, a primary power source of the correct voltage must be used. The winding designated as the primary then serves as a secondary. Of course, it provides power at the voltage for which it was originally designed. For example, the transformer in Fig. 12-3 can be used to provide a 120-V secondary source from a 20-V primary source, as shown in Fig. 12-4. As you can see, labeling one coil "primary" and another "secondary" is somewhat arbitrary. It is based on the intended use of the transformer, that is, the intended primary power source.

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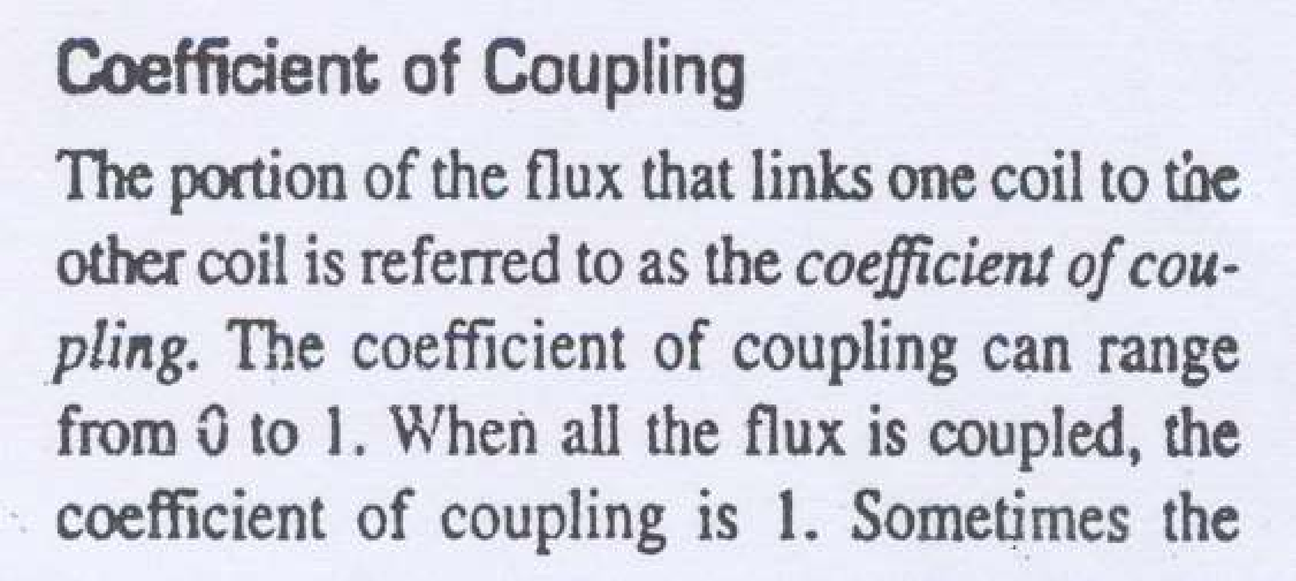

Coefficient of Coupling

The portion of the flux that links one coil to the other coil is referred to as the *coefficient of coupling*. The coefficient of coupling can range from 0 to 1. When all the flux is coupled, the coefficient of coupling is 1. Sometimes the

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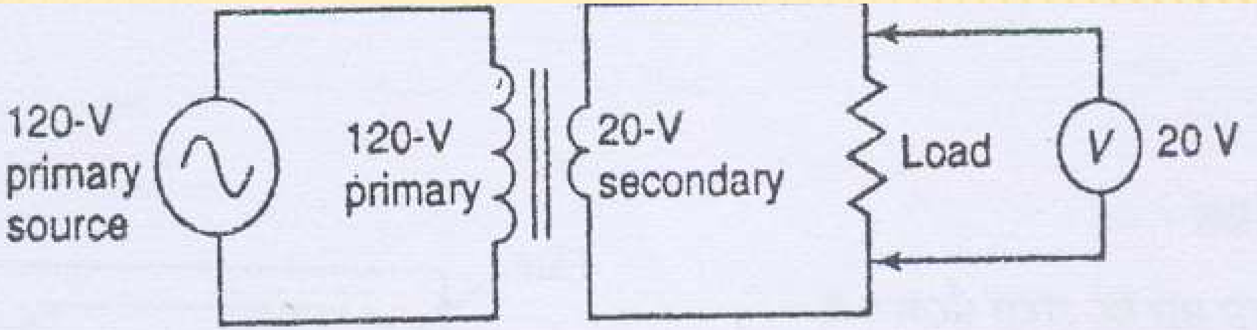

Fig. 12-3 Primary-secondary terminology. The primary winding receives power from a power source.

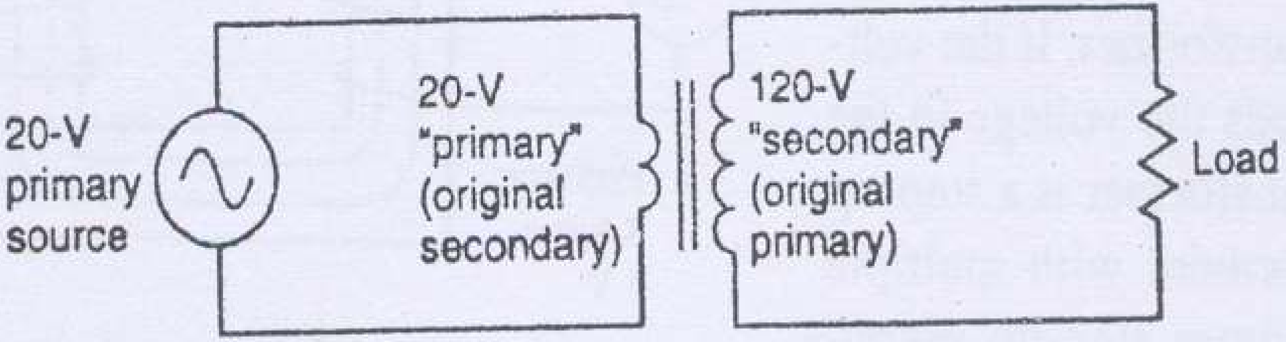

Fig. 12-4 Reversing the primary-secondary function.

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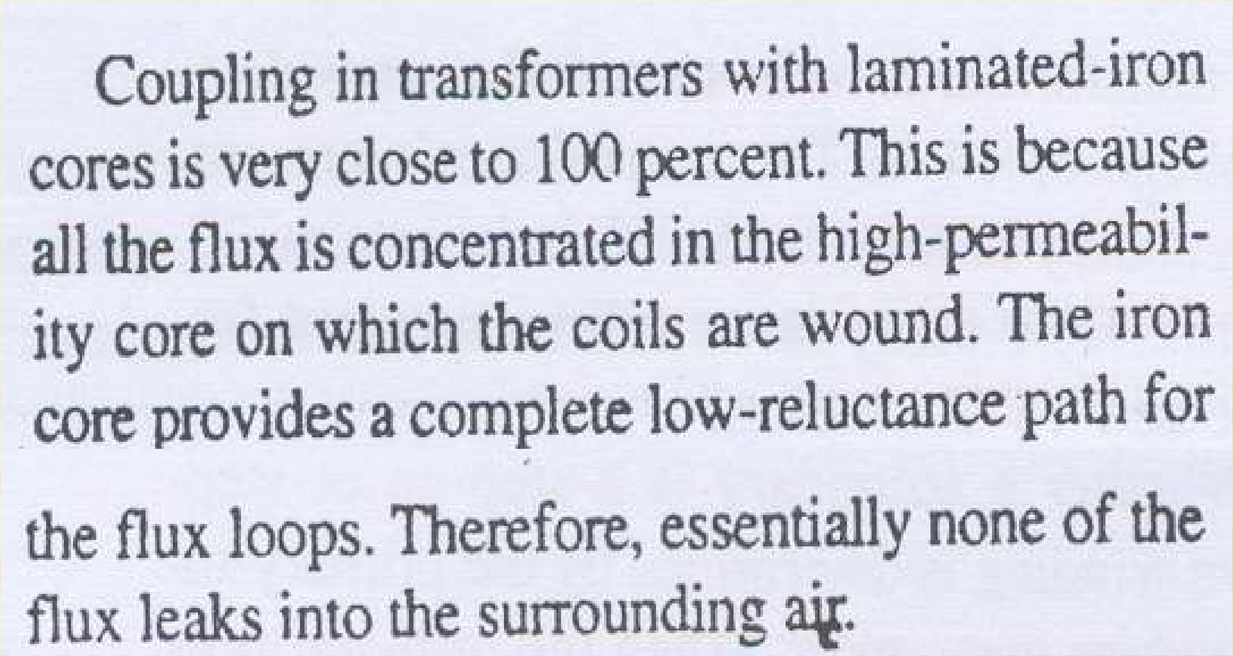

Coupling in transformers with laminated-iron cores is very close to 100 percent. This is because all the flux is concentrated in the high-permeability core on which the coils are wound. The iron core provides a complete low-reluctance path for the flux loops. Therefore, essentially none of the flux leaks into the surrounding air.

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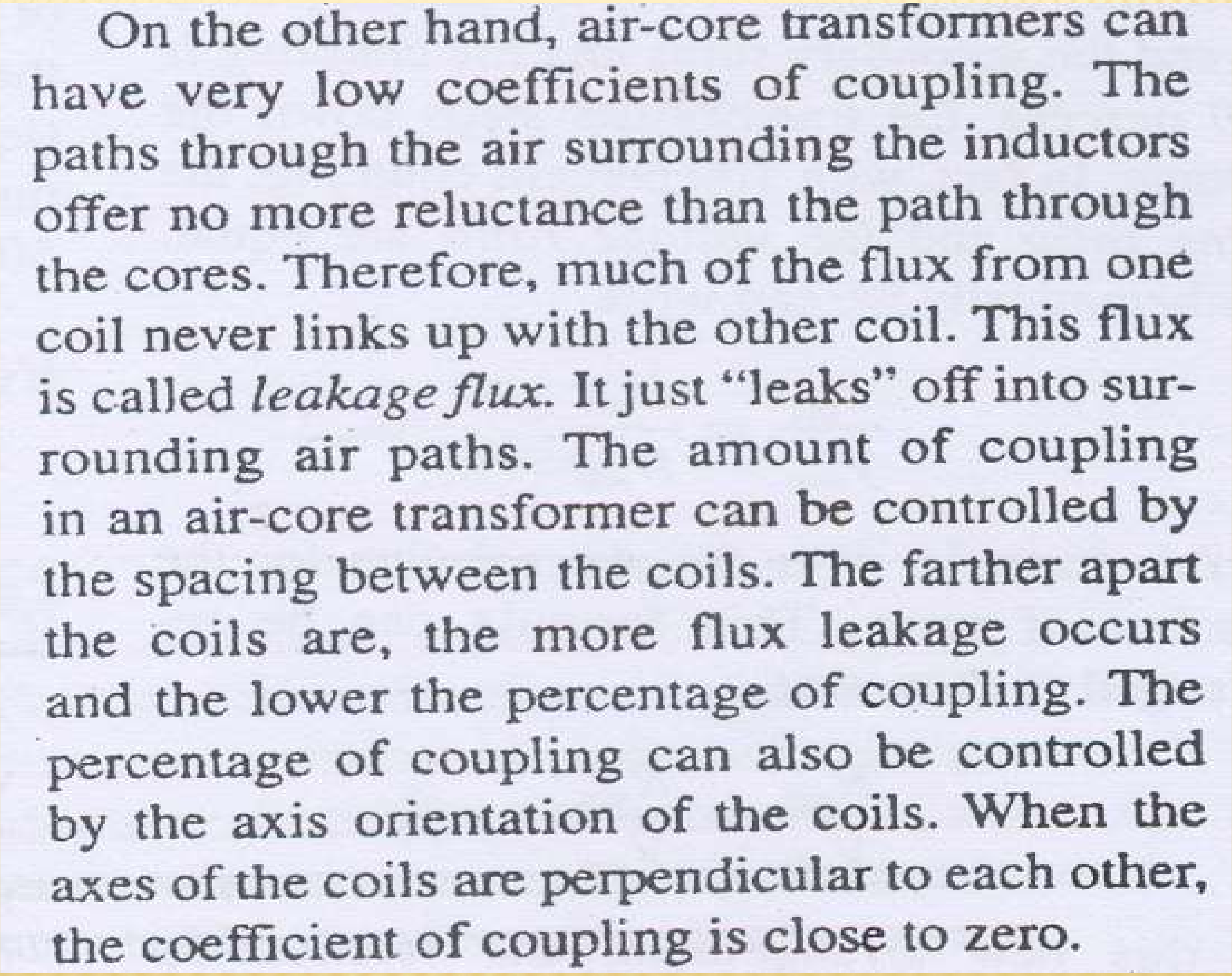

On the other hand, air-core transformers can have very low coefficients of coupling. The paths through the air surrounding the inductors offer no more reluctance than the path through the cores. Therefore, much of the flux from one coil never links up with the other coil. This flux is called *leakage flux*. It just "leaks" off into surrounding air paths. The amount of coupling in an air-core transformer can be controlled by the spacing between the coils. The farther apart the coils are, the more flux leakage occurs and the lower the percentage of coupling. The percentage of coupling can also be controlled by the axis orientation of the coils. When the axes of the coils are perpendicular to each other, the coefficient of coupling is close to zero.

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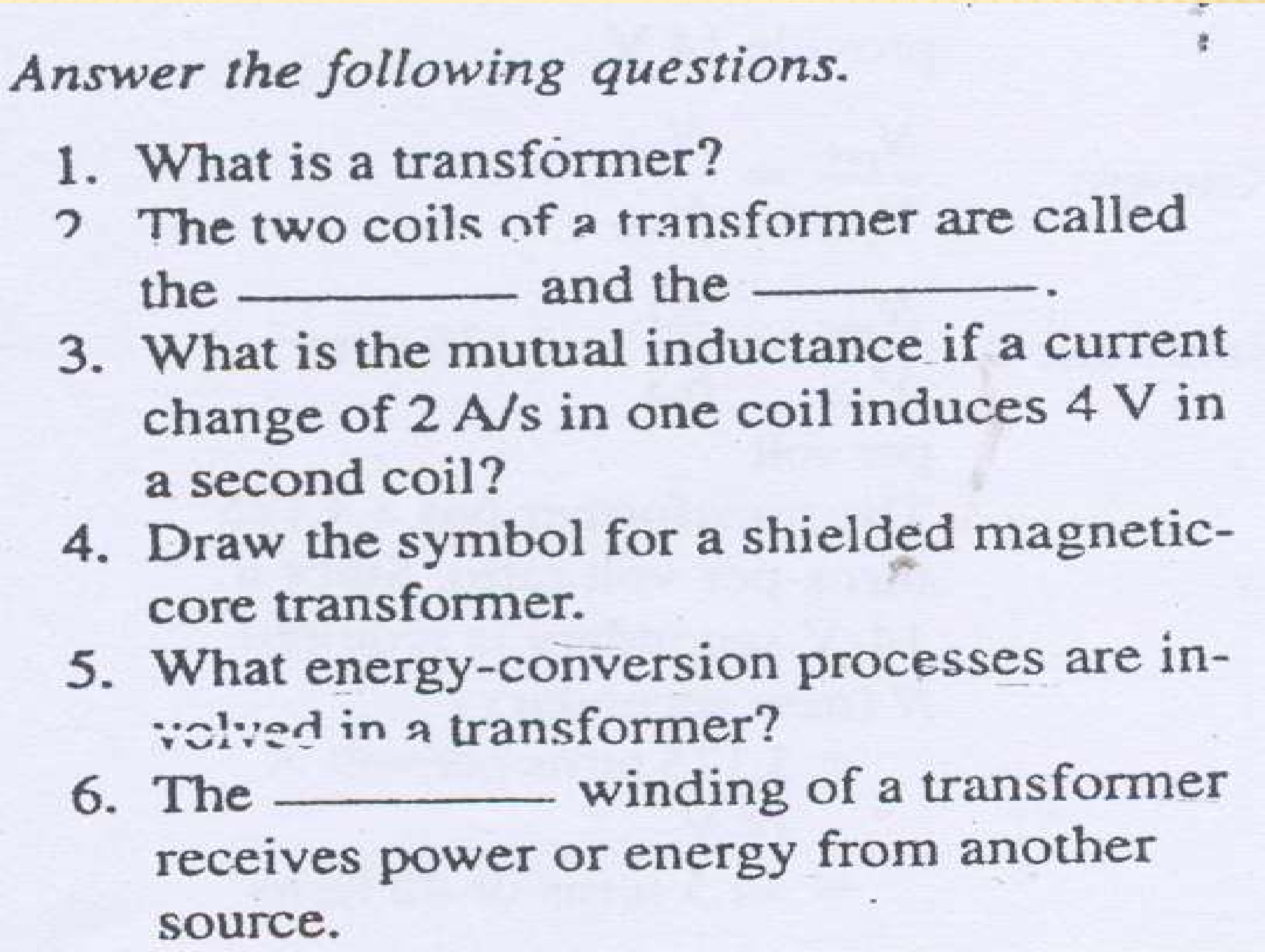

Answer the following questions.

1. What is a transformer?
2. The two coils of a transformer are called the ________ and the ________.
3. What is the mutual inductance if a current change of 2 A/s in one coil induces 4 V in a second coil?
4. Draw the symbol for a shielded magnetic-core transformer.
5. What energy-conversion processes are involved in a transformer?
6. The ________ winding of a transformer receives power or energy from another source.

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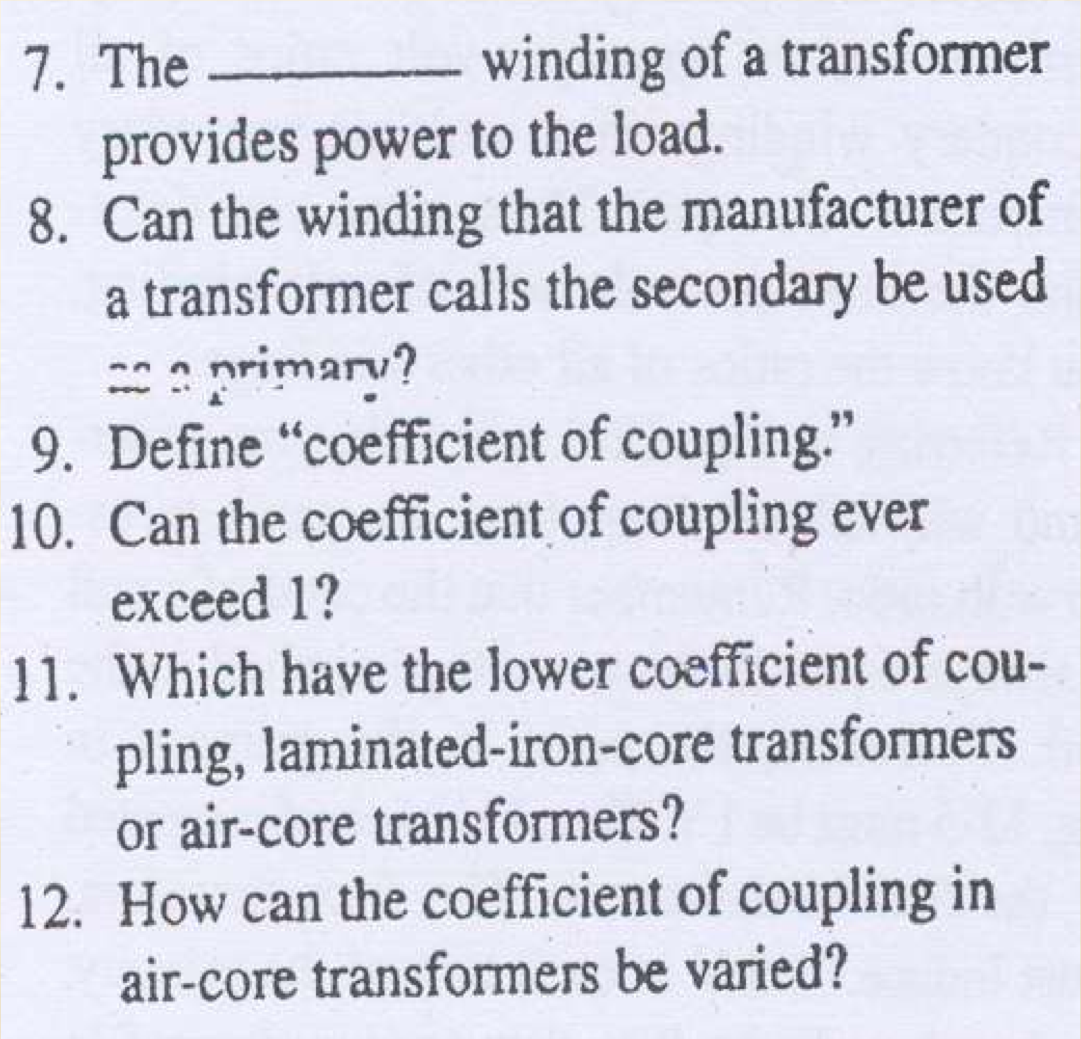

7. The ________ winding of a transformer provides power to the load.
8. Can the winding that the manufacturer of a transformer calls the secondary be used as a primary?
9. Define "coefficient of coupling."
10. Can the coefficient of coupling ever exceed 1?
11. Which have the lower coefficient of coupling, laminated-iron-core transformers or air-core transformers?
12. How can the coefficient of coupling in air-core transformers be varied?

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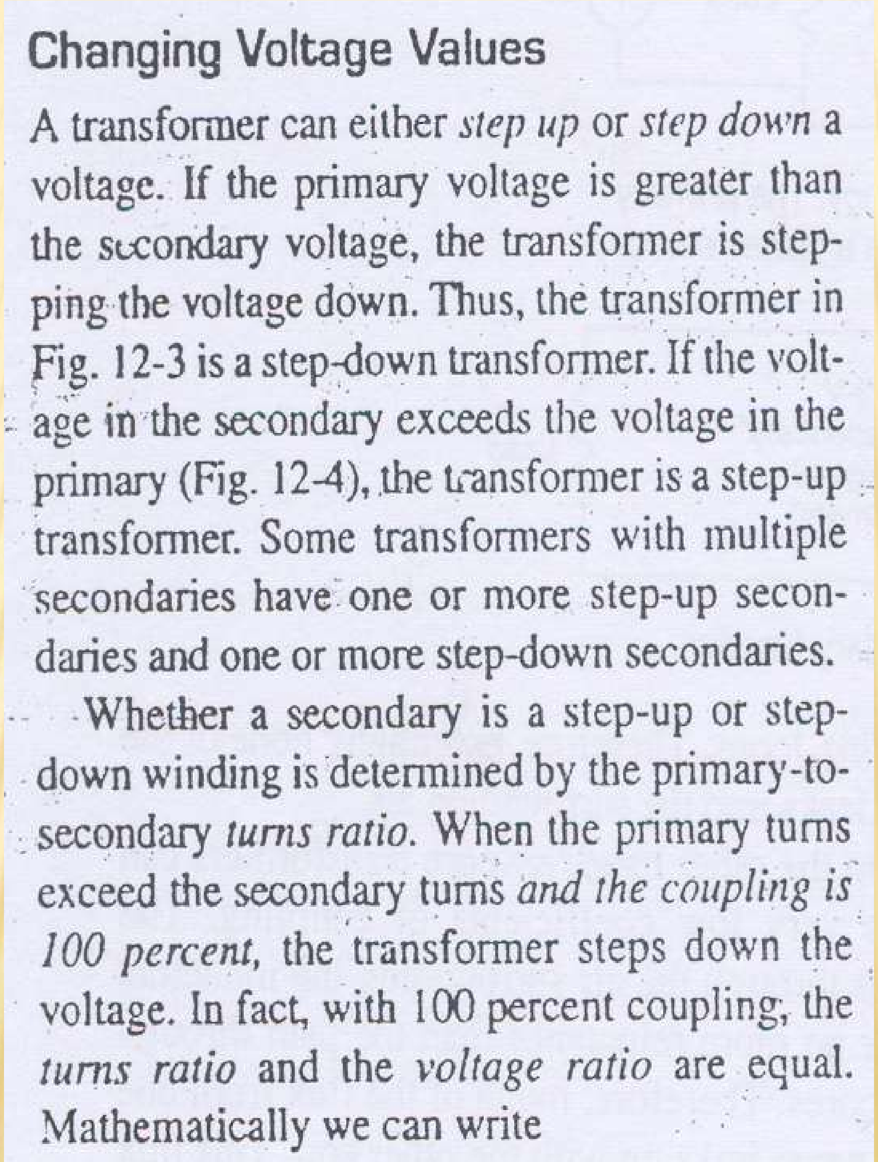

Changing Voltage Values

A transformer can either *step up* or *step down* a voltage. If the primary voltage is greater than the secondary voltage, the transformer is stepping the voltage down. Thus, the transformer in Fig. 12-3 is a step-down transformer. If the voltage in the secondary exceeds the voltage in the primary (Fig. 12-4), the transformer is a step-up transformer. Some transformers with multiple secondaries have one or more step-up secondaries and one or more step-down secondaries.

Whether a secondary is a step-up or step-down winding is determined by the primary-to-secondary *turns ratio*. When the primary turns exceed the secondary turns *and the coupling is 100 percent*, the transformer steps down the voltage. In fact, with 100 percent coupling, the *turns ratio* and the *voltage ratio* are equal. Mathematically we can write

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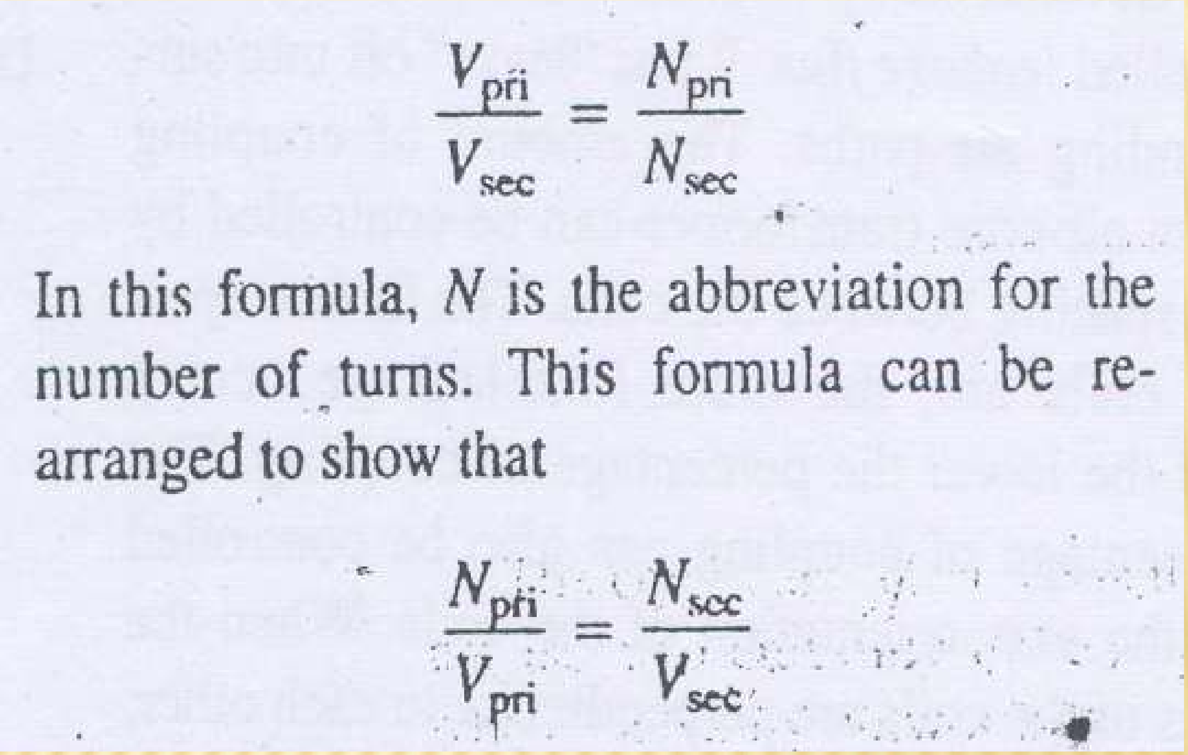

$$\frac{V_{pri}}{V_{sec}} = \frac{N_{pri}}{N_{sec}}$$

In this formula, *N* is the abbreviation for the number of turns. This formula can be rearranged to show that

$$\frac{N_{pri}}{V_{pri}} = \frac{N_{sec}}{V_{sec}}$$

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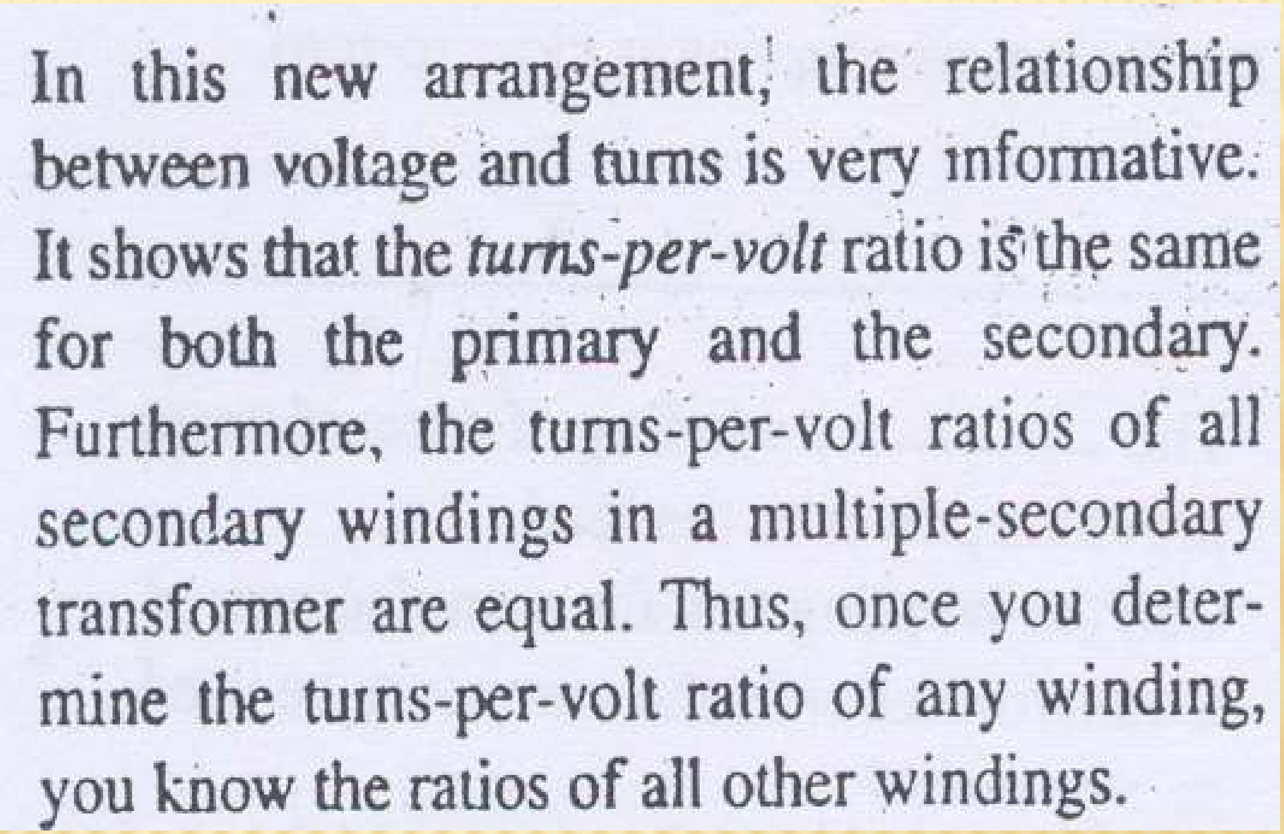

In this new arrangement, the relationship between voltage and turns is very informative. It shows that the *turns-per-volt* ratio is the same for both the primary and the secondary. Furthermore, the turns-per-volt ratios of all secondary windings in a multiple-secondary transformer are equal. Thus, once you determine the turns-per-volt ratio of any winding, you know the ratios of all other windings.

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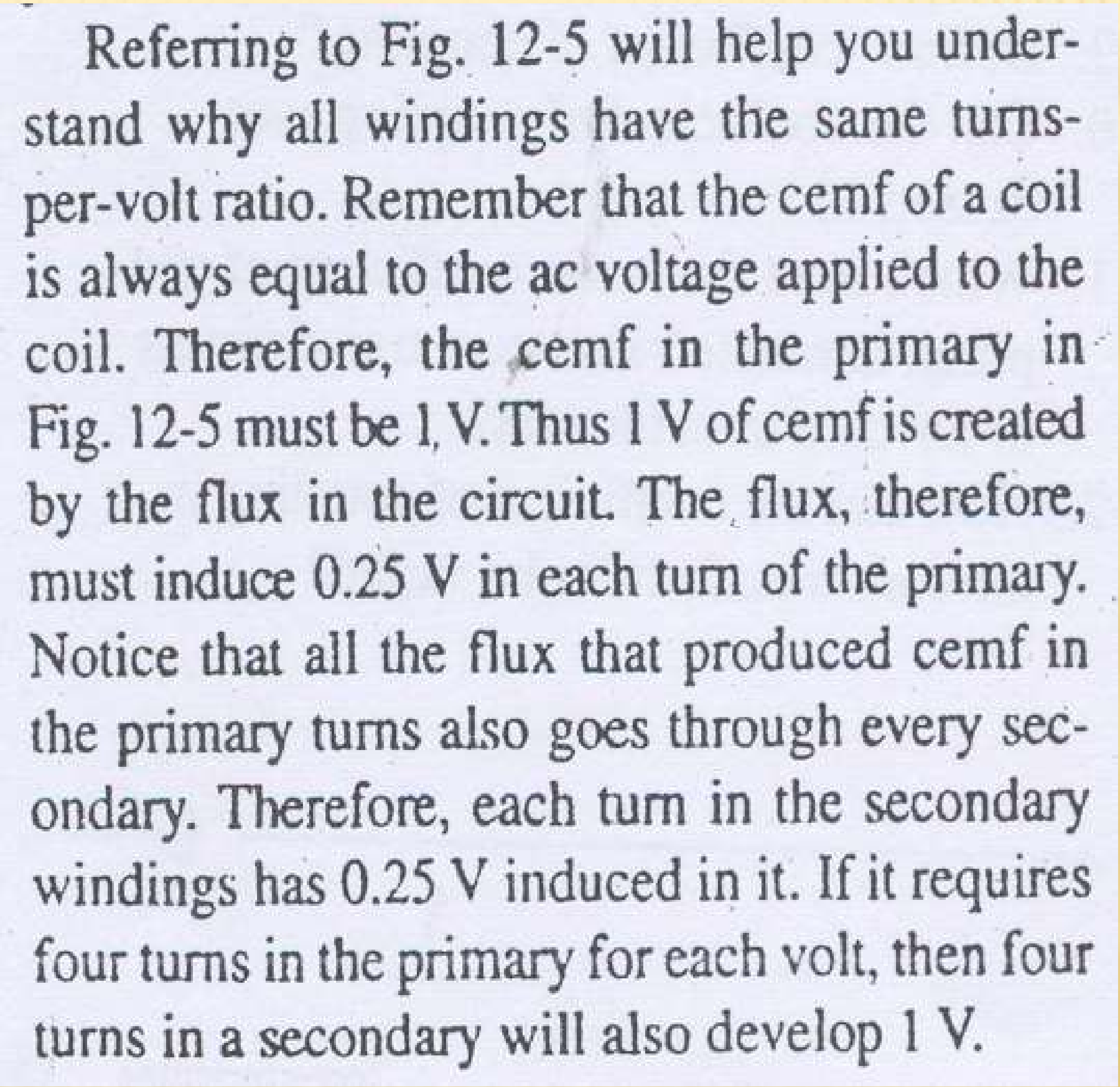

Referring to Fig. 12-5 will help you understand why all windings have the same turns-per-volt ratio. Remember that the cemf of a coil is always equal to the ac voltage applied to the coil. Therefore, the cemf in the primary in Fig. 12-5 must be 1 V. Thus 1 V of cemf is created by the flux in the circuit. The flux, therefore, must induce 0.25 V in each turn of the primary. Notice that all the flux that produced cemf in the primary turns also goes through every secondary. Therefore, each turn in the secondary windings has 0.25 V induced in it. If it requires four turns in the primary for each volt, then four turns in a secondary will also develop 1 V.

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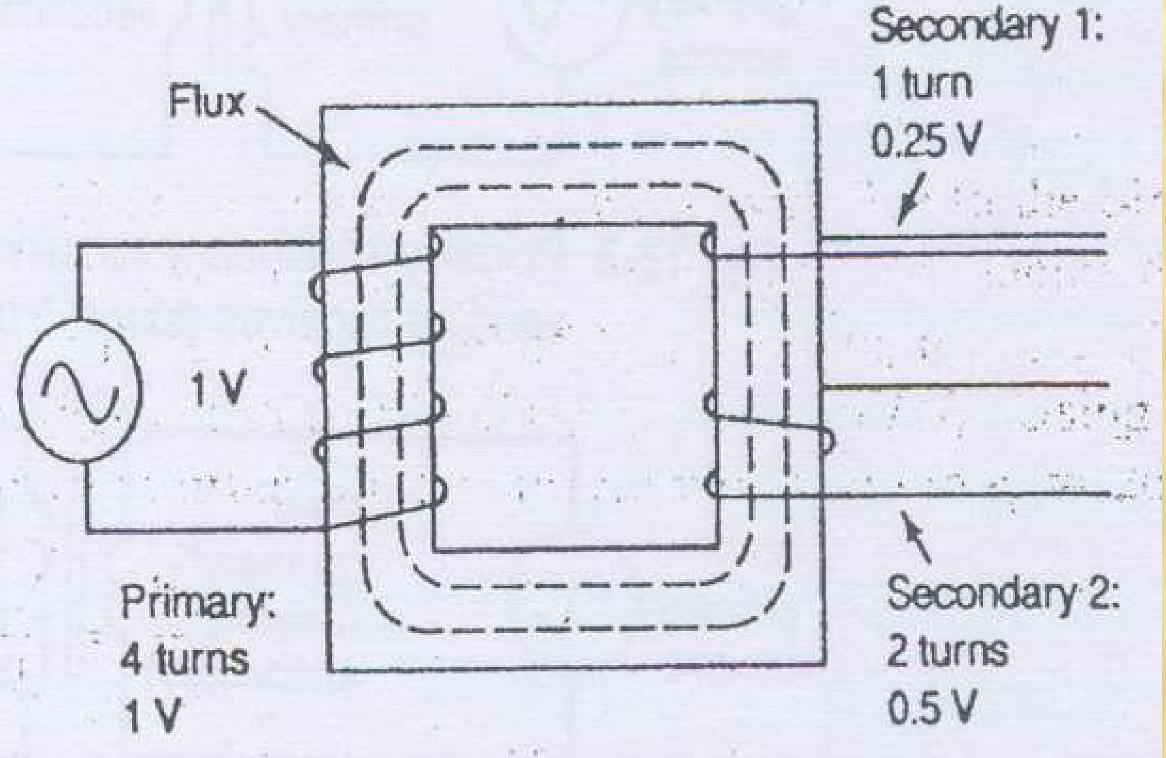

Fig. 12-5 Turns per volt. The turns-per-volt ratio is the same in all windings.

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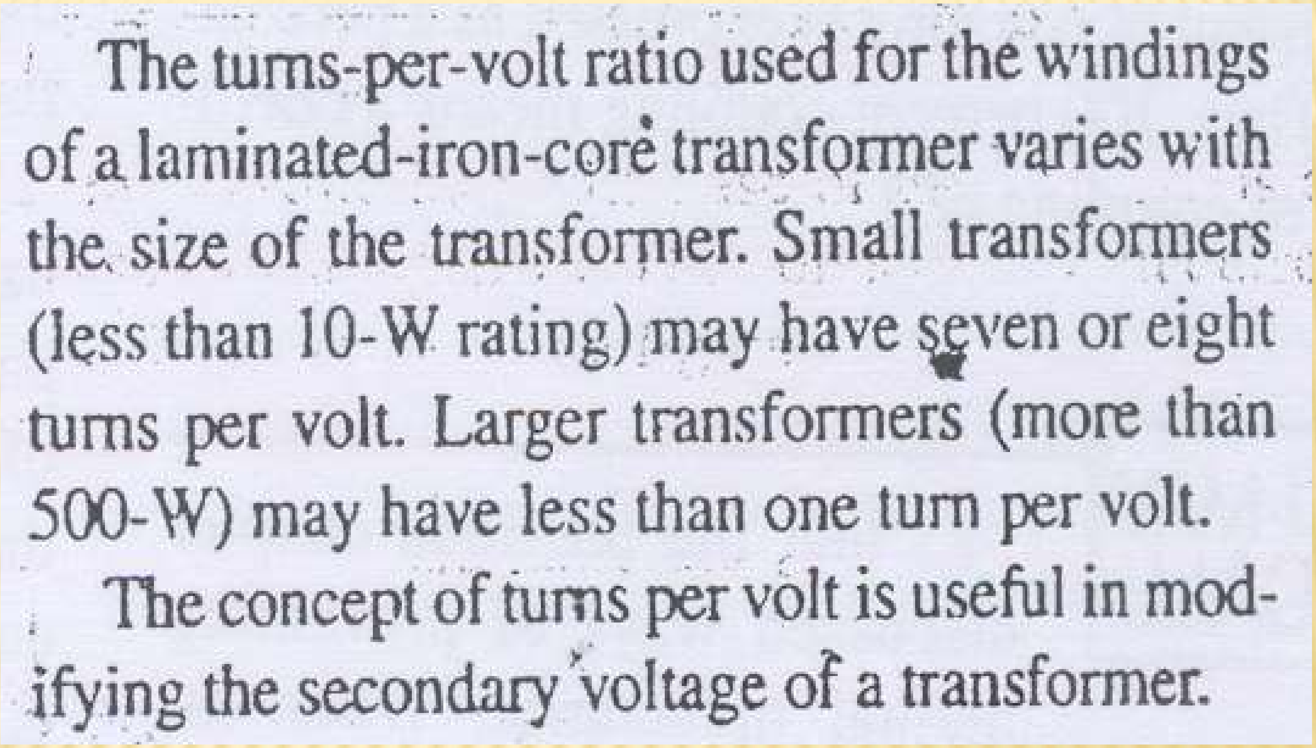

The turns-per-volt ratio used for the windings of a laminated-iron-core transformer varies with the size of the transformer. Small transformers (less than 10-W rating) may have seven or eight turns per volt. Larger transformers (more than 500-W) may have less than one turn per volt.

The concept of turns per volt is useful in modifying the secondary voltage of a transformer.

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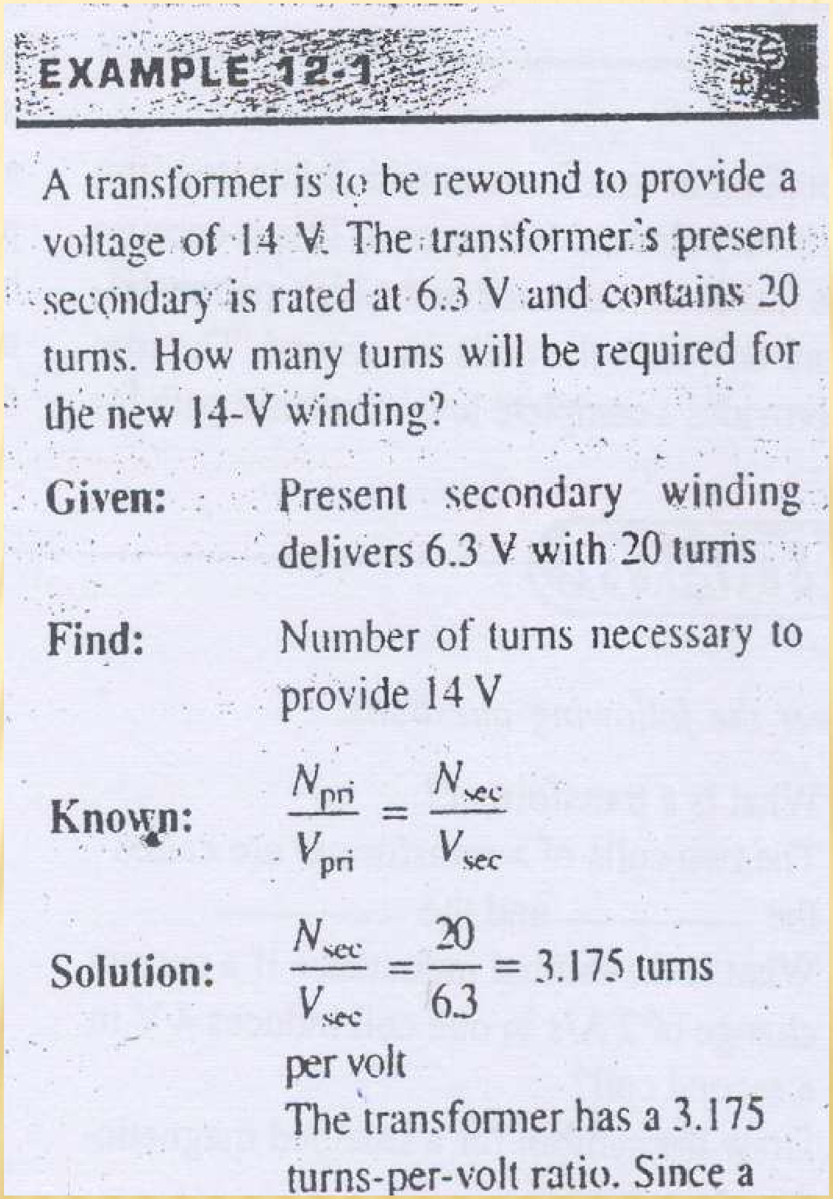

EXAMPLE 12-1

A transformer is to be rewound to provide a voltage of 14 V. The transformer's present secondary is rated at 6.3 V and contains 20 turns. How many turns will be required for the new 14-V winding?

Given: Present secondary winding delivers 6.3 V with 20 turns

Find: Number of turns necessary to provide 14 V

Known: $\frac{N_{pri}}{V_{pri}} = \frac{N_{sec}}{V_{sec}}$

Solution: $\frac{N_{sec}}{V_{sec}} = \frac{20}{6.3} = 3.175$ turns per volt

The transformer has a 3.175 turns-per-volt ratio. Since a

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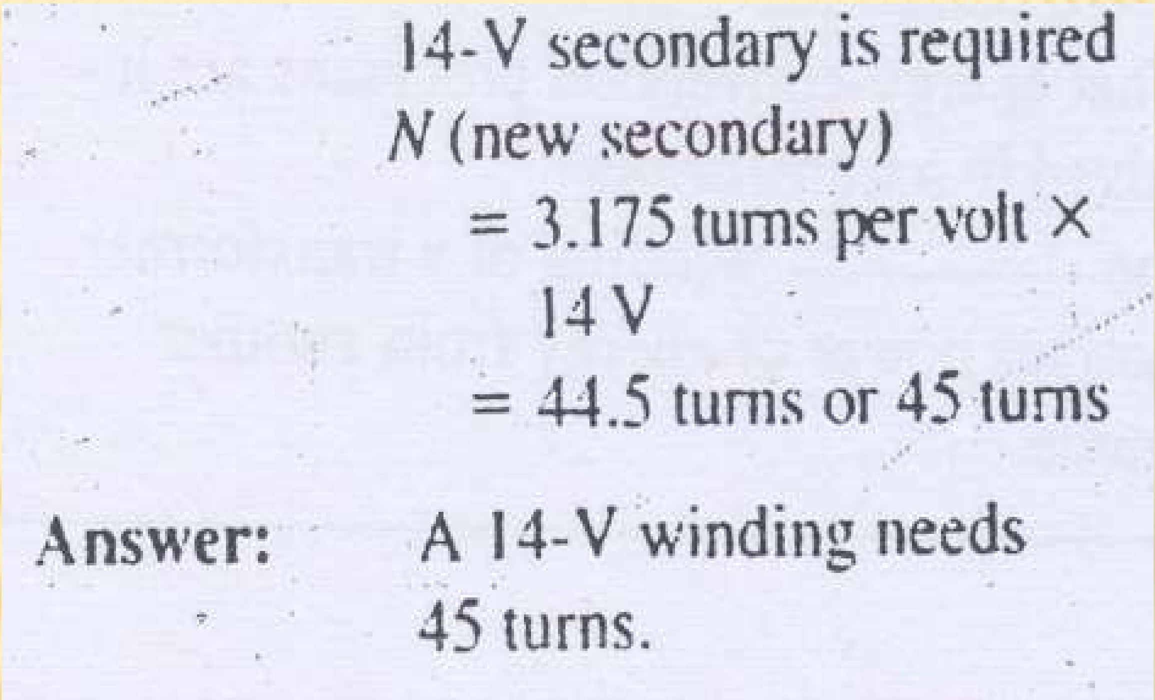

14-V secondary is required

N (new secondary)

$= 3.175$ turns per volt × 14 V

$= 44.5$ turns or 45 turns

Answer: A 14-V winding needs 45 turns.

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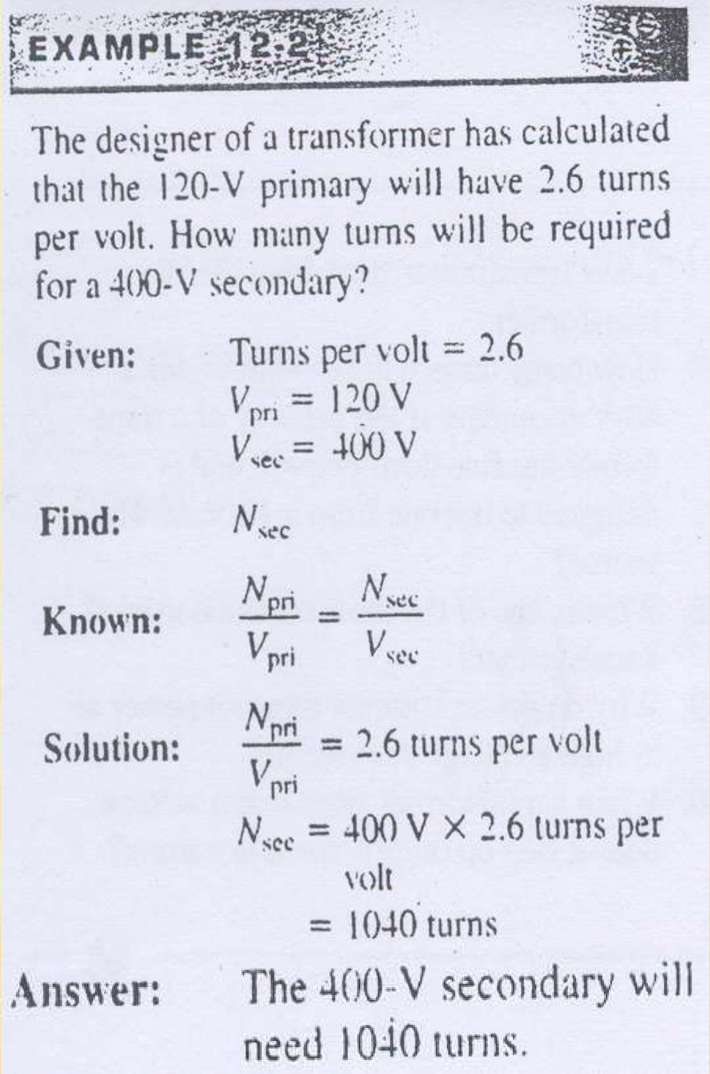

EXAMPLE 12-2

The designer of a transformer has calculated that the 120-V primary will have 2.6 turns per volt. How many turns will be required for a 400-V secondary?

Given: Turns per volt = 2.6

$V_{\text{pri}} = 120\text{ V}$

$V_{\text{sec}} = 400\text{ V}$

Find: N_{sec}

Known: $\dfrac{N_{\text{pri}}}{V_{\text{pri}}} = \dfrac{N_{\text{sec}}}{V_{\text{sec}}}$

Solution: $\dfrac{N_{\text{pri}}}{V_{\text{pri}}} = 2.6$ turns per volt

$N_{\text{sec}} = 400\text{ V} \times 2.6$ turns per volt

$= 1040$ turns

Answer: The 400-V secondary will need 1040 turns.

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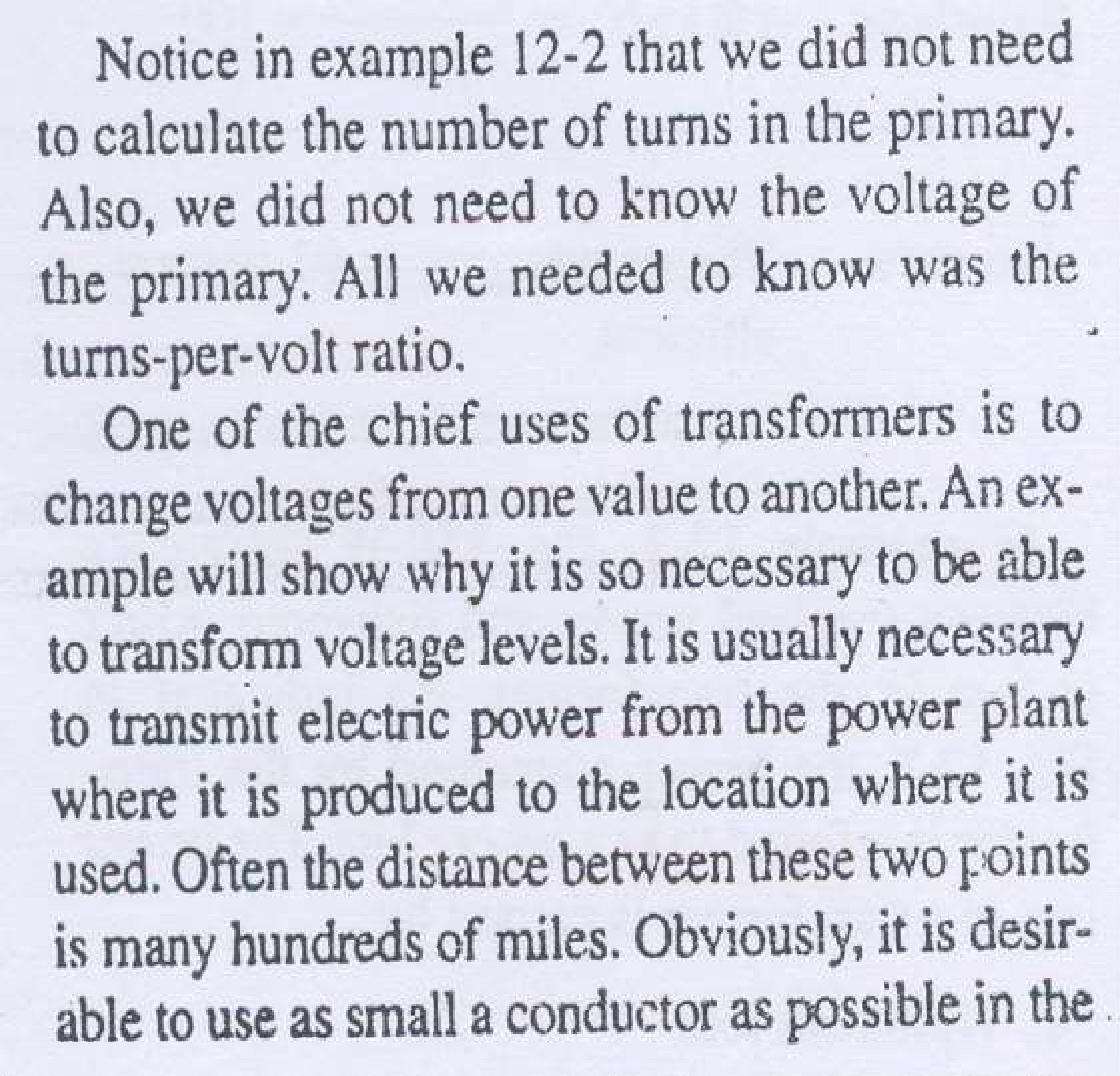

Notice in example 12-2 that we did not need to calculate the number of turns in the primary. Also, we did not need to know the voltage of the primary. All we needed to know was the turns-per-volt ratio.

One of the chief uses of transformers is to change voltages from one value to another. An example will show why it is so necessary to be able to transform voltage levels. It is usually necessary to transmit electric power from the power plant where it is produced to the location where it is used. Often the distance between these two points is many hundreds of miles. Obviously, it is desirable to use as small a conductor as possible in the

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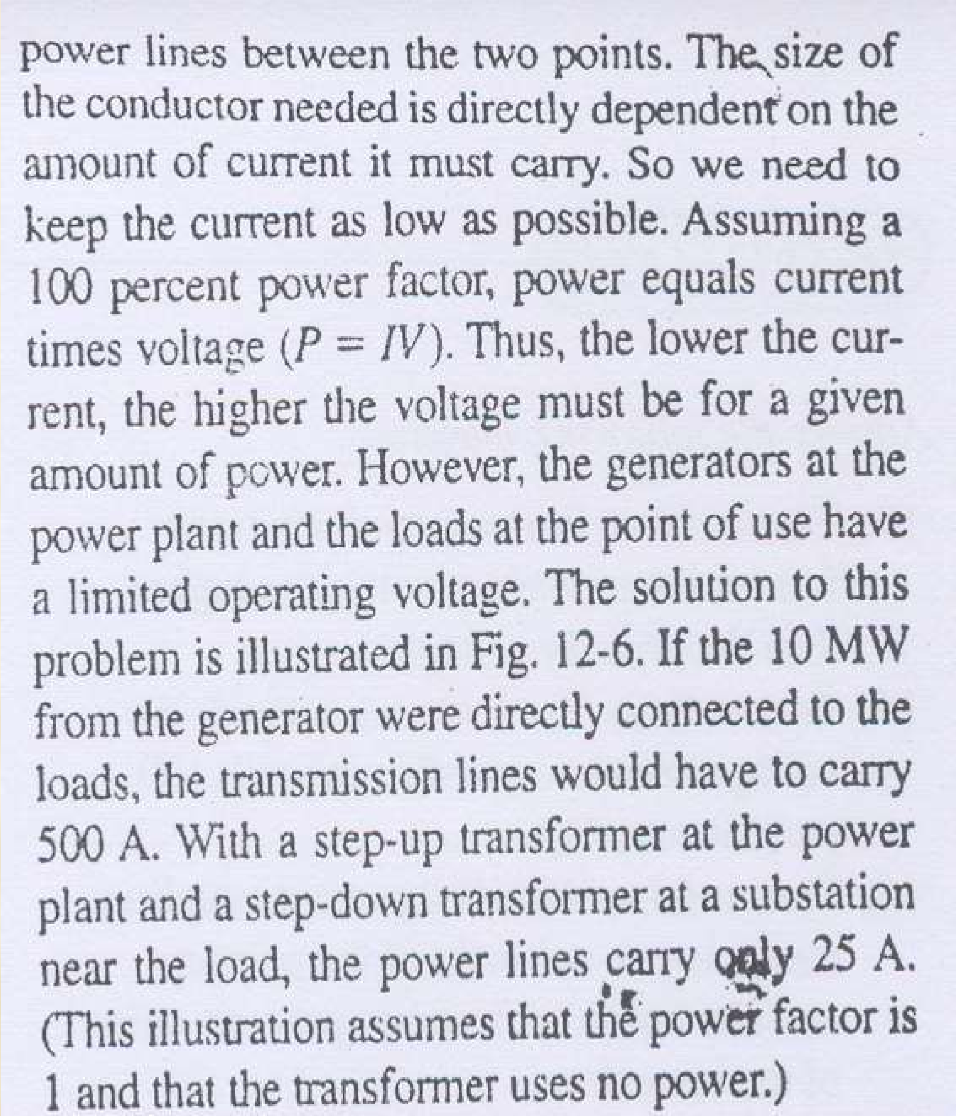

power lines between the two points. The size of the conductor needed is directly dependent on the amount of current it must carry. So we need to keep the current as low as possible. Assuming a 100 percent power factor, power equals current times voltage ($P = IV$). Thus, the lower the current, the higher the voltage must be for a given amount of power. However, the generators at the power plant and the loads at the point of use have a limited operating voltage. The solution to this problem is illustrated in Fig. 12-6. If the 10 MW from the generator were directly connected to the loads, the transmission lines would have to carry 500 A. With a step-up transformer at the power plant and a step-down transformer at a substation near the load, the power lines carry only 25 A. (This illustration assumes that the power factor is 1 and that the transformer uses no power.)

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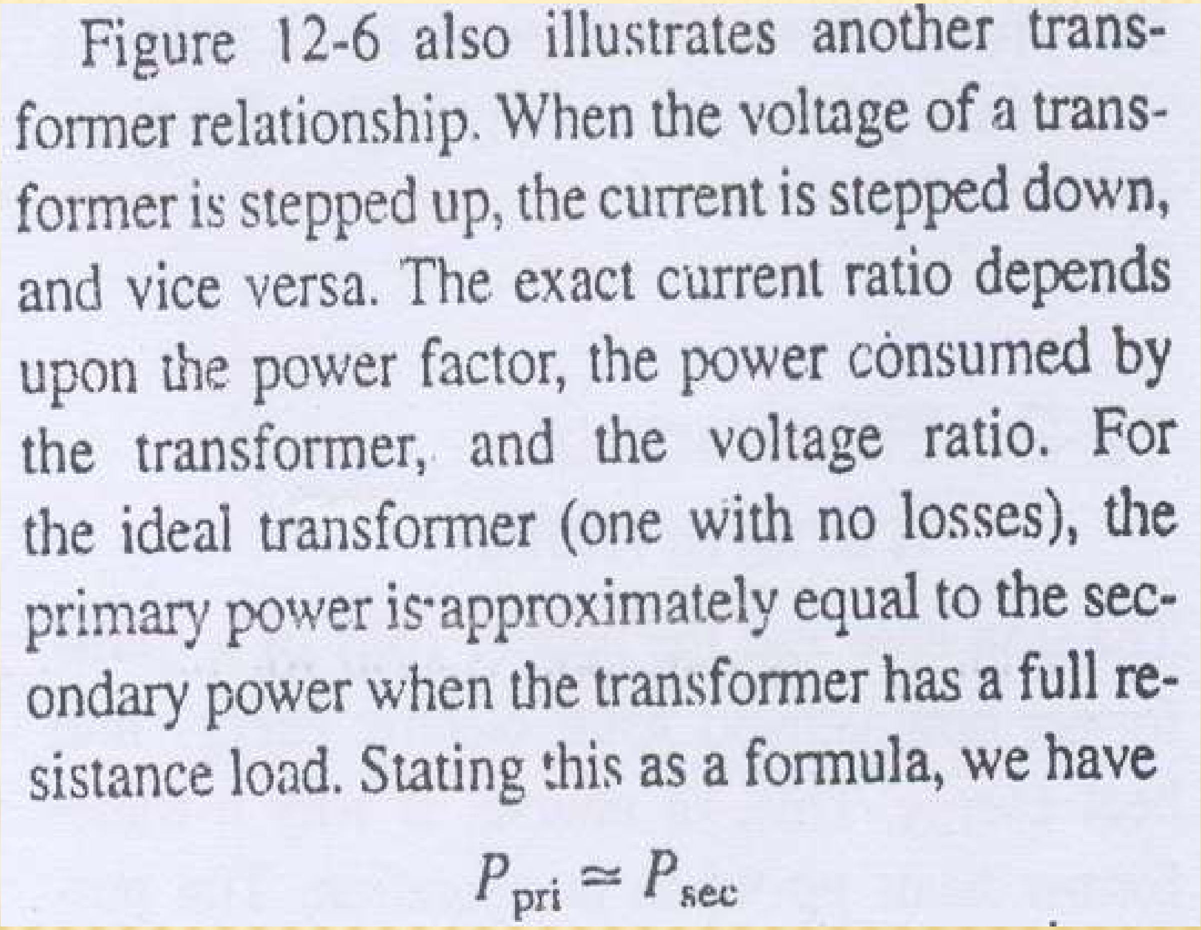

Figure 12-6 also illustrates another transformer relationship. When the voltage of a transformer is stepped up, the current is stepped down, and vice versa. The exact current ratio depends upon the power factor, the power consumed by the transformer, and the voltage ratio. For the ideal transformer (one with no losses), the primary power is approximately equal to the secondary power when the transformer has a full resistance load. Stating this as a formula, we have

$$P_{\text{pri}} \simeq P_{\text{sec}}$$

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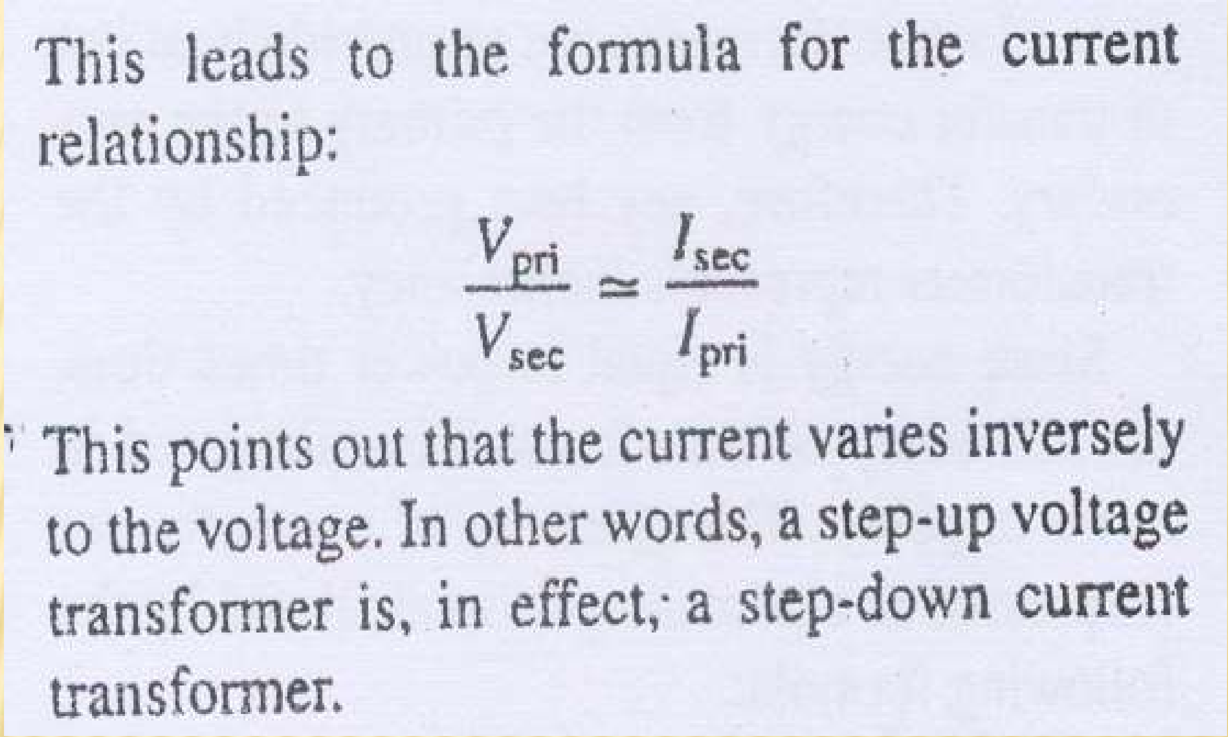

This leads to the formula for the current relationship:

$$\frac{V_{\text{pri}}}{V_{\text{sec}}} \simeq \frac{I_{\text{sec}}}{I_{\text{pri}}}$$

This points out that the current varies inversely to the voltage. In other words, a step-up voltage transformer is, in effect, a step-down current transformer.

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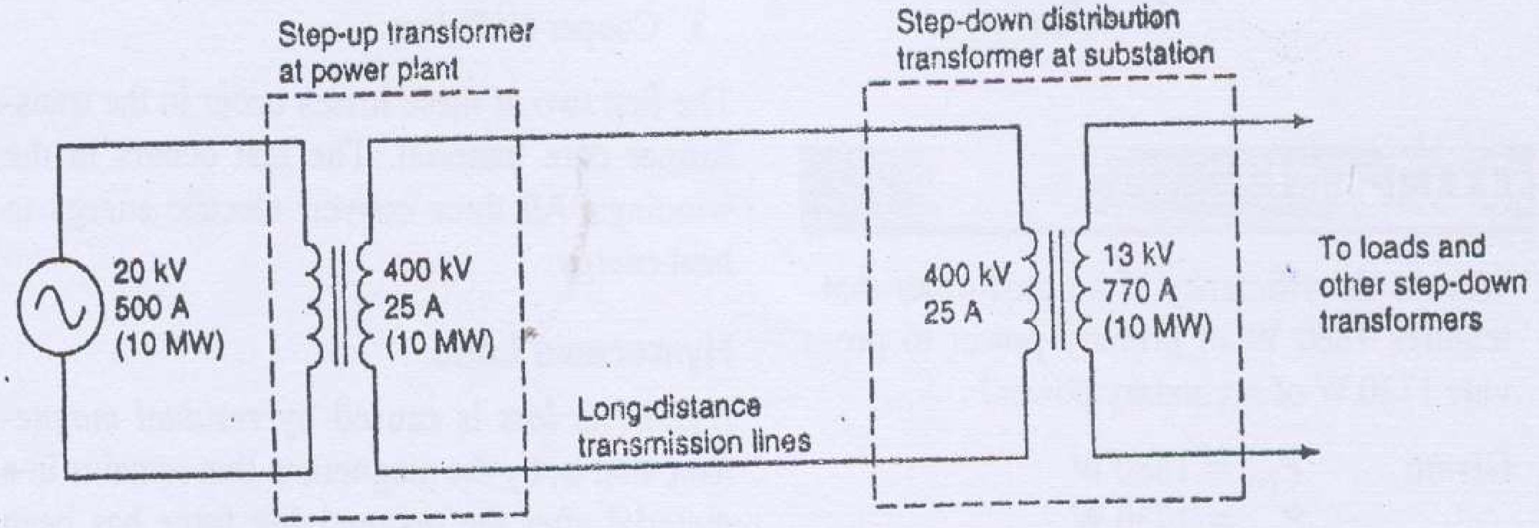

Fig. 12-6 Advantage of high-voltage power lines. The higher the voltage, the lower the current for a given amount of power.

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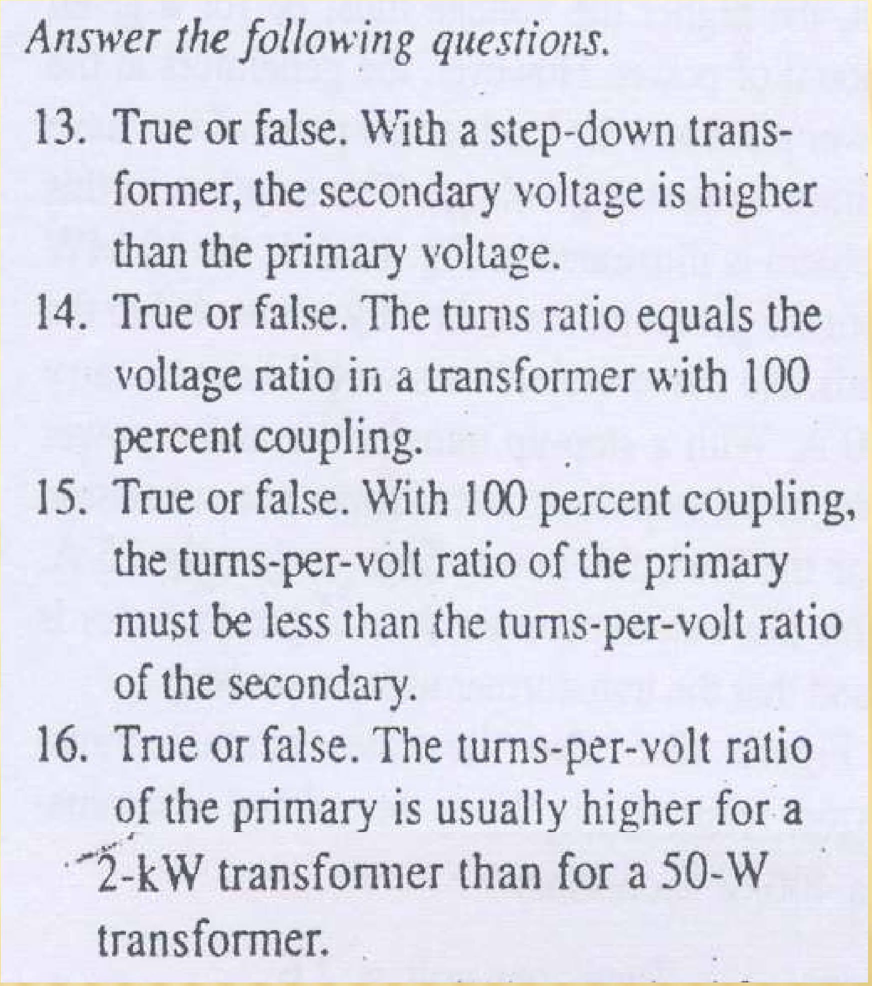

Answer the following questions.

13. True or false. With a step-down transformer, the secondary voltage is higher than the primary voltage.
14. True or false. The turns ratio equals the voltage ratio in a transformer with 100 percent coupling.
15. True or false. With 100 percent coupling, the turns-per-volt ratio of the primary must be less than the turns-per-volt ratio of the secondary.
16. True or false. The turns-per-volt ratio of the primary is usually higher for a 2-kW transformer than for a 50-W transformer.

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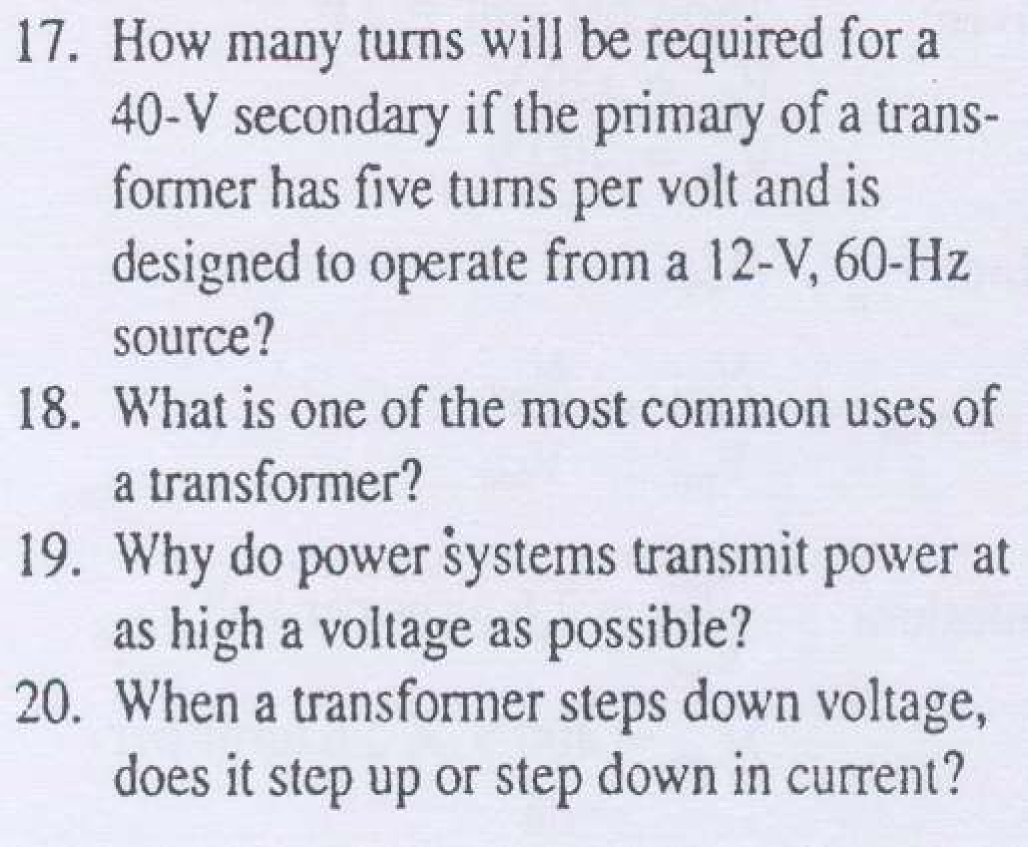

17. How many turns will be required for a 40-V secondary if the primary of a transformer has five turns per volt and is designed to operate from a 12-V, 60-Hz source?
18. What is one of the most common uses of a transformer?
19. Why do power systems transmit power at as high a voltage as possible?
20. When a transformer steps down voltage, does it step up or step down in current?

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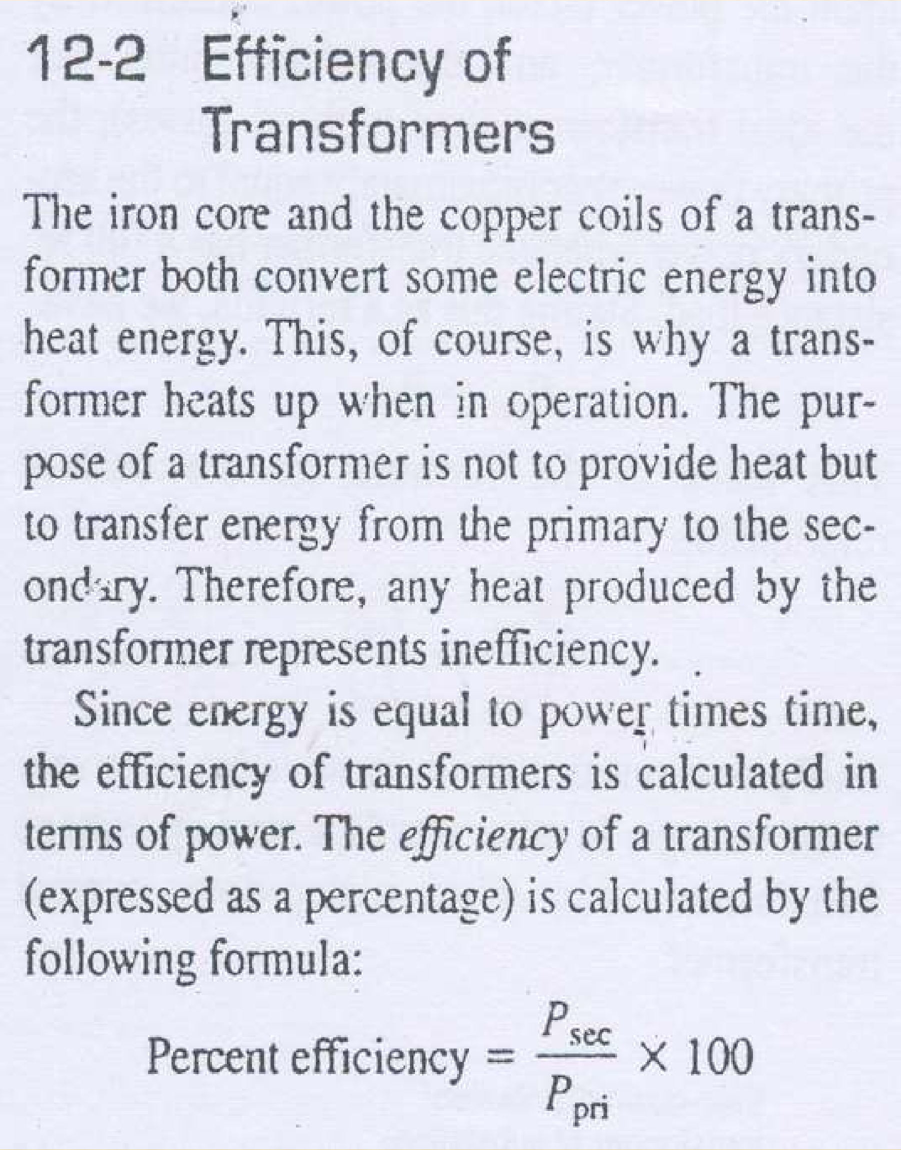

12-2 Efficiency of Transformers

The iron core and the copper coils of a transformer both convert some electric energy into heat energy. This, of course, is why a transformer heats up when in operation. The purpose of a transformer is not to provide heat but to transfer energy from the primary to the secondary. Therefore, any heat produced by the transformer represents inefficiency.

Since energy is equal to power times time, the efficiency of transformers is calculated in terms of power. The *efficiency* of a transformer (expressed as a percentage) is calculated by the following formula:

$$\text{Percent efficiency} = \frac{P_{\text{sec}}}{P_{\text{pri}}} \times 100$$

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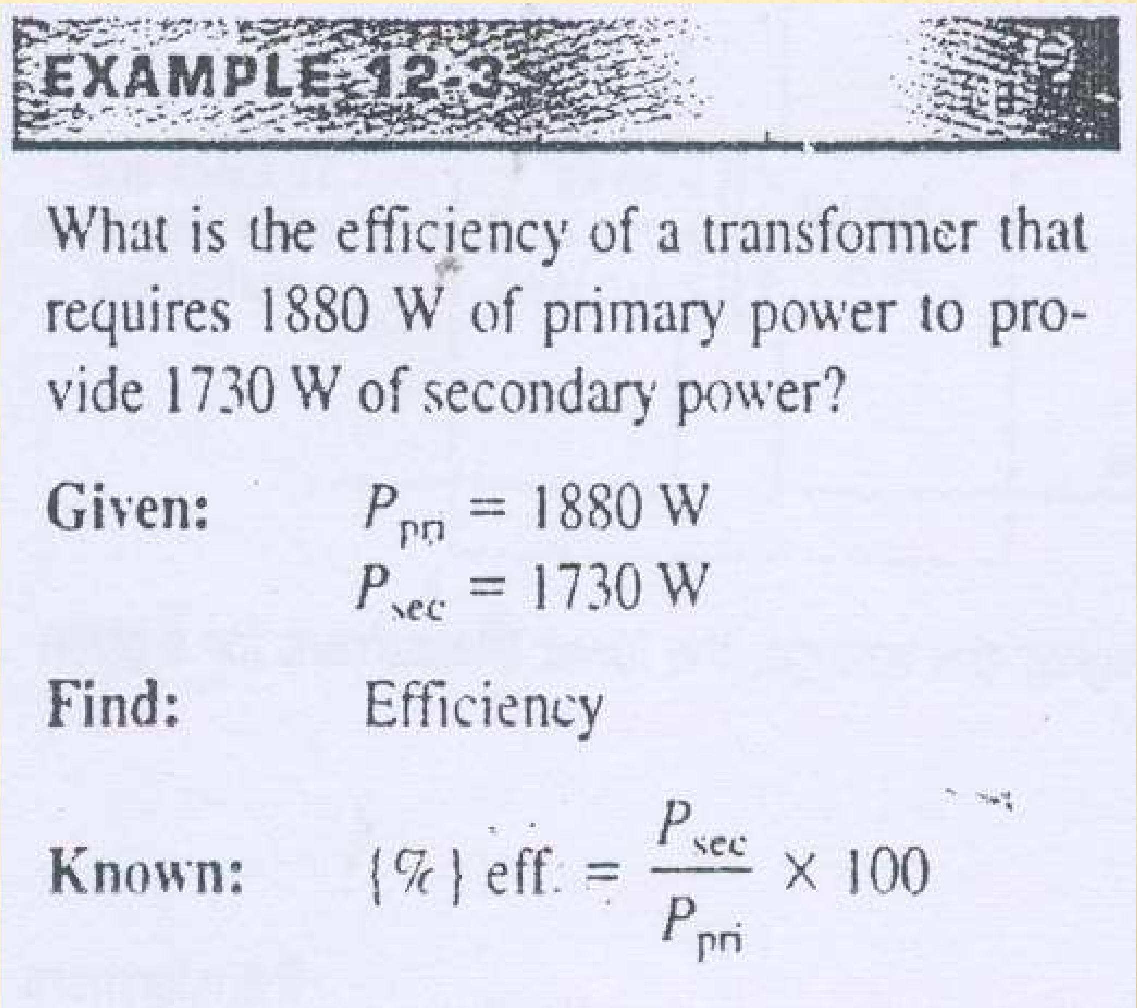

EXAMPLE 12-3

What is the efficiency of a transformer that requires 1880 W of primary power to provide 1730 W of secondary power?

Given: $P_{pri} = 1880\text{ W}$
$P_{sec} = 1730\text{ W}$

Find: Efficiency

Known: $$\{\%\}\text{ eff.} = \frac{P_{sec}}{P_{pri}} \times 100$$

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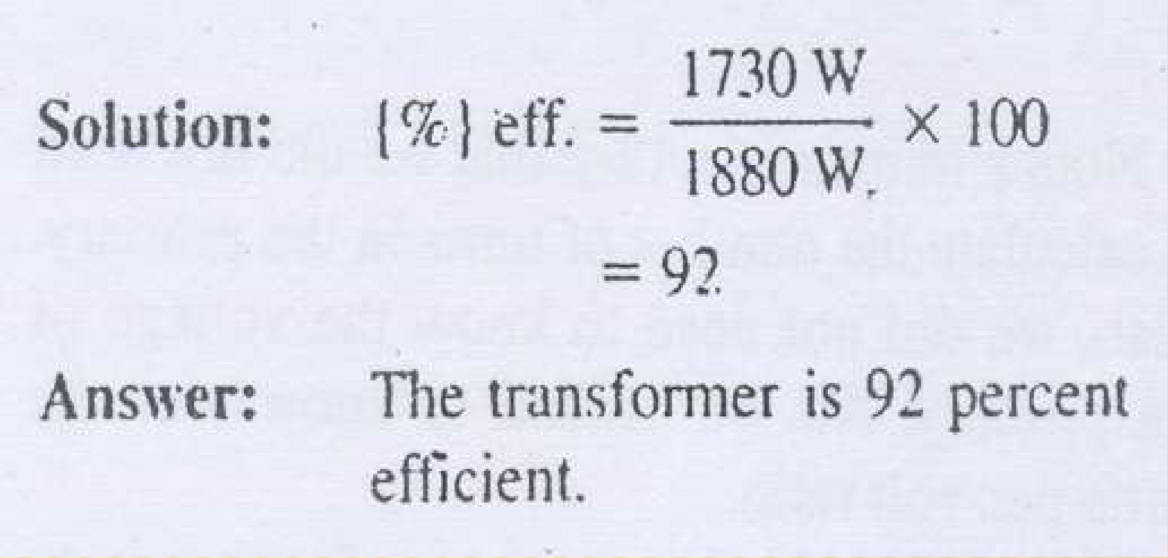

Solution:

$$\{\%\}\ \text{eff.} = \frac{1730\ \text{W}}{1880\ \text{W}} \times 100$$

$$= 92$$

Answer: The transformer is 92 percent efficient.

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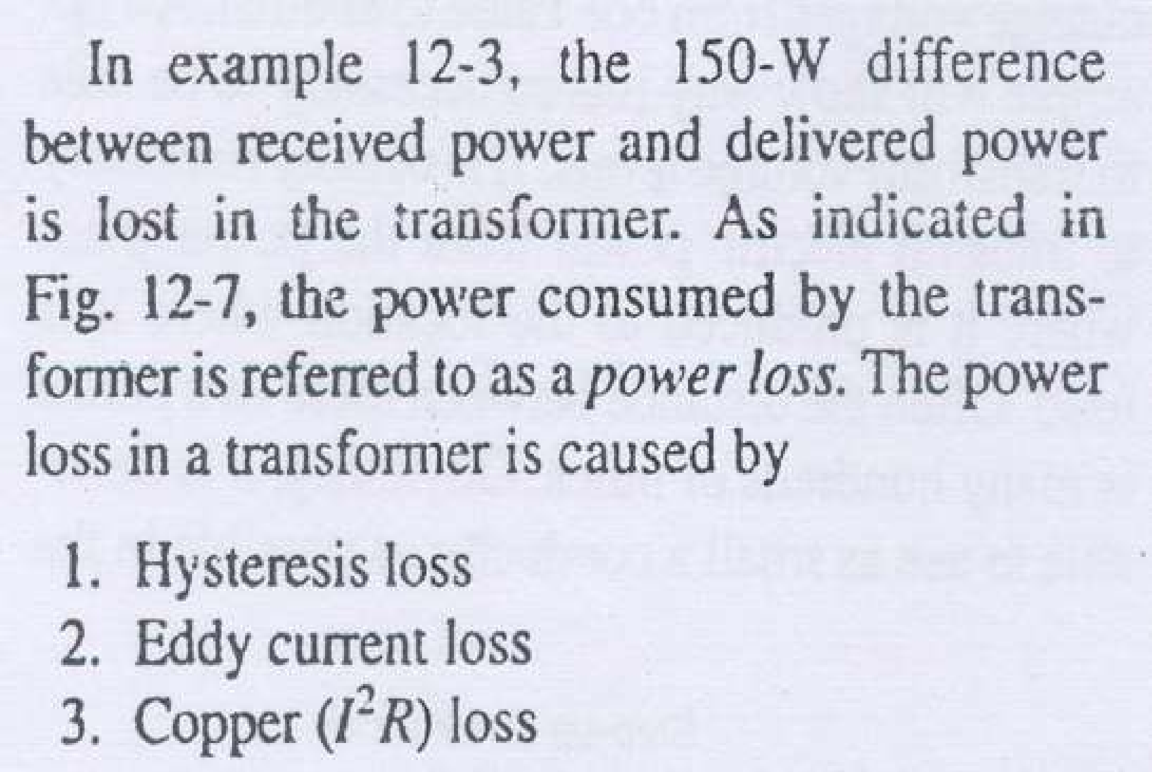

In example 12-3, the 150-W difference between received power and delivered power is lost in the transformer. As indicated in Fig. 12-7, the power consumed by the transformer is referred to as a *power loss.* The power loss in a transformer is caused by

1. Hysteresis loss
2. Eddy current loss
3. Copper (I^2R) loss

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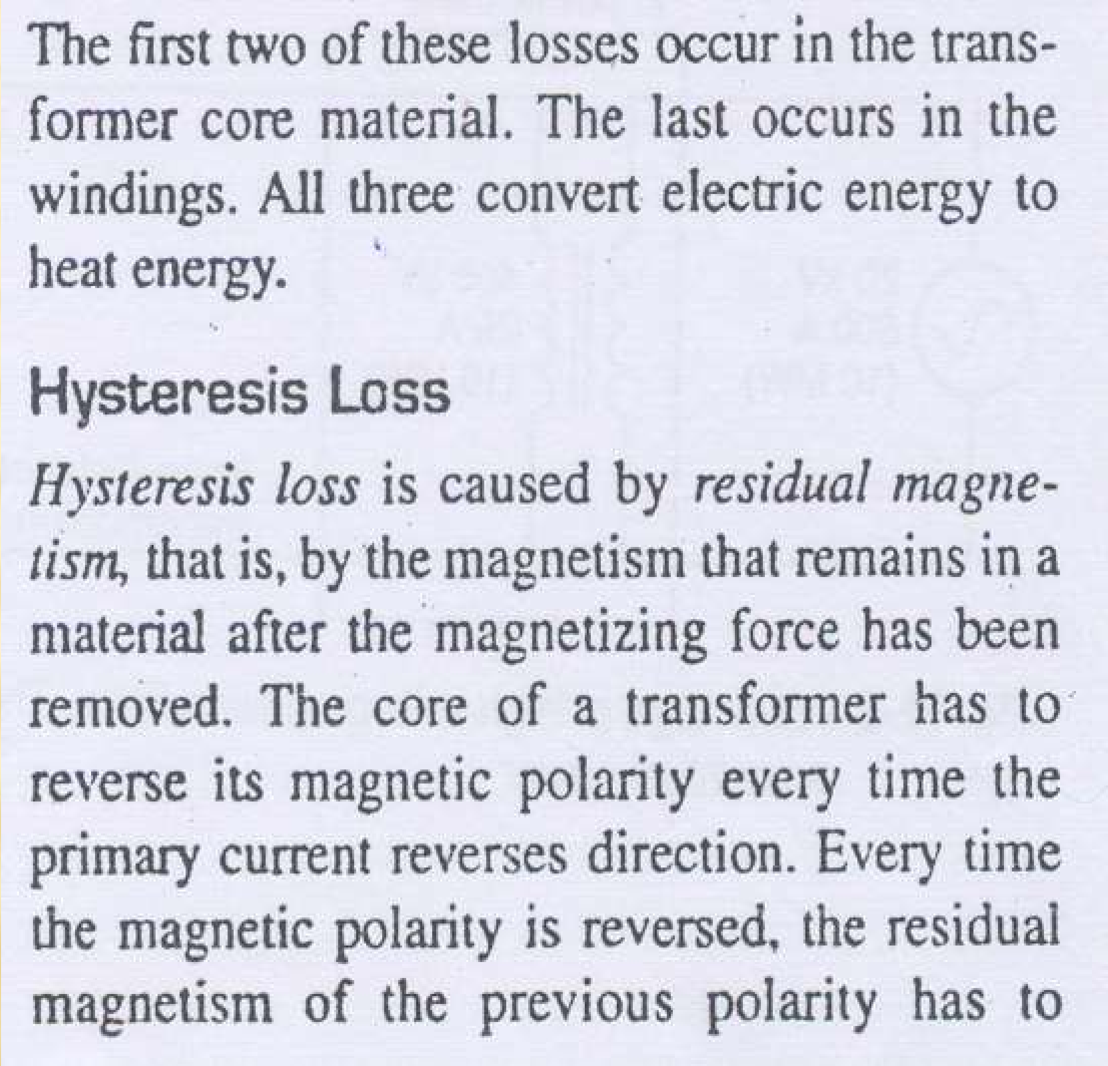

The first two of these losses occur in the transformer core material. The last occurs in the windings. All three convert electric energy to heat energy.

Hysteresis Loss

Hysteresis loss is caused by *residual magnetism*, that is, by the magnetism that remains in a material after the magnetizing force has been removed. The core of a transformer has to reverse its magnetic polarity every time the primary current reverses direction. Every time the magnetic polarity is reversed, the residual magnetism of the previous polarity has to

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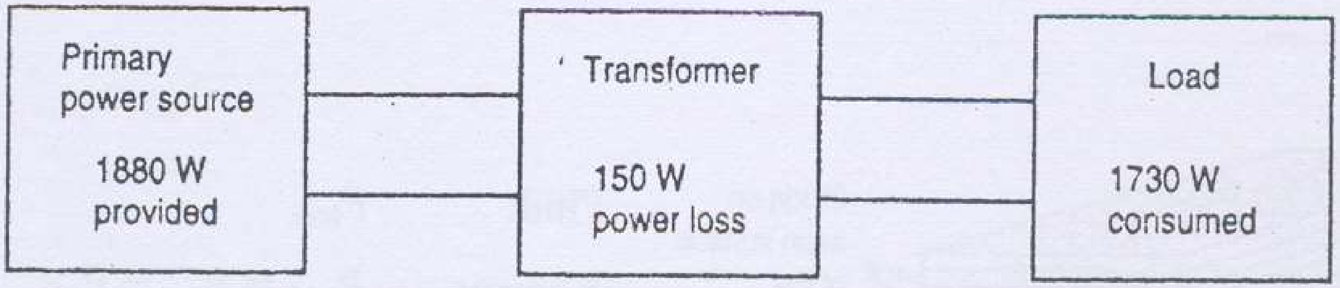
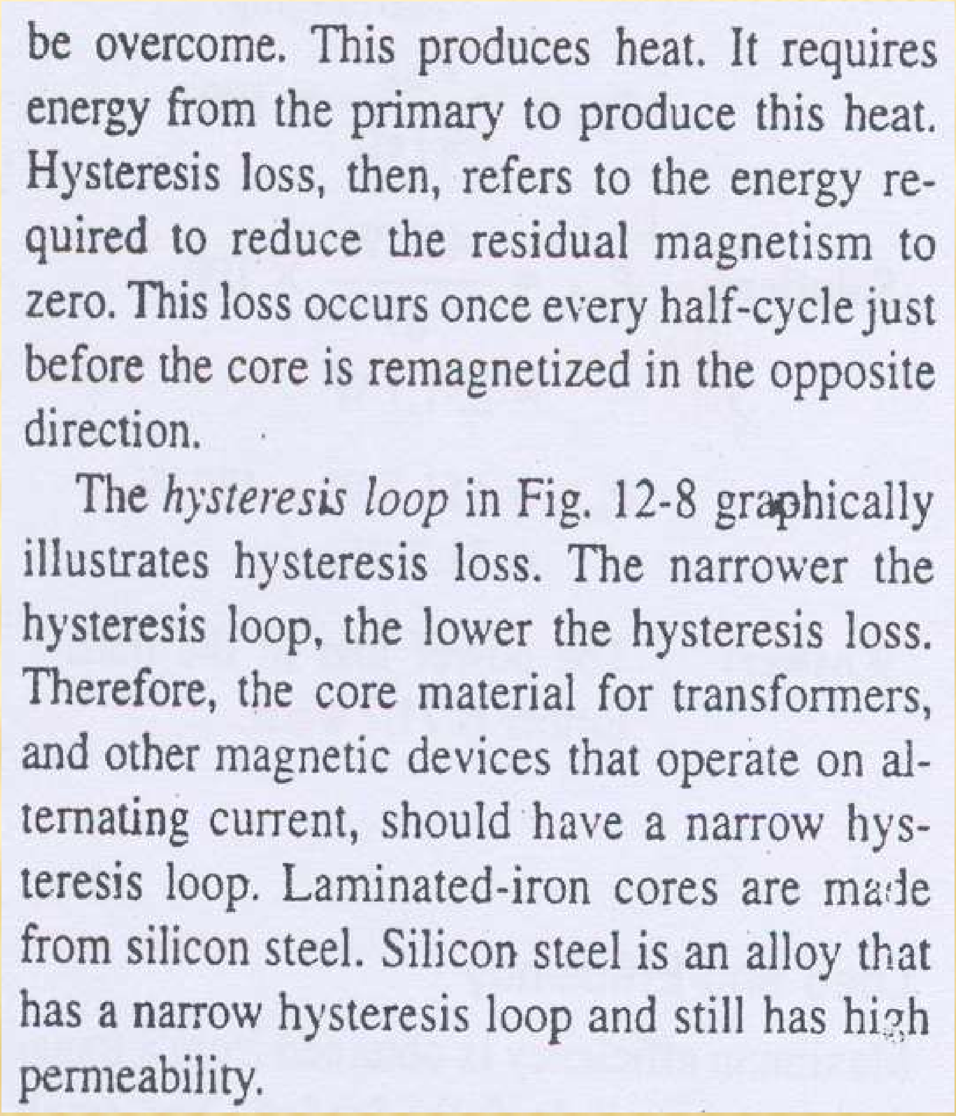


Fig. 12-7 Transformer efficiency. Power loss occurs because the transformer converts some electric energy into heat energy.

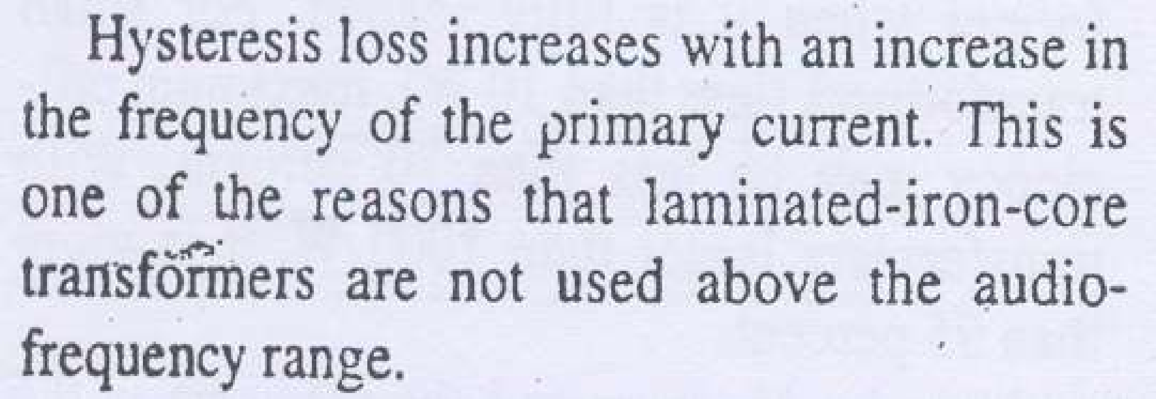
Transformers



be overcome. This produces heat. It requires energy from the primary to produce this heat. Hysteresis loss, then, refers to the energy required to reduce the residual magnetism to zero. This loss occurs once every half-cycle just before the core is remagnetized in the opposite direction.

The *hysteresis loop* in Fig. 12-8 graphically illustrates hysteresis loss. The narrower the hysteresis loop, the lower the hysteresis loss. Therefore, the core material for transformers, and other magnetic devices that operate on alternating current, should have a narrow hysteresis loop. Laminated-iron cores are made from silicon steel. Silicon steel is an alloy that has a narrow hysteresis loop and still has high permeability.

Transformers



Hysteresis loss increases with an increase in the frequency of the primary current. This is one of the reasons that laminated-iron-core transformers are not used above the audio-frequency range.

Transformers

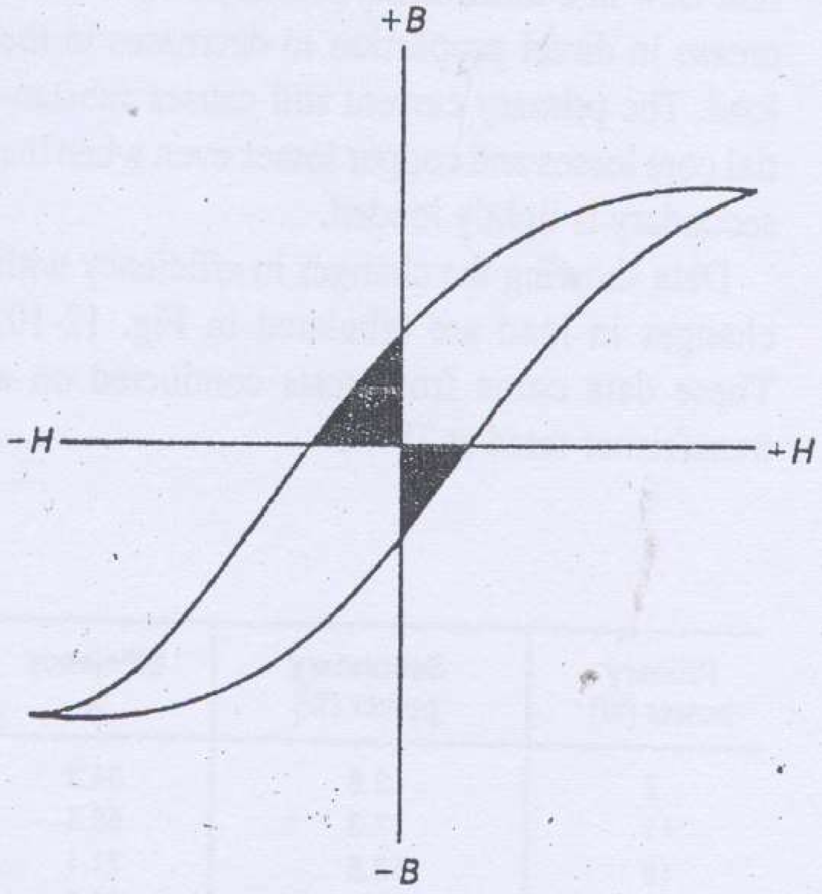
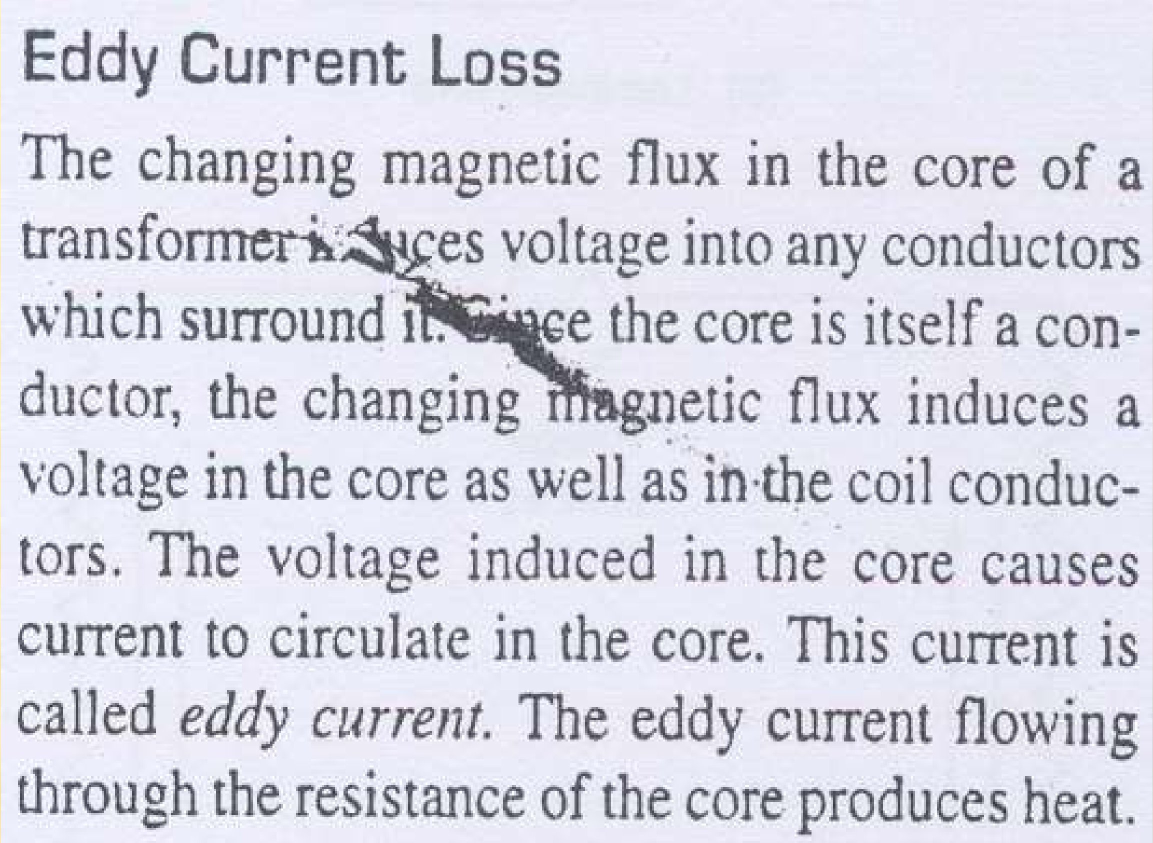


Fig. 12-8 Hysteresis loop. Magnetic energy is converted to heat energy in the shaded regions of the loop.

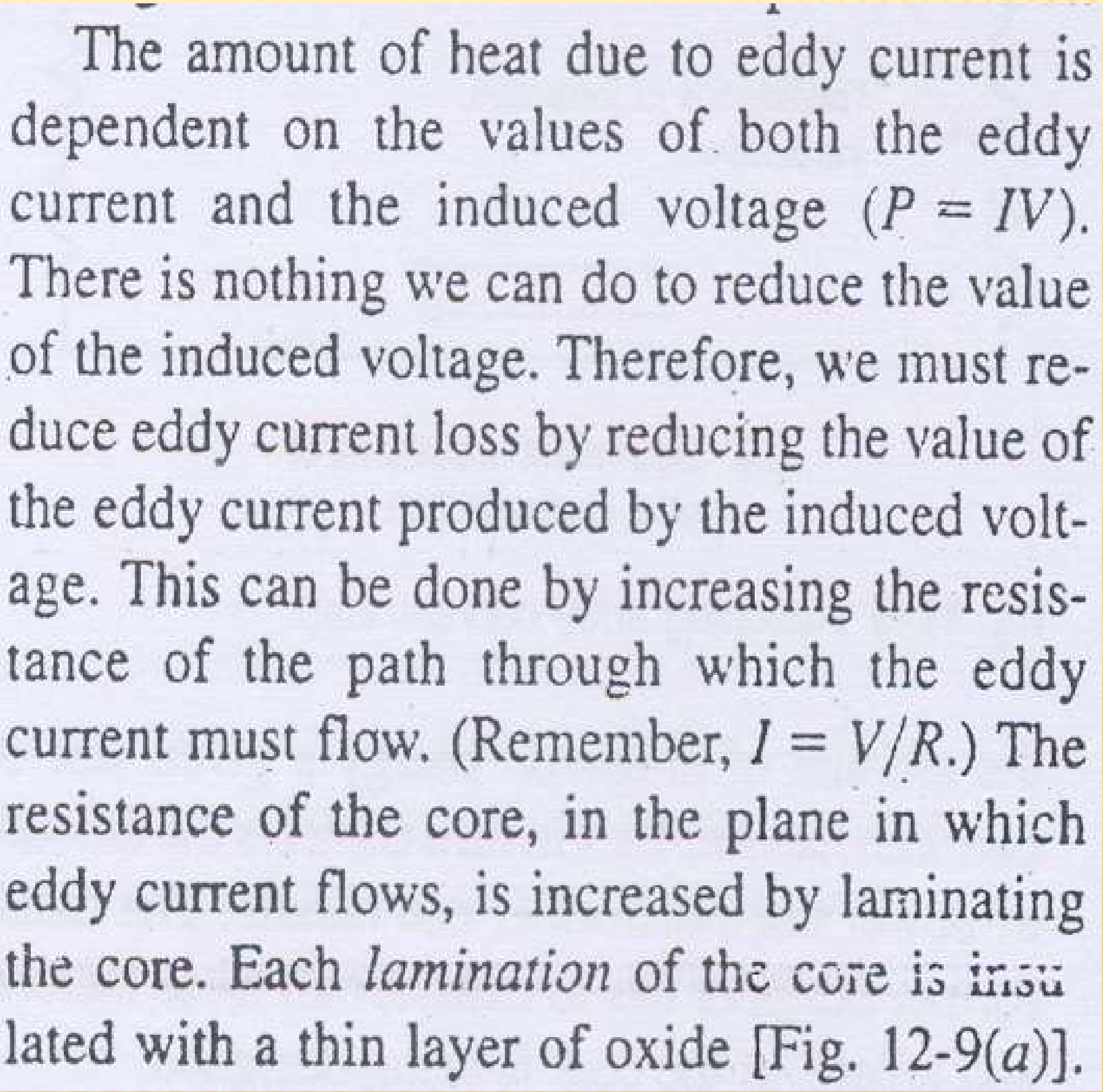
Transformers



Eddy Current Loss

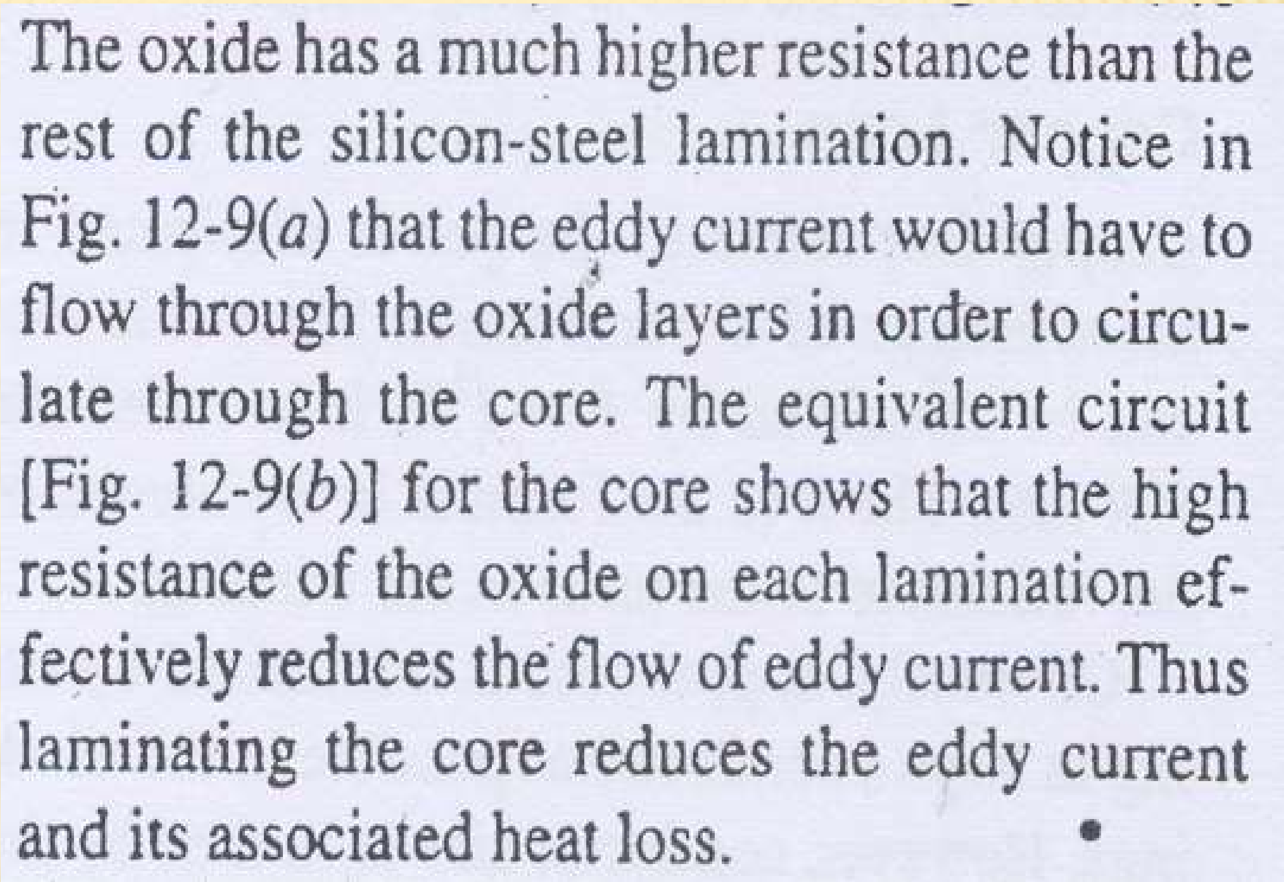
The changing magnetic flux in the core of a transformer induces voltage into any conductors which surround it. Since the core is itself a conductor, the changing magnetic flux induces a voltage in the core as well as in the coil conductors. The voltage induced in the core causes current to circulate in the core. This current is called *eddy current.* The eddy current flowing through the resistance of the core produces heat.

Transformers



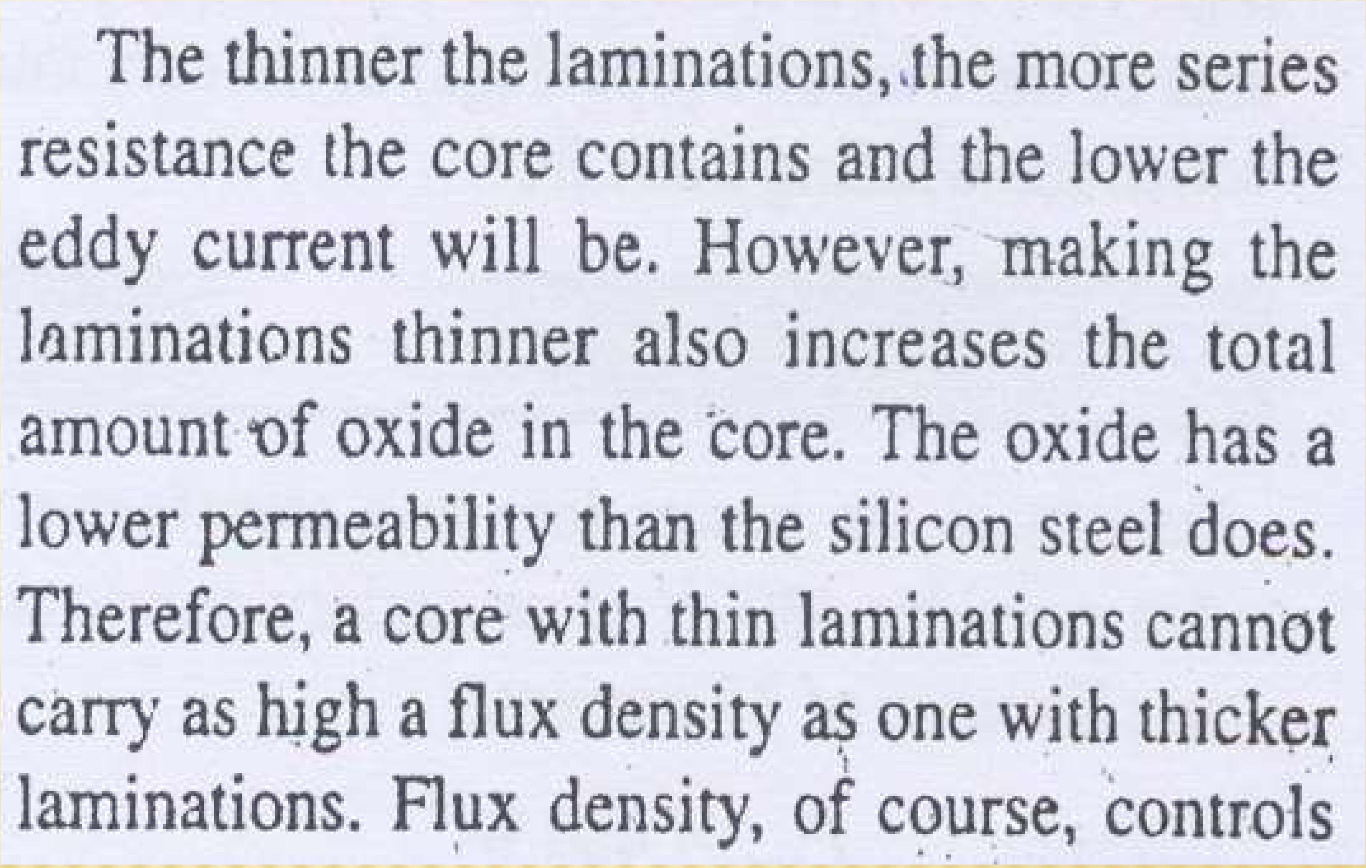
The amount of heat due to eddy current is dependent on the values of both the eddy current and the induced voltage ($P = IV$). There is nothing we can do to reduce the value of the induced voltage. Therefore, we must reduce eddy current loss by reducing the value of the eddy current produced by the induced voltage. This can be done by increasing the resistance of the path through which the eddy current must flow. (Remember, $I = V/R$.) The resistance of the core, in the plane in which eddy current flows, is increased by laminating the core. Each *lamination* of the core is insulated with a thin layer of oxide [Fig. 12-9(a)].

Transformers



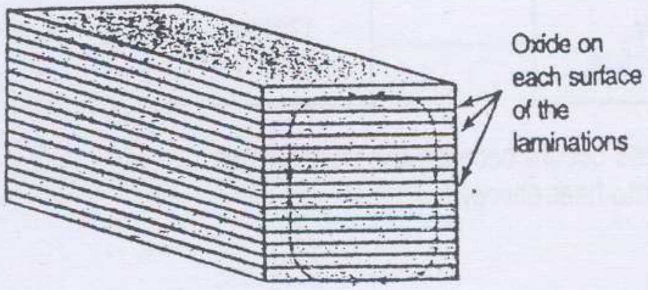
The oxide has a much higher resistance than the rest of the silicon-steel lamination. Notice in Fig. 12-9(*a*) that the eddy current would have to flow through the oxide layers in order to circulate through the core. The equivalent circuit [Fig. 12-9(*b*)] for the core shows that the high resistance of the oxide on each lamination effectively reduces the flow of eddy current. Thus laminating the core reduces the eddy current and its associated heat loss.

Transformers

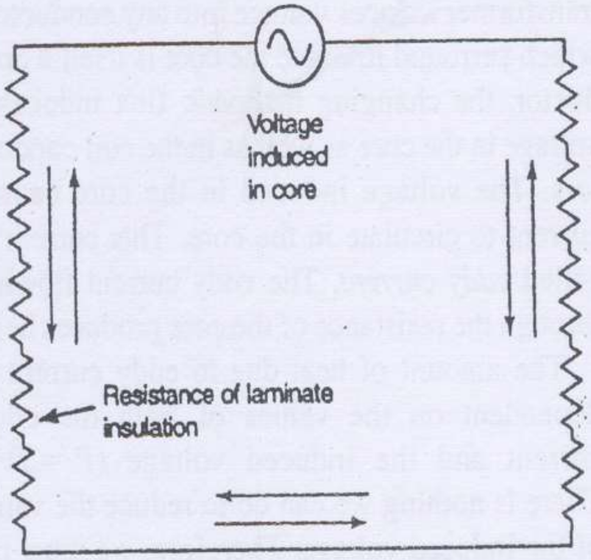


The thinner the laminations, the more series resistance the core contains and the lower the eddy current will be. However, making the laminations thinner also increases the total amount of oxide in the core. The oxide has a lower permeability than the silicon steel does. Therefore, a core with thin laminations cannot carry as high a flux density as one with thicker laminations. Flux density, of course, controls

Transformers



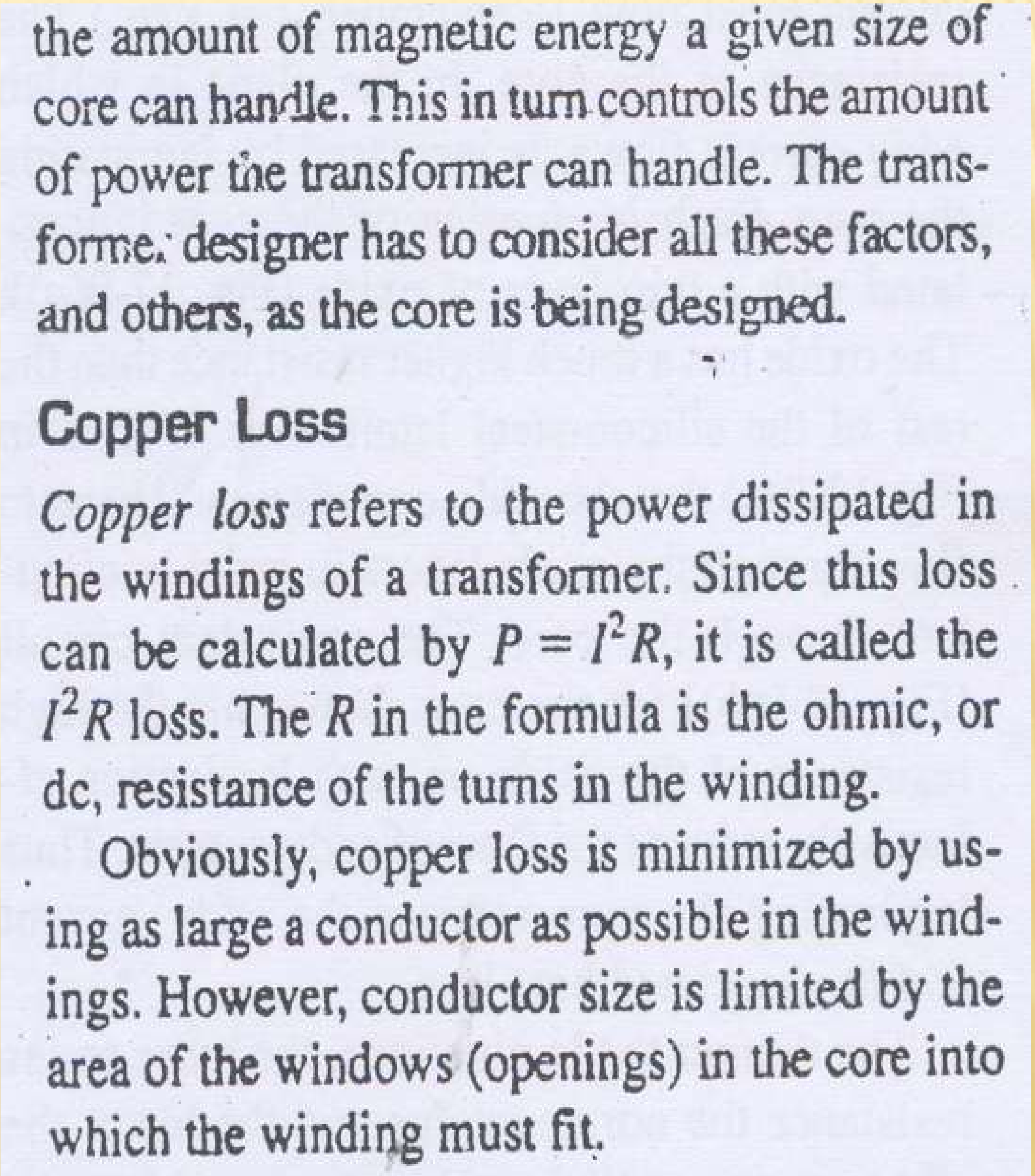
(a) Laminated core



(b) Equivalent resistance of core cross section

Fig. 12-9 Reducing eddy current loss.

Transformers



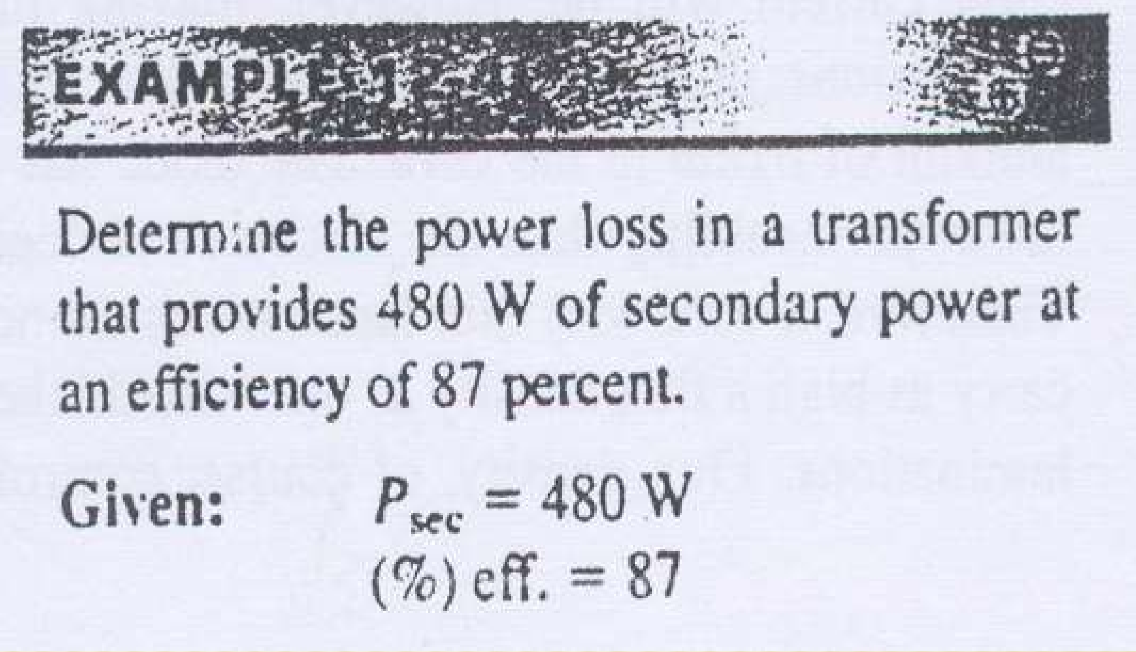
the amount of magnetic energy a given size of core can handle. This in turn controls the amount of power the transformer can handle. The transformer designer has to consider all these factors, and others, as the core is being designed.

Copper Loss

Copper loss refers to the power dissipated in the windings of a transformer. Since this loss can be calculated by $P = I^2R$, it is called the I^2R loss. The R in the formula is the ohmic, or dc, resistance of the turns in the winding.

Obviously, copper loss is minimized by using as large a conductor as possible in the windings. However, conductor size is limited by the area of the windows (openings) in the core into which the winding must fit.

Transformers



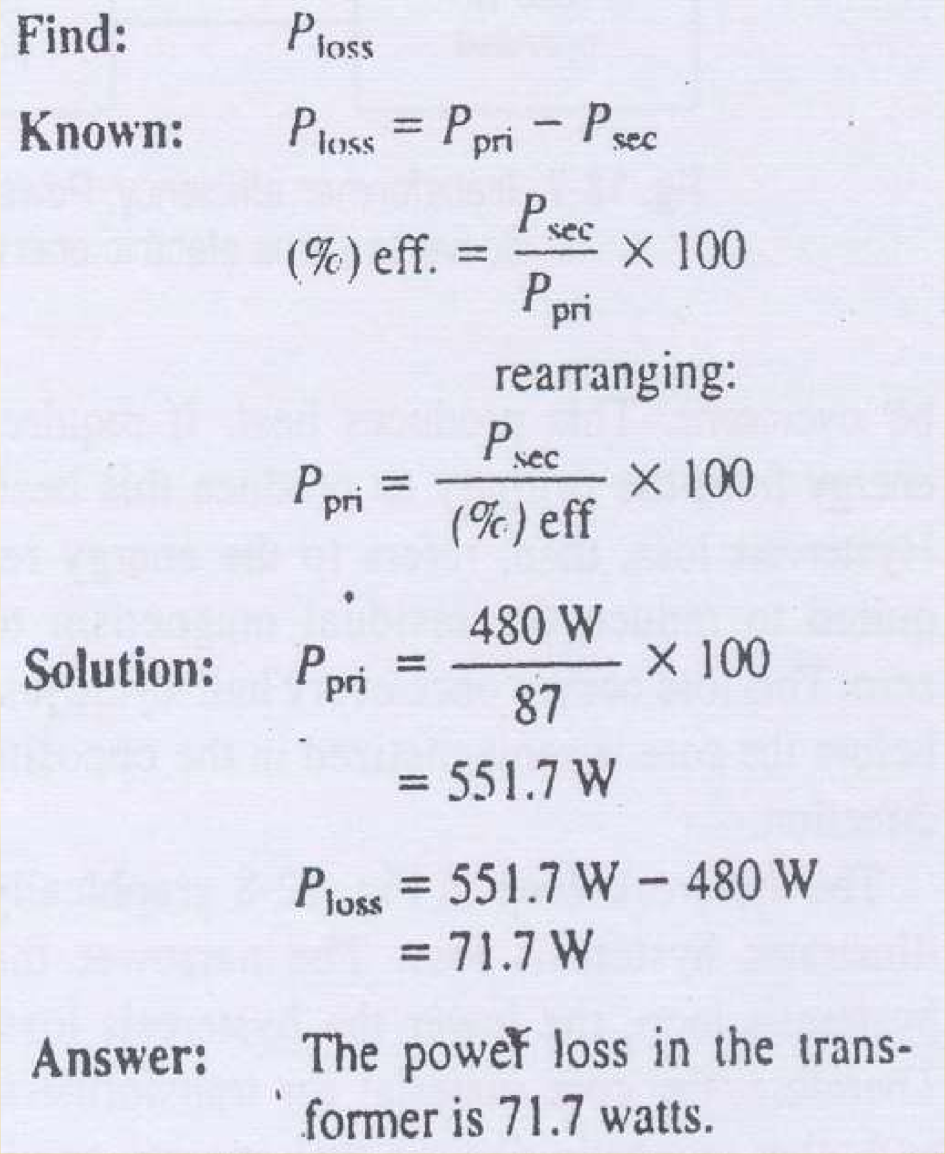
EXAMPLE [illegible]

Determine the power loss in a transformer that provides 480 W of secondary power at an efficiency of 87 percent.

Given: $P_{sec} = 480$ W

(%) eff. = 87

Transformers



Find: P_{loss}

Known: $P_{\text{loss}} = P_{\text{pri}} - P_{\text{sec}}$

$$(\%)\ \text{eff.} = \frac{P_{\text{sec}}}{P_{\text{pri}}} \times 100$$

rearranging:

$$P_{\text{pri}} = \frac{P_{\text{sec}}}{(\%)\ \text{eff}} \times 100$$

Solution:

$$P_{\text{pri}} = \frac{480\ \text{W}}{87} \times 100$$

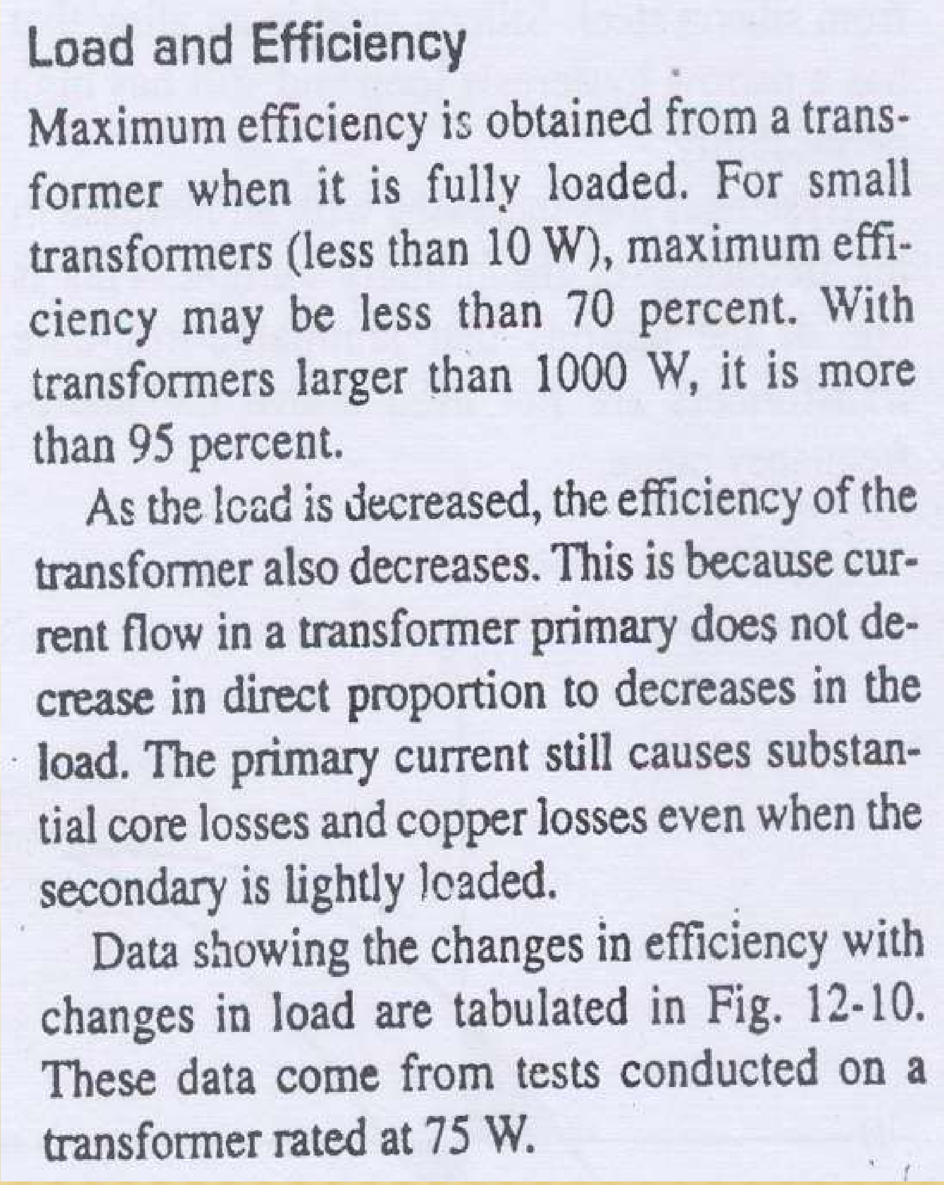
$$= 551.7\ \text{W}$$

$$P_{\text{loss}} = 551.7\ \text{W} - 480\ \text{W}$$

$$= 71.7\ \text{W}$$

Answer: The power loss in the transformer is 71.7 watts.

Transformers



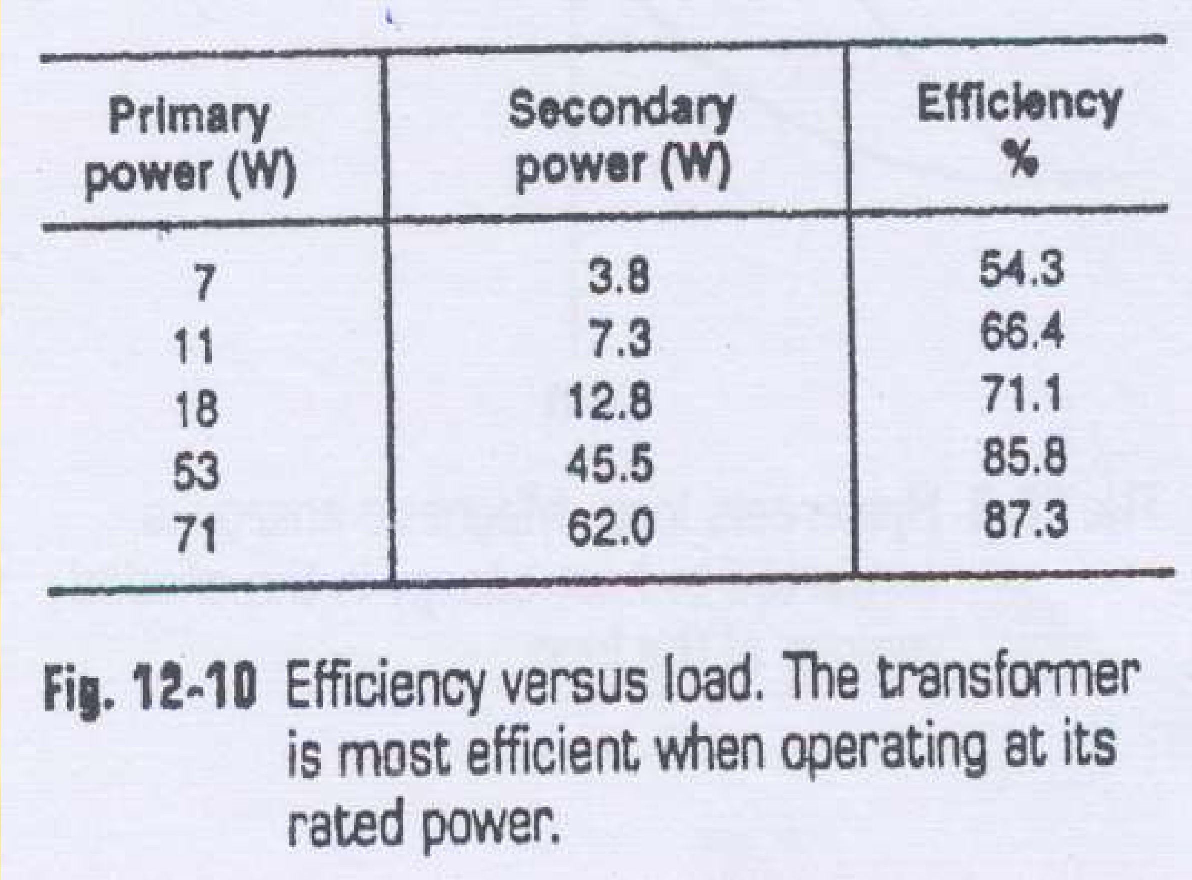
Load and Efficiency

Maximum efficiency is obtained from a transformer when it is fully loaded. For small transformers (less than 10 W), maximum efficiency may be less than 70 percent. With transformers larger than 1000 W, it is more than 95 percent.

As the load is decreased, the efficiency of the transformer also decreases. This is because current flow in a transformer primary does not decrease in direct proportion to decreases in the load. The primary current still causes substantial core losses and copper losses even when the secondary is lightly loaded.

Data showing the changes in efficiency with changes in load are tabulated in Fig. 12-10. These data come from tests conducted on a transformer rated at 75 W.

Transformers

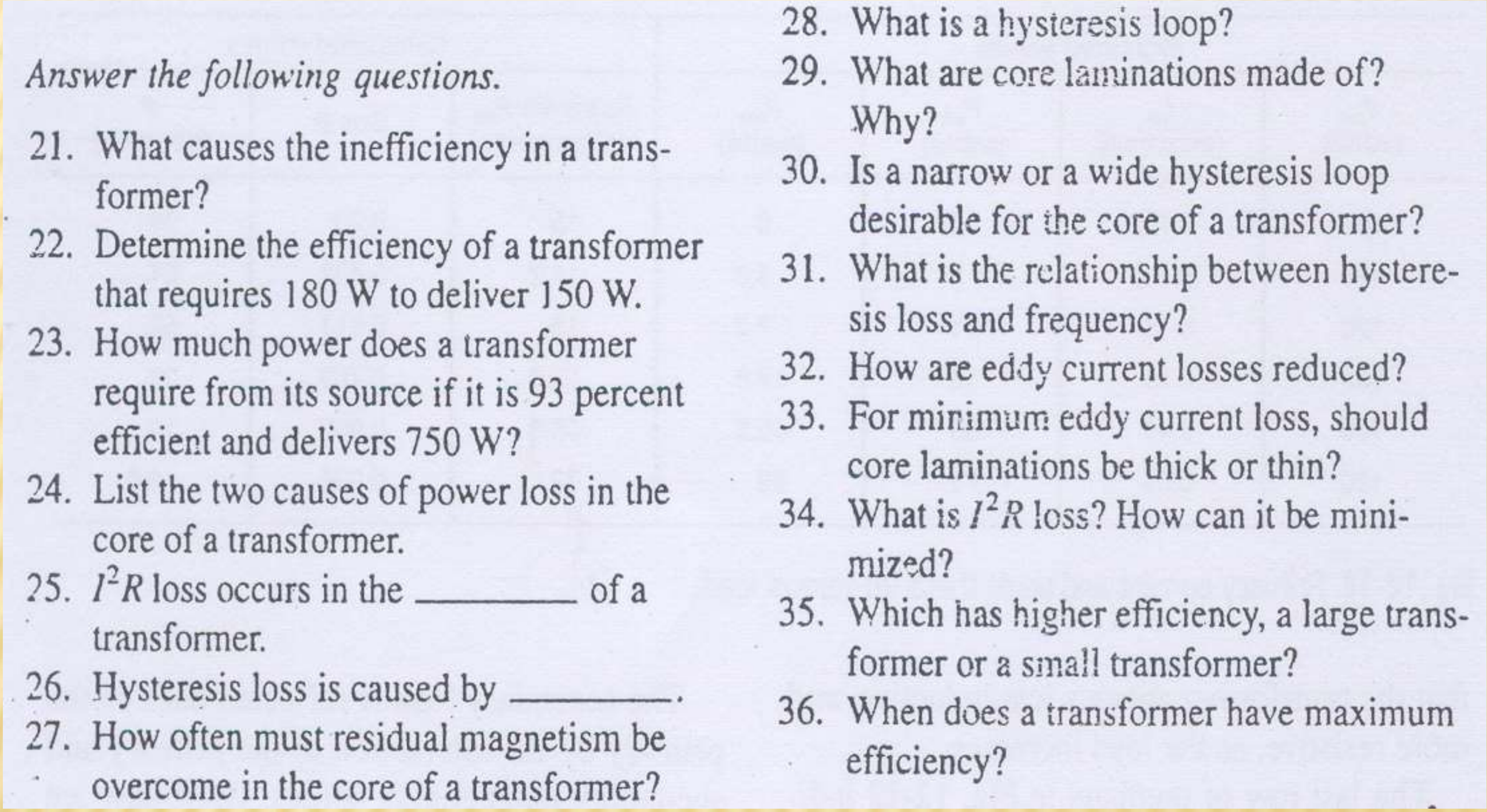


Primary power (W)	Secondary power (W)	Efficiency %
7	3.8	54.3
11	7.3	66.4
18	12.8	71.1
53	45.5	85.8
71	62.0	87.3

Fig. 12-10 Efficiency versus load. The transformer is most efficient when operating at its rated power.

Self-Test

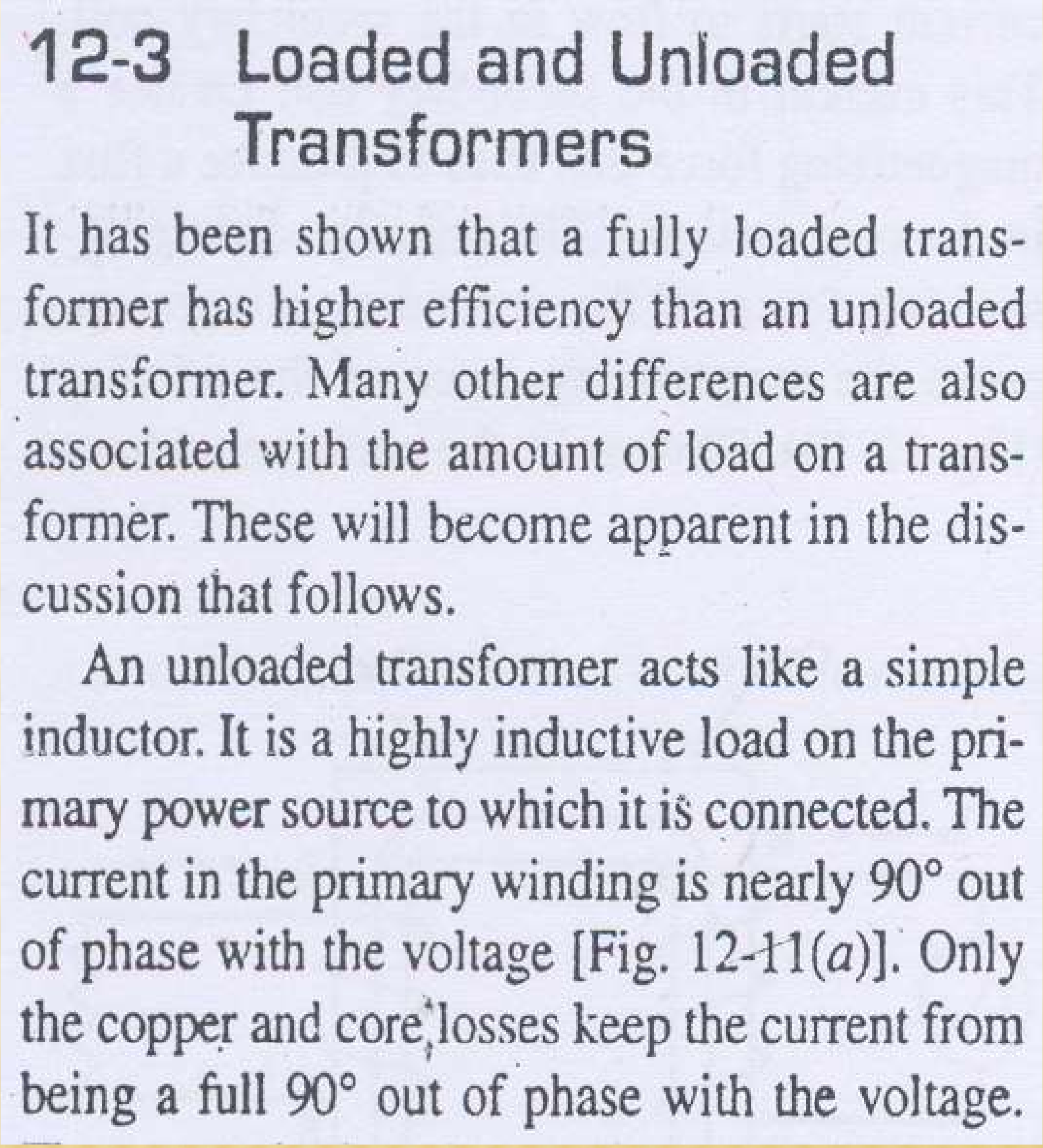
Transformers



Answer the following questions.

21. What causes the inefficiency in a transformer?
22. Determine the efficiency of a transformer that requires 180 W to deliver 150 W.
23. How much power does a transformer require from its source if it is 93 percent efficient and delivers 750 W?
24. List the two causes of power loss in the core of a transformer.
25. I^2R loss occurs in the ________ of a transformer.
26. Hysteresis loss is caused by ________.
27. How often must residual magnetism be overcome in the core of a transformer?
28. What is a hysteresis loop?
29. What are core laminations made of? Why?
30. Is a narrow or a wide hysteresis loop desirable for the core of a transformer?
31. What is the relationship between hysteresis loss and frequency?
32. How are eddy current losses reduced?
33. For minimum eddy current loss, should core laminations be thick or thin?
34. What is I^2R loss? How can it be minimized?
35. Which has higher efficiency, a large transformer or a small transformer?
36. When does a transformer have maximum efficiency?

Transformers

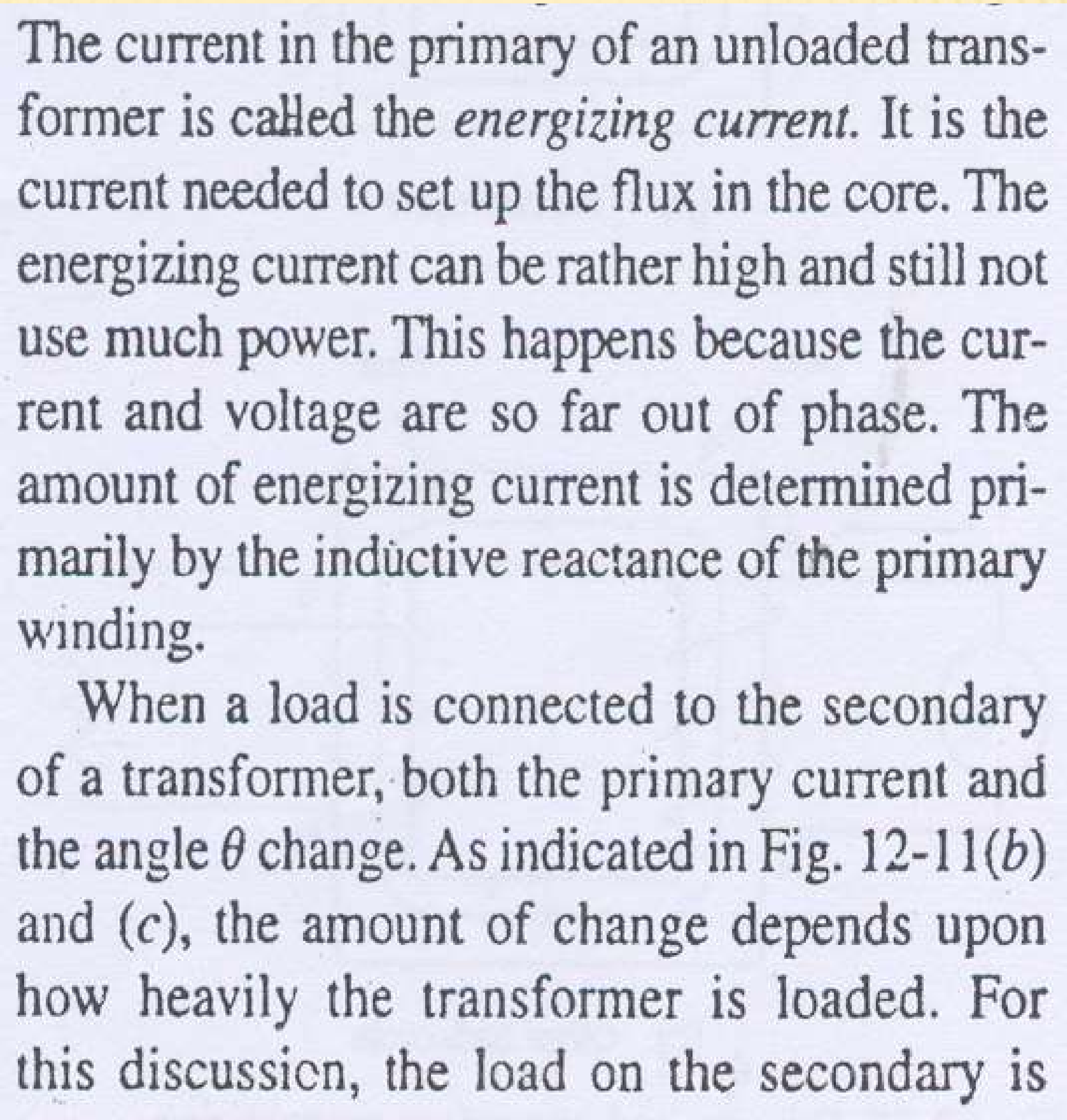


12-3 Loaded and Unloaded Transformers

It has been shown that a fully loaded transformer has higher efficiency than an unloaded transformer. Many other differences are also associated with the amount of load on a transformer. These will become apparent in the discussion that follows.

An unloaded transformer acts like a simple inductor. It is a highly inductive load on the primary power source to which it is connected. The current in the primary winding is nearly 90° out of phase with the voltage [Fig. 12-11(*a*)]. Only the copper and core losses keep the current from being a full 90° out of phase with the voltage.

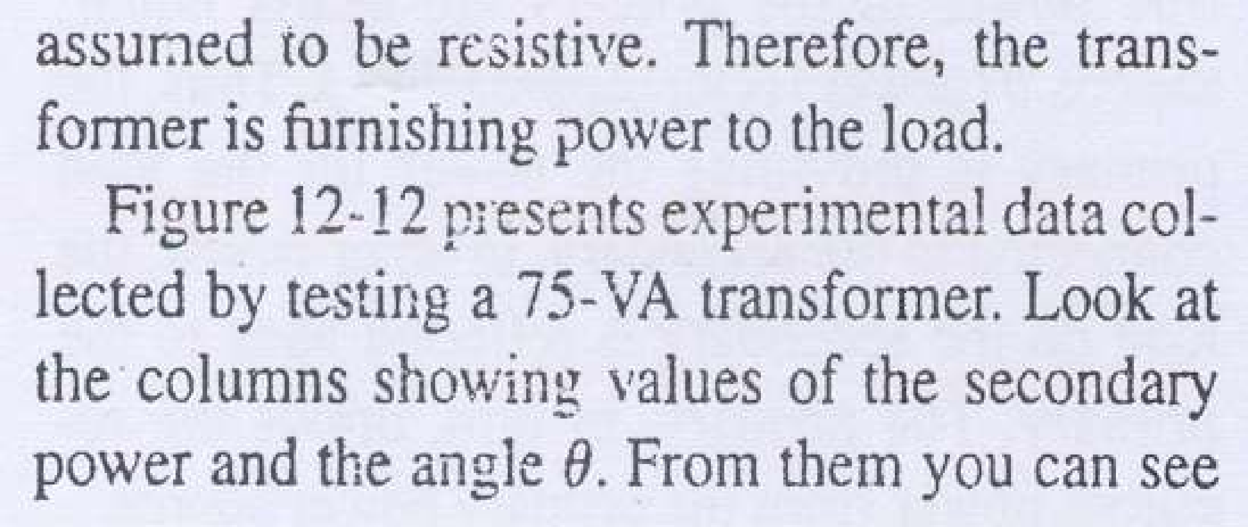
Transformers



The current in the primary of an unloaded transformer is called the *energizing current.* It is the current needed to set up the flux in the core. The energizing current can be rather high and still not use much power. This happens because the current and voltage are so far out of phase. The amount of energizing current is determined primarily by the inductive reactance of the primary winding.

When a load is connected to the secondary of a transformer, both the primary current and the angle θ change. As indicated in Fig. 12-11(*b*) and (*c*), the amount of change depends upon how heavily the transformer is loaded. For this discussion, the load on the secondary is

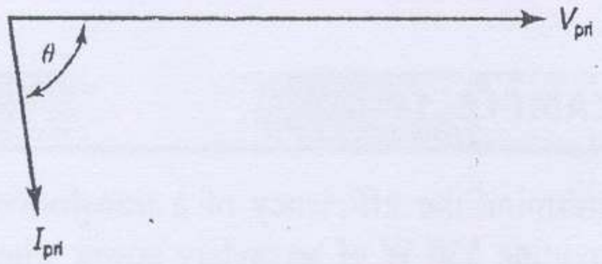
Transformers



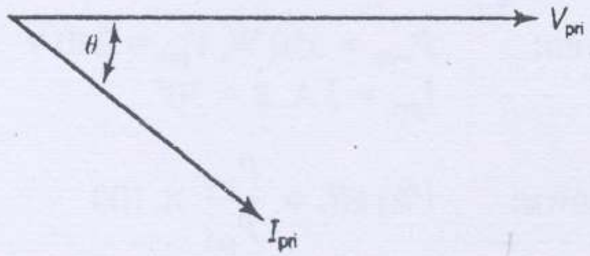
assumed to be resistive. Therefore, the transformer is furnishing power to the load.

Figure 12-12 presents experimental data collected by testing a 75-VA transformer. Look at the columns showing values of the secondary power and the angle θ. From them you can see

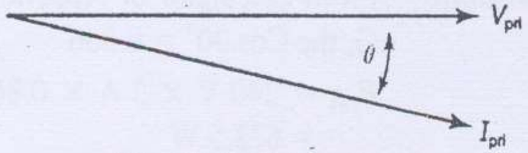
Transformers



(*a*) Unloaded transformer



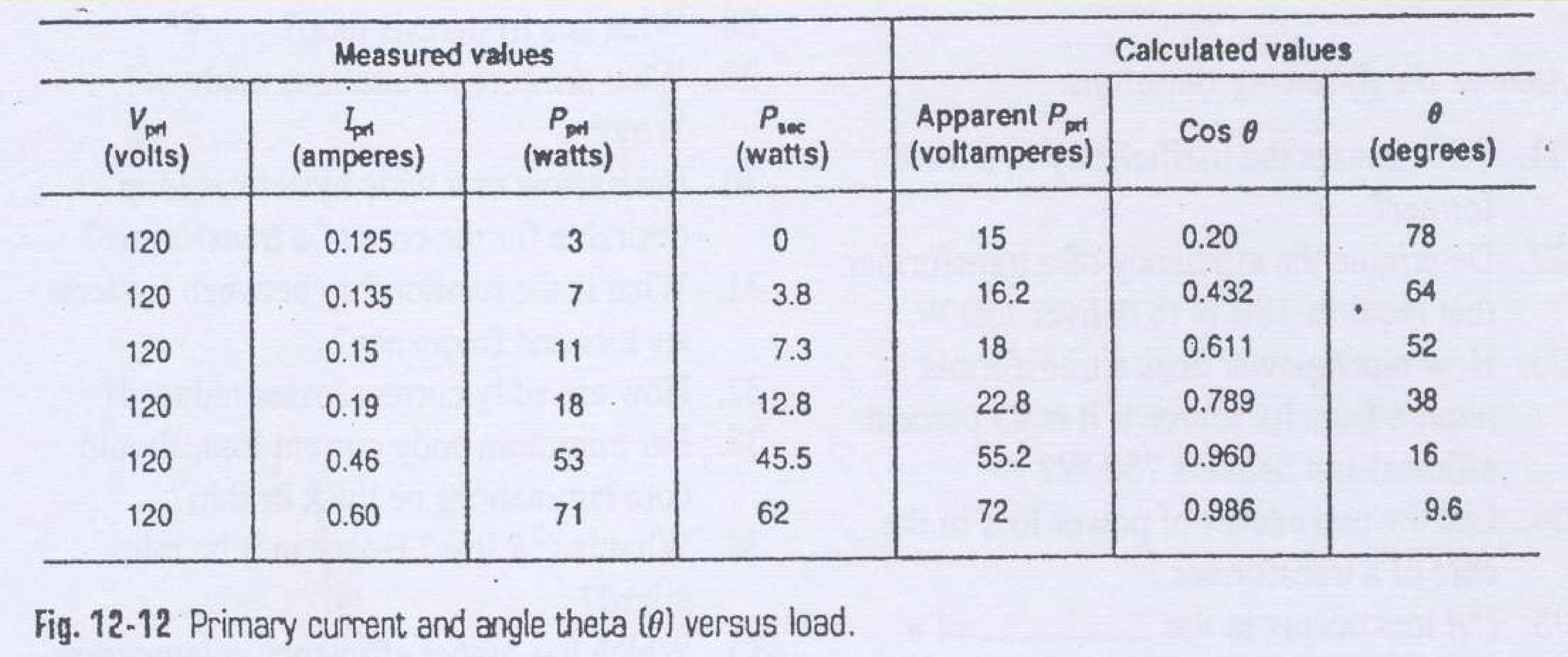
(*b*) Partially loaded transformer



(*c*) Fully loaded transformer

Fig. 12-11 Primary current and voltage phase relationships. When fully loaded, a transformer appears to be close to a resistive load.

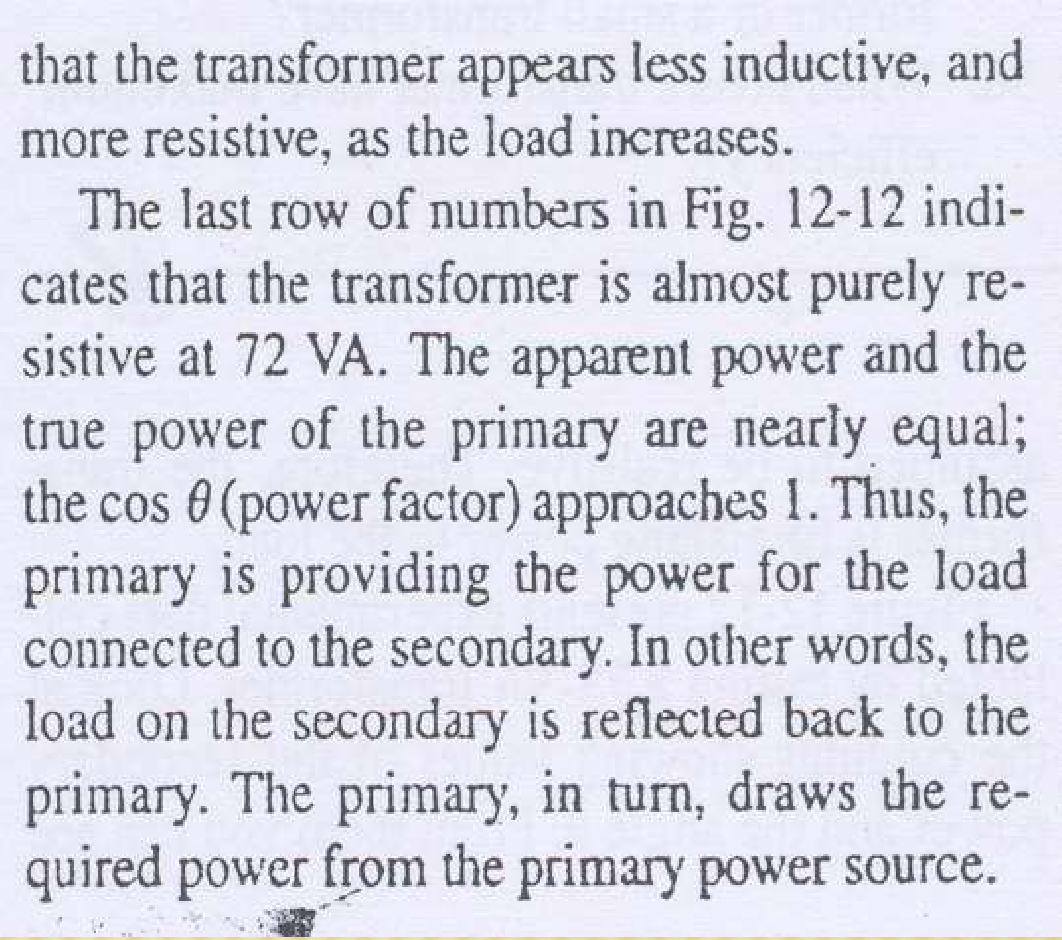
Transformers



Measured values				Calculated values		
V_{pri} (volts)	I_{pri} (amperes)	P_{pri} (watts)	P_{sec} (watts)	Apparent P_{pri} (voltamperes)	Cos θ	θ (degrees)
120	0.125	3	0	15	0.20	78
120	0.135	7	3.8	16.2	0.432	64
120	0.15	11	7.3	18	0.611	52
120	0.19	18	12.8	22.8	0.789	38
120	0.46	53	45.5	55.2	0.960	16
120	0.60	71	62	72	0.986	9.6

Fig. 12-12 Primary current and angle theta (θ) versus load.

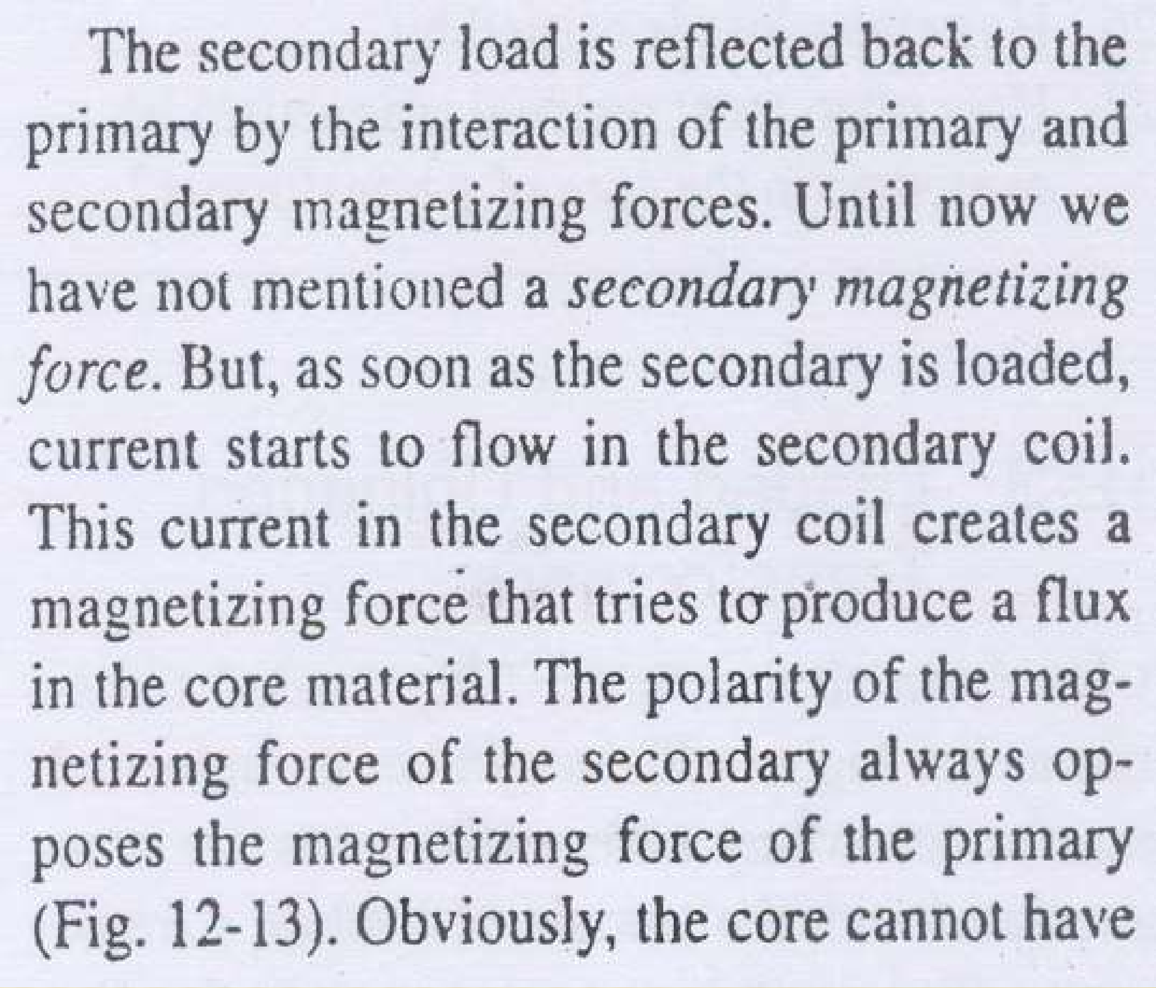
Transformers



that the transformer appears less inductive, and more resistive, as the load increases.

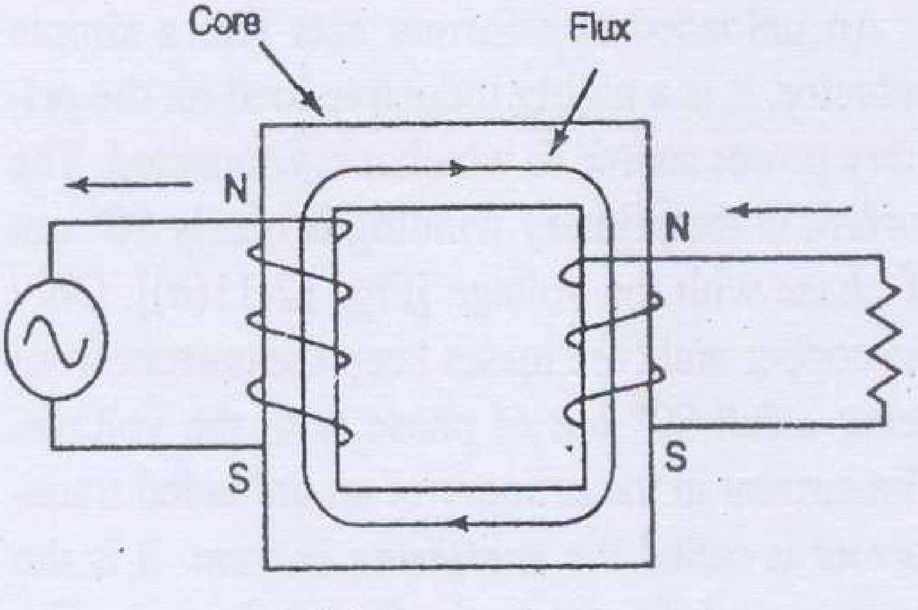
The last row of numbers in Fig. 12-12 indicates that the transformer is almost purely resistive at 72 VA. The apparent power and the true power of the primary are nearly equal; the cos θ (power factor) approaches 1. Thus, the primary is providing the power for the load connected to the secondary. In other words, the load on the secondary is reflected back to the primary. The primary, in turn, draws the required power from the primary power source.

Transformers



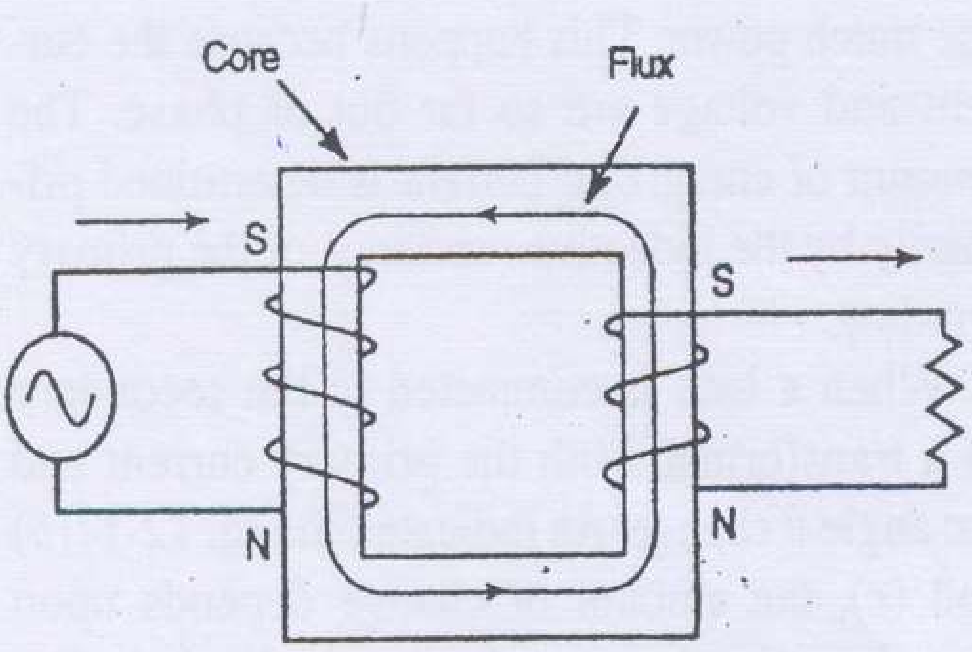
The secondary load is reflected back to the primary by the interaction of the primary and secondary magnetizing forces. Until now we have not mentioned a *secondary magnetizing force*. But, as soon as the secondary is loaded, current starts to flow in the secondary coil. This current in the secondary coil creates a magnetizing force that tries to produce a flux in the core material. The polarity of the magnetizing force of the secondary always opposes the magnetizing force of the primary (Fig. 12-13). Obviously, the core cannot have

Transformers



(a) One half-cycle

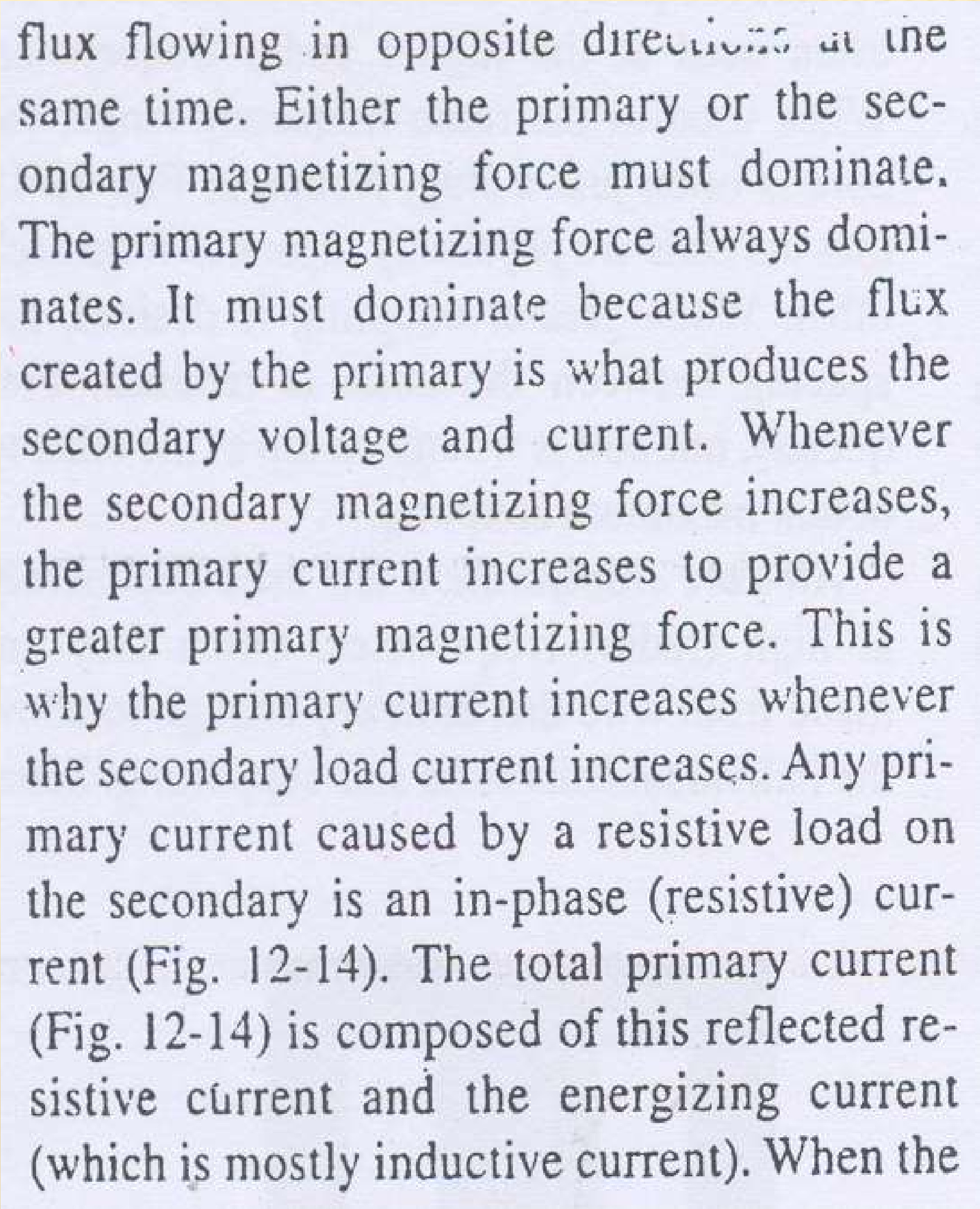
Transformers



(*b*) Other half-cycle

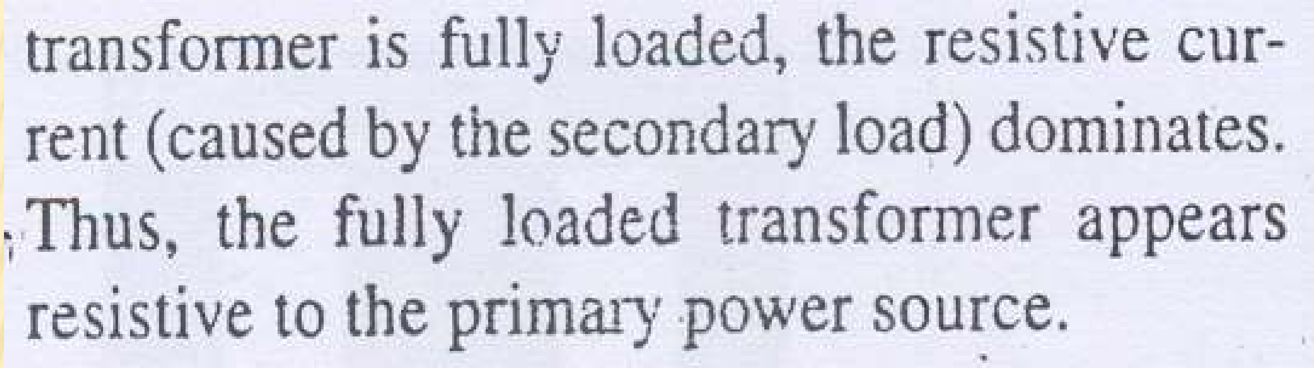
Fig. 12-13 Primary and secondary magnetizing forces oppose each other. However, notice that the primary force dominates.

Transformers



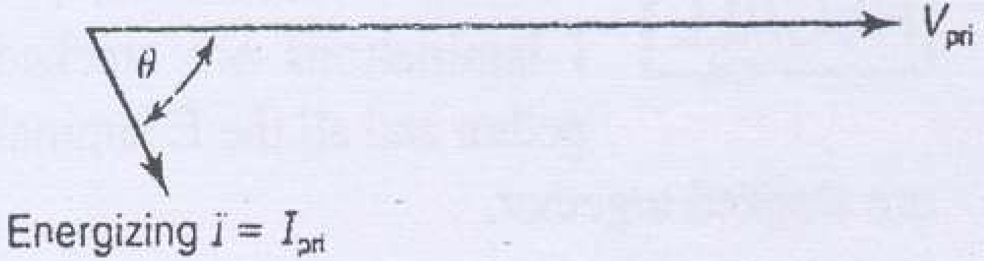
flux flowing in opposite directions at the same time. Either the primary or the secondary magnetizing force must dominate. The primary magnetizing force always dominates. It must dominate because the flux created by the primary is what produces the secondary voltage and current. Whenever the secondary magnetizing force increases, the primary current increases to provide a greater primary magnetizing force. This is why the primary current increases whenever the secondary load current increases. Any primary current caused by a resistive load on the secondary is an in-phase (resistive) current (Fig. 12-14). The total primary current (Fig. 12-14) is composed of this reflected resistive current and the energizing current (which is mostly inductive current). When the

Transformers

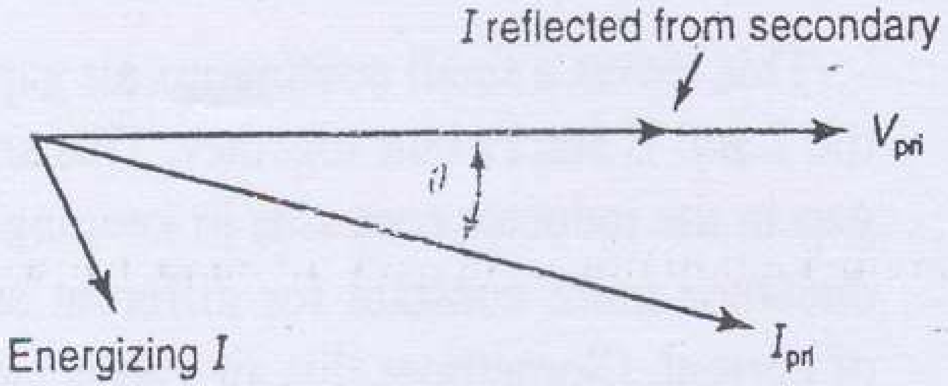


transformer is fully loaded, the resistive current (caused by the secondary load) dominates. Thus, the fully loaded transformer appears resistive to the primary power source.

Transformers



(*a*) Unloaded condition

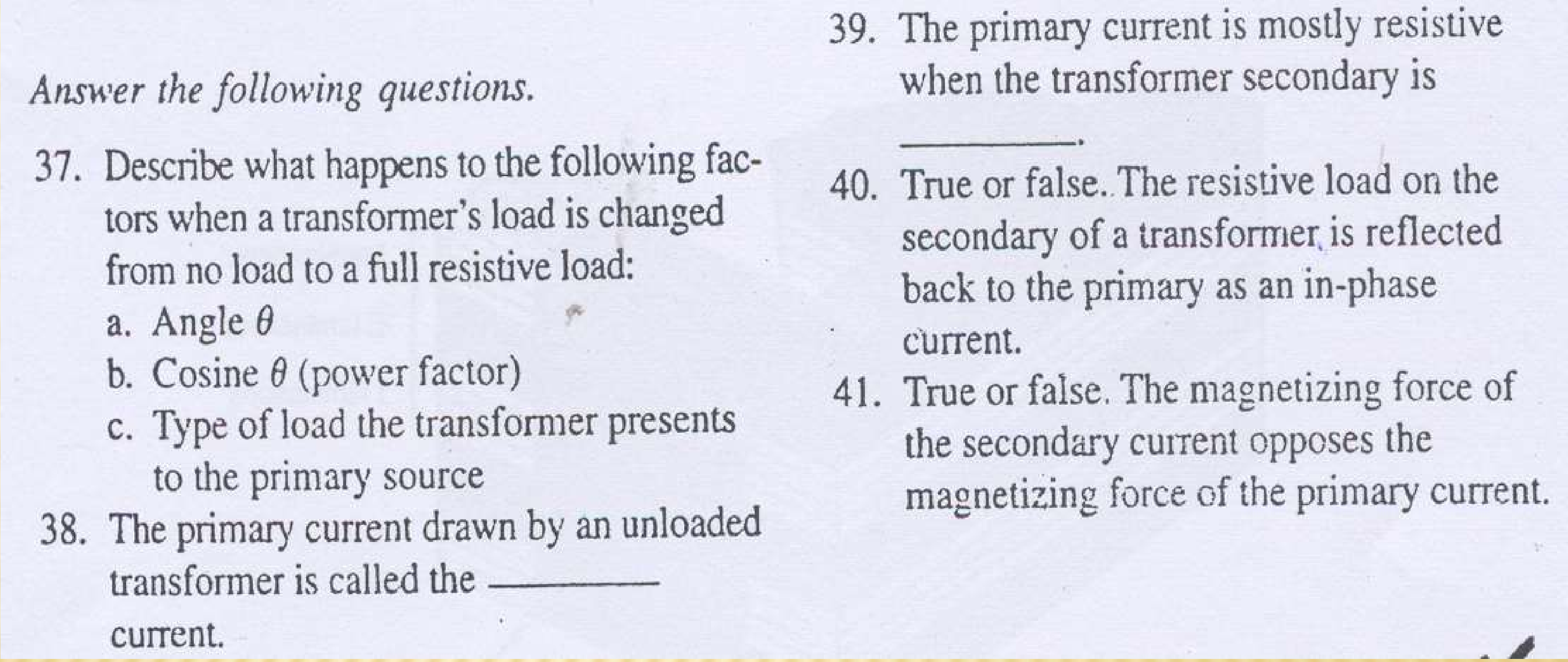


(*b*) Loaded condition

Fig. 12-14 Reflected load current.

Self-Test

Transformers



Answer the following questions.

37. Describe what happens to the following factors when a transformer's load is changed from no load to a full resistive load:
    a. Angle θ
    b. Cosine θ (power factor)
    c. Type of load the transformer presents to the primary source

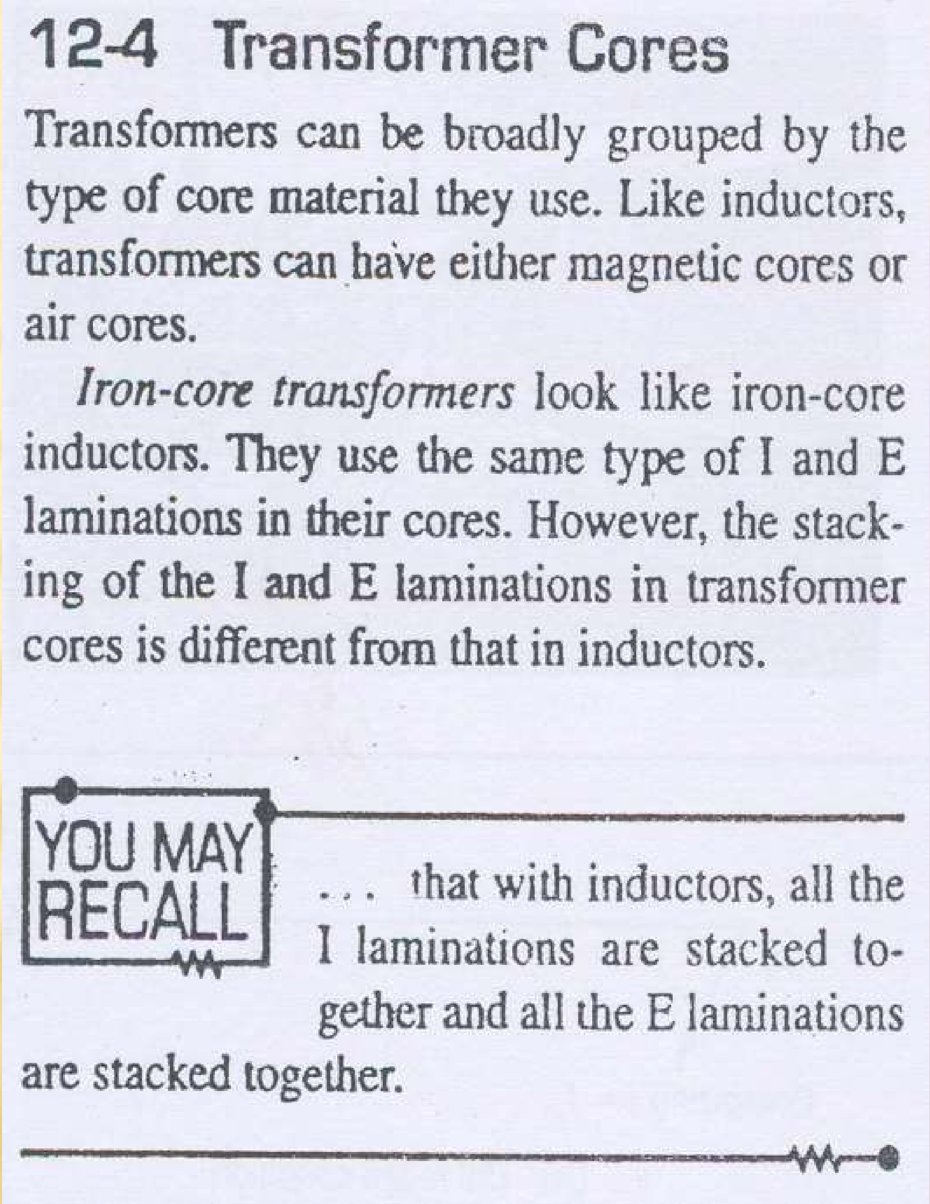
38. The primary current drawn by an unloaded transformer is called the ____________ current.

39. The primary current is mostly resistive when the transformer secondary is ____________.

40. True or false. The resistive load on the secondary of a transformer is reflected back to the primary as an in-phase current.

41. True or false. The magnetizing force of the secondary current opposes the magnetizing force of the primary current.

Transformers



12-4 Transformer Cores

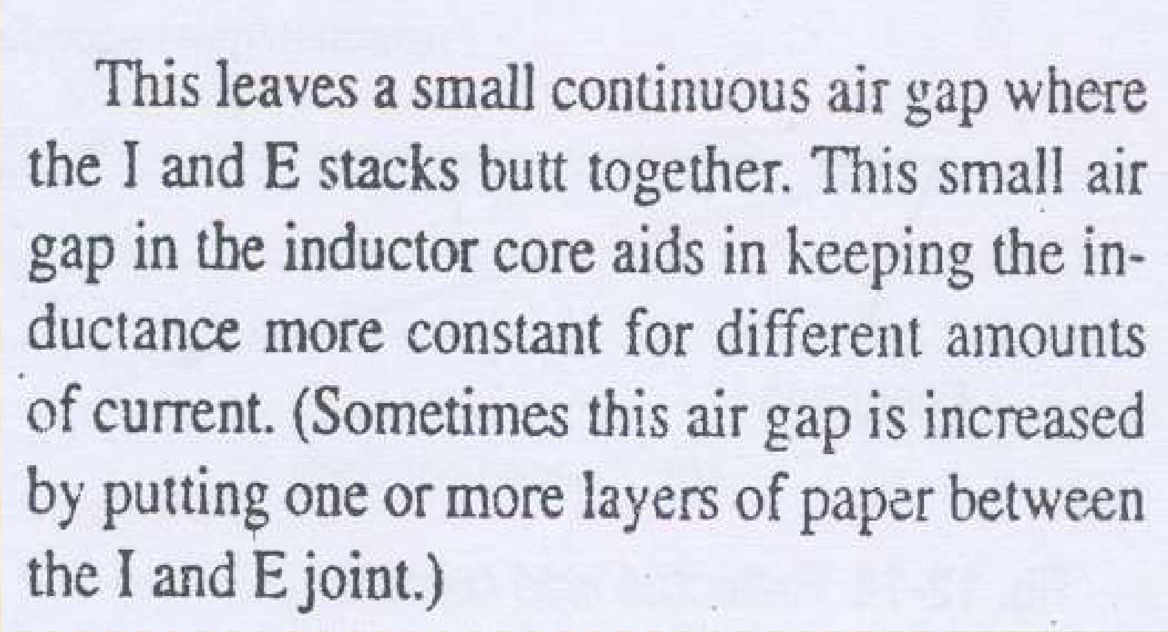
Transformers can be broadly grouped by the type of core material they use. Like inductors, transformers can have either magnetic cores or air cores.

Iron-core transformers look like iron-core inductors. They use the same type of I and E laminations in their cores. However, the stacking of the I and E laminations in transformer cores is different from that in inductors.

YOU MAY RECALL

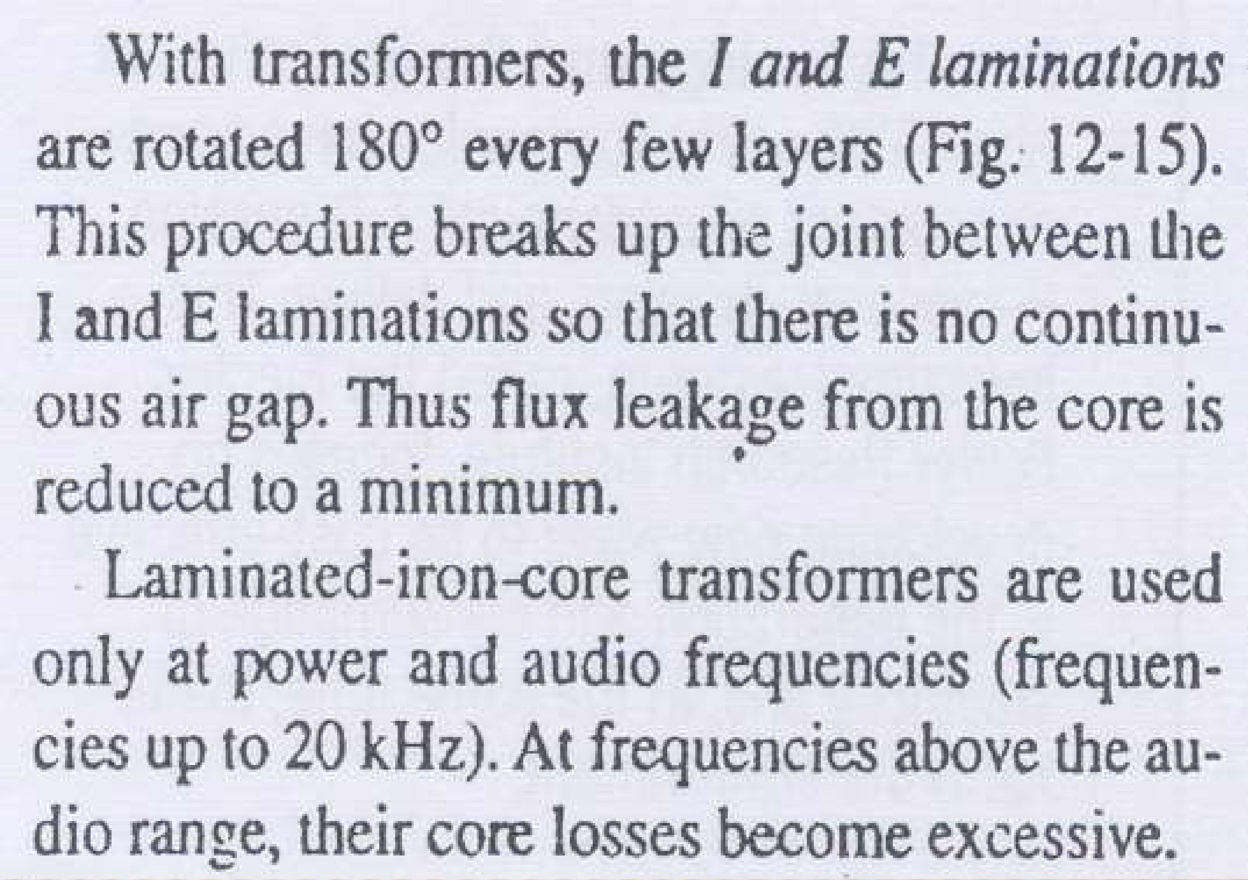
... that with inductors, all the I laminations are stacked together and all the E laminations are stacked together.

Transformers



This leaves a small continuous air gap where the I and E stacks butt together. This small air gap in the inductor core aids in keeping the inductance more constant for different amounts of current. (Sometimes this air gap is increased by putting one or more layers of paper between the I and E joint.)

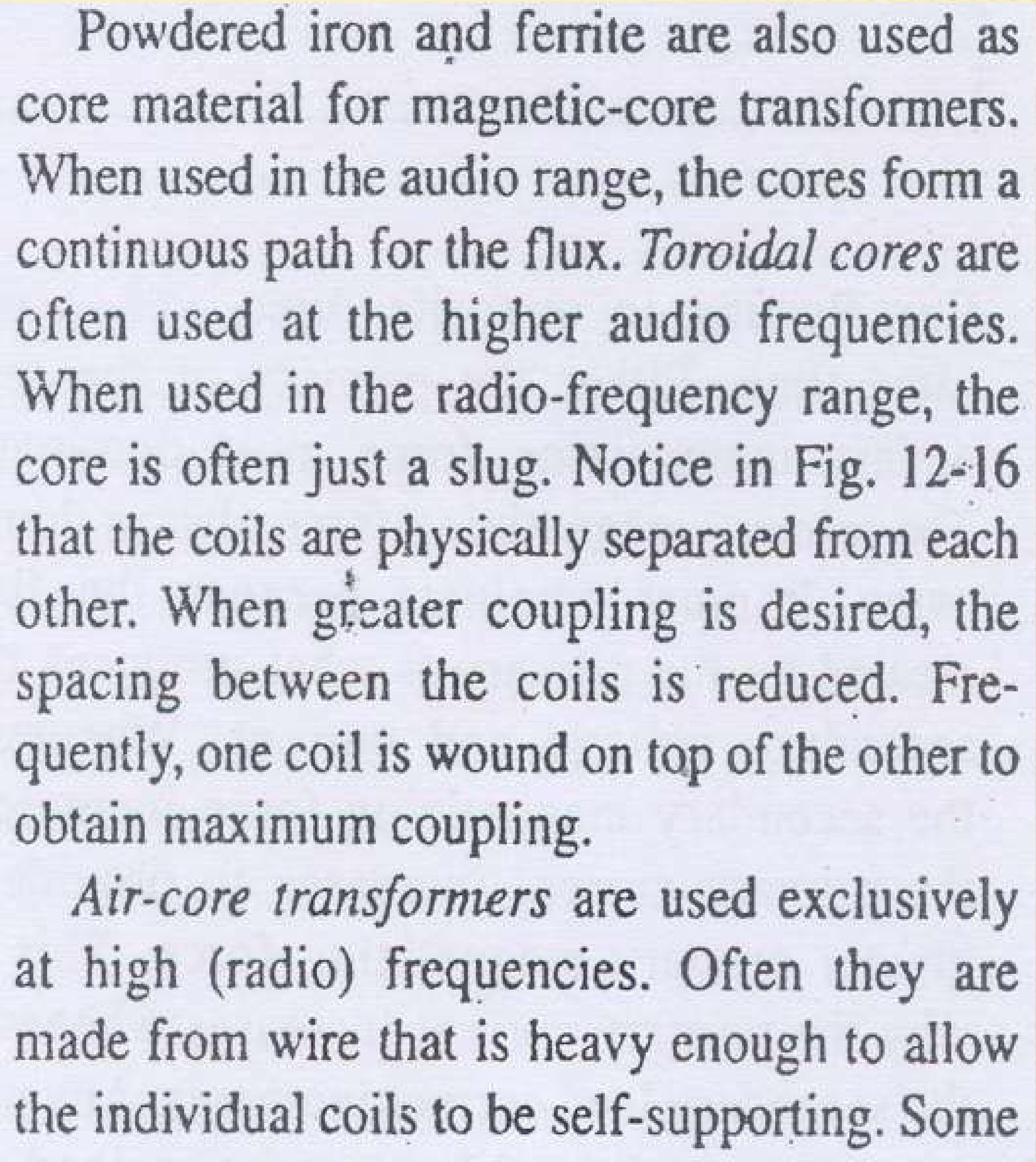
Transformers



With transformers, the *I and E laminations* are rotated 180° every few layers (Fig. 12-15). This procedure breaks up the joint between the I and E laminations so that there is no continuous air gap. Thus flux leakage from the core is reduced to a minimum.

Laminated-iron-core transformers are used only at power and audio frequencies (frequencies up to 20 kHz). At frequencies above the audio range, their core losses become excessive.

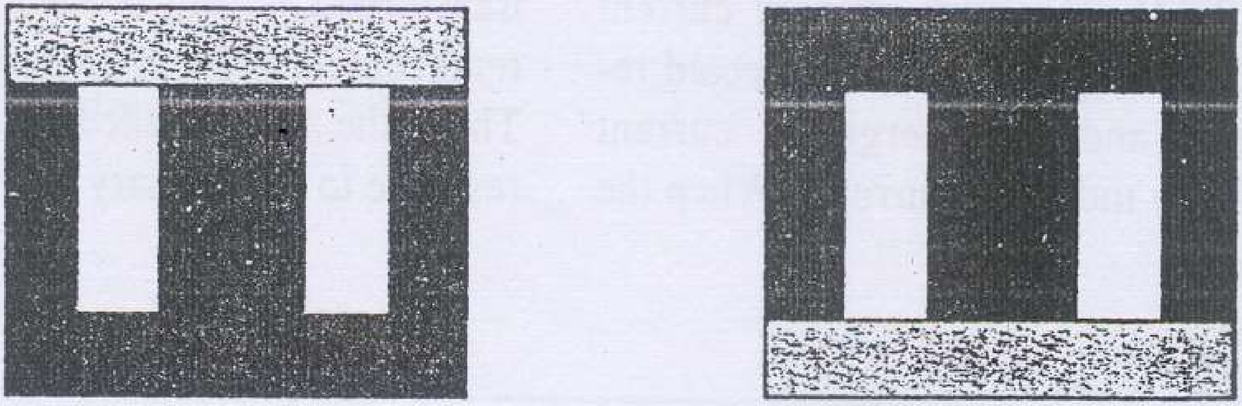
Transformers



Powdered iron and ferrite are also used as core material for magnetic-core transformers. When used in the audio range, the cores form a continuous path for the flux. *Toroidal cores* are often used at the higher audio frequencies. When used in the radio-frequency range, the core is often just a slug. Notice in Fig. 12-16 that the coils are physically separated from each other. When greater coupling is desired, the spacing between the coils is reduced. Frequently, one coil is wound on top of the other to obtain maximum coupling.

Air-core transformers are used exclusively at high (radio) frequencies. Often they are made from wire that is heavy enough to allow the individual coils to be self-supporting. Some

Transformers



(a) First four layers

(b) Second four layers

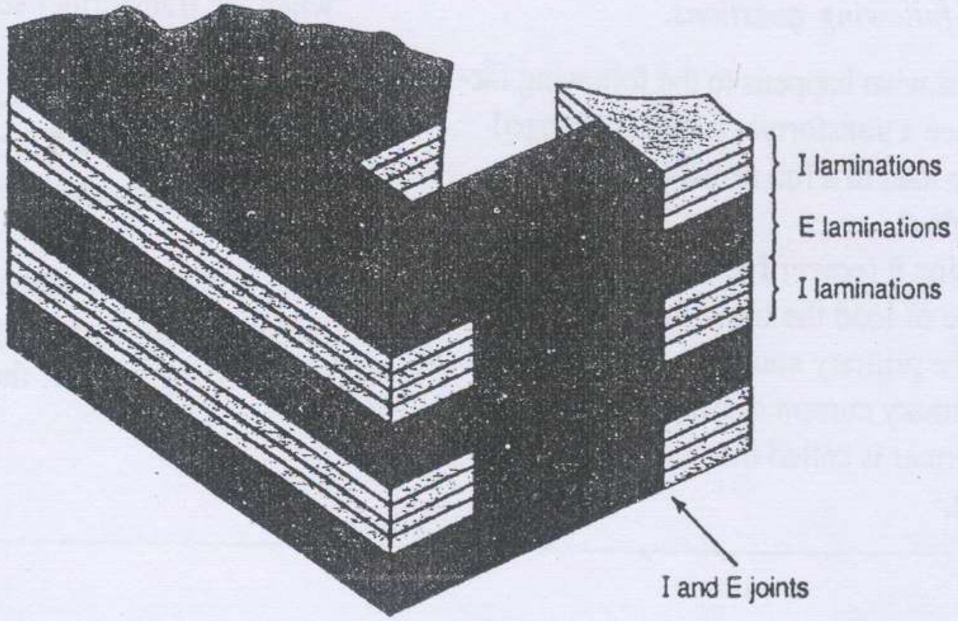


Fig. 12-15 Stacking of I and E laminations.

Transformers

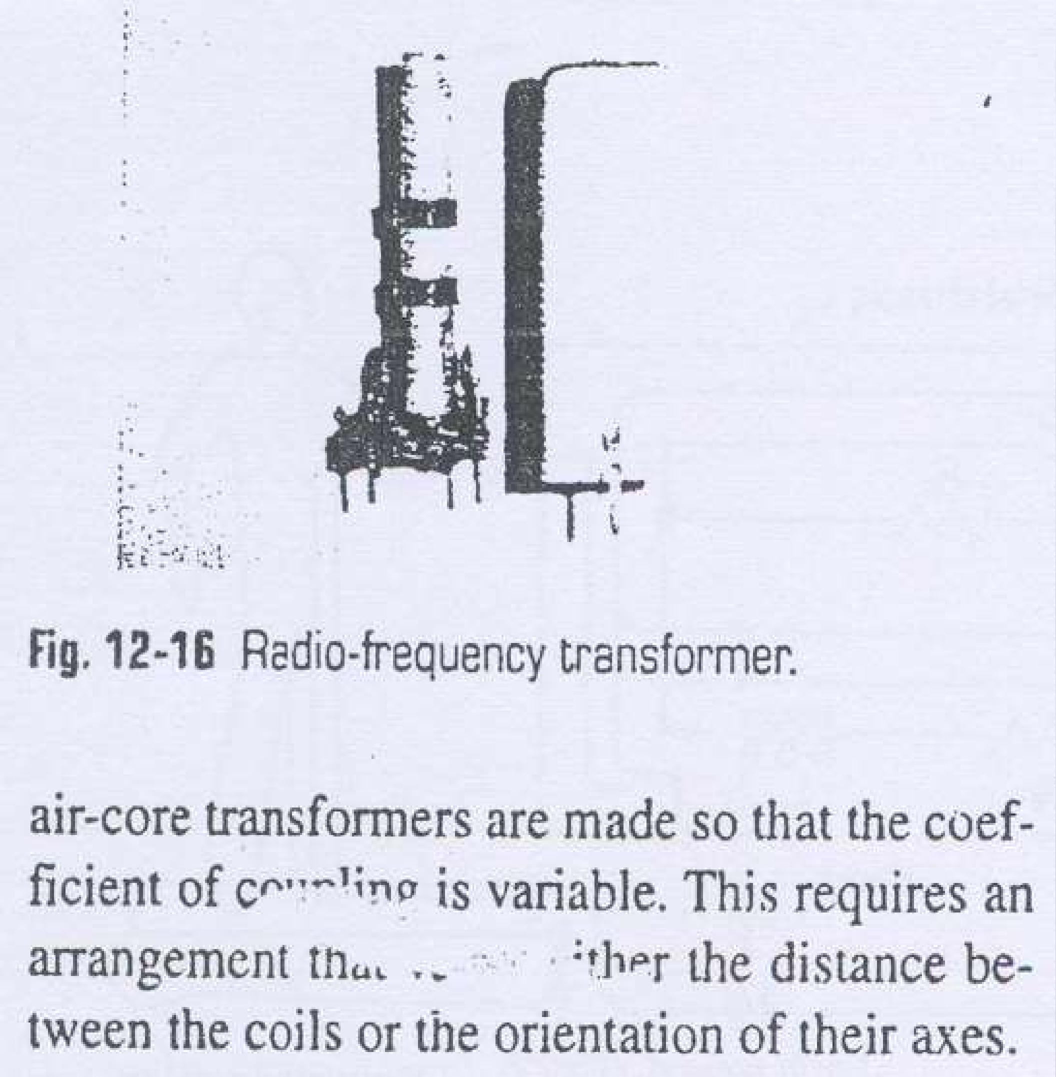
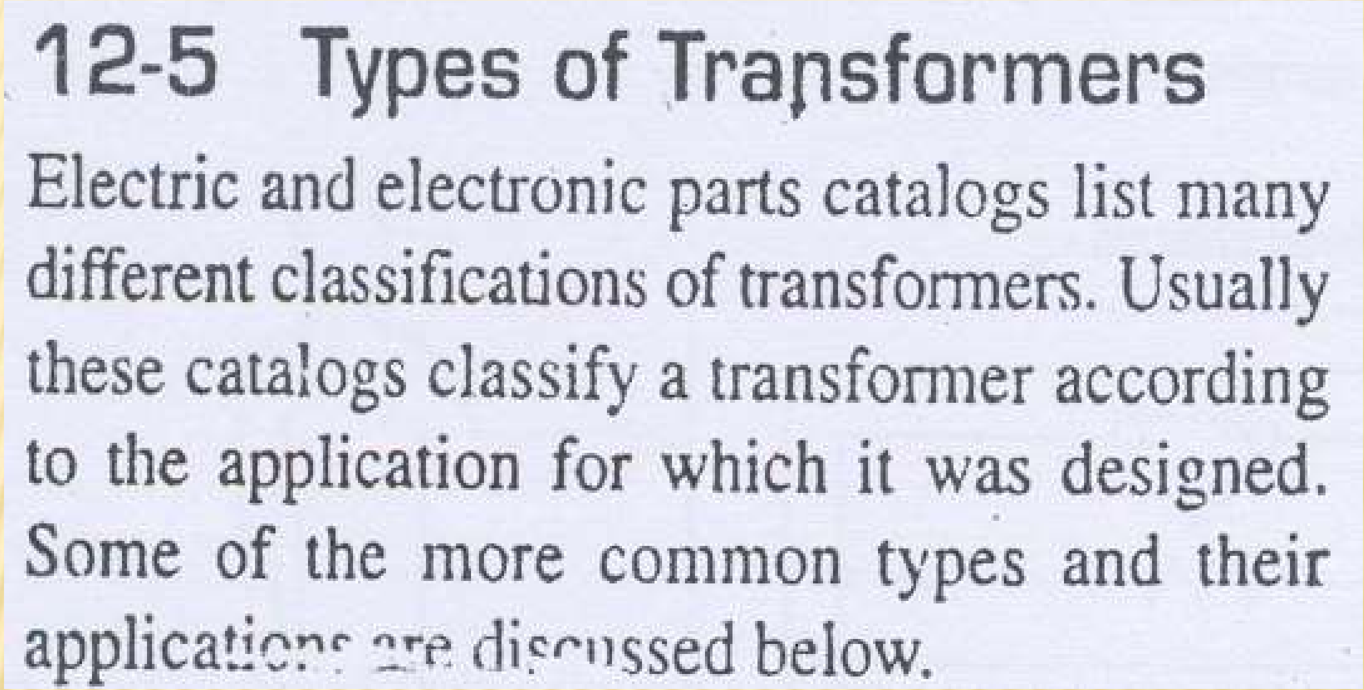


Fig. 12-16 Radio-frequency transformer.

air-core transformers are made so that the coefficient of coupling is variable. This requires an arrangement that varies either the distance between the coils or the orientation of their axes.

Transformers

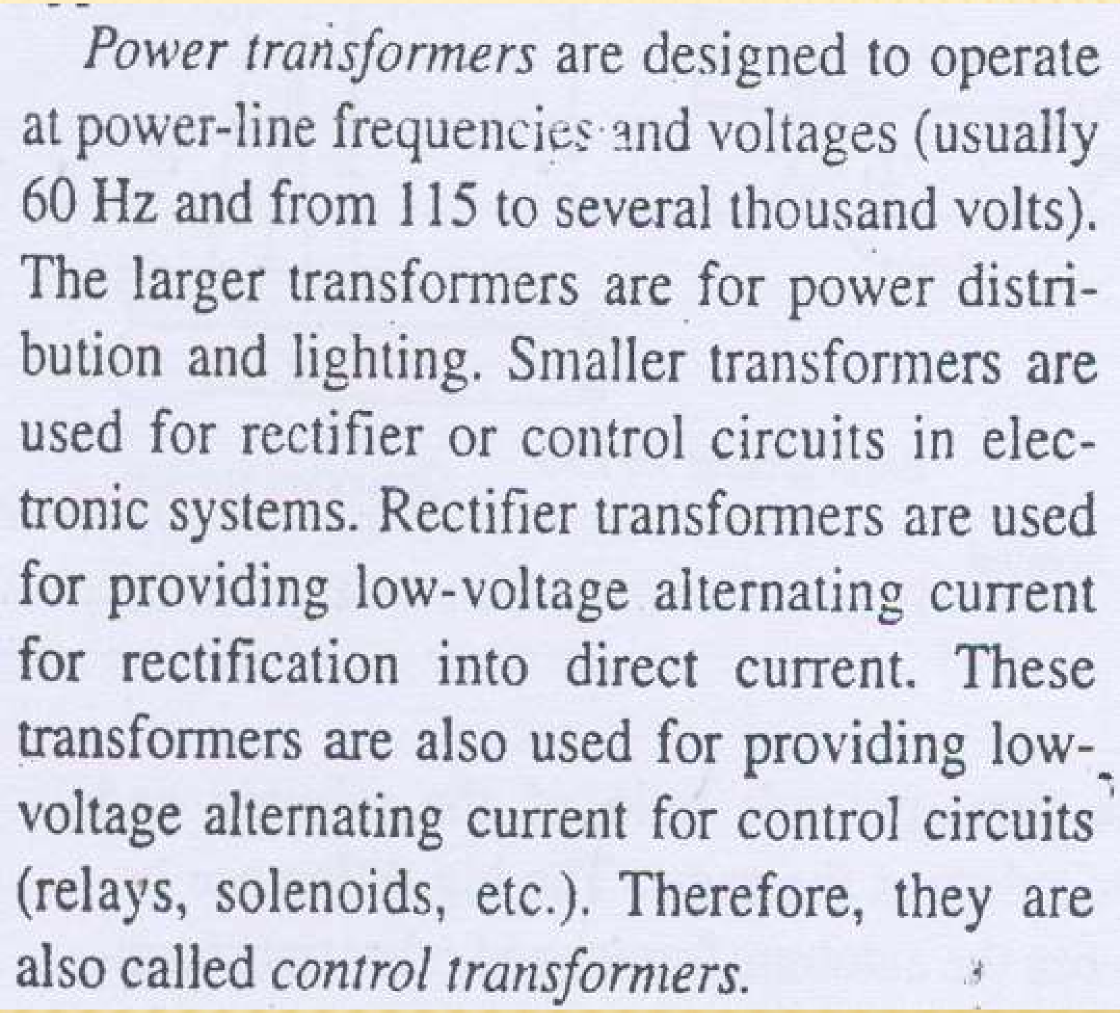


12-5 Types of Transformers

Electric and electronic parts catalogs list many different classifications of transformers. Usually these catalogs classify a transformer according to the application for which it was designed. Some of the more common types and their applications are discussed below.

12-5 Types of Transformers

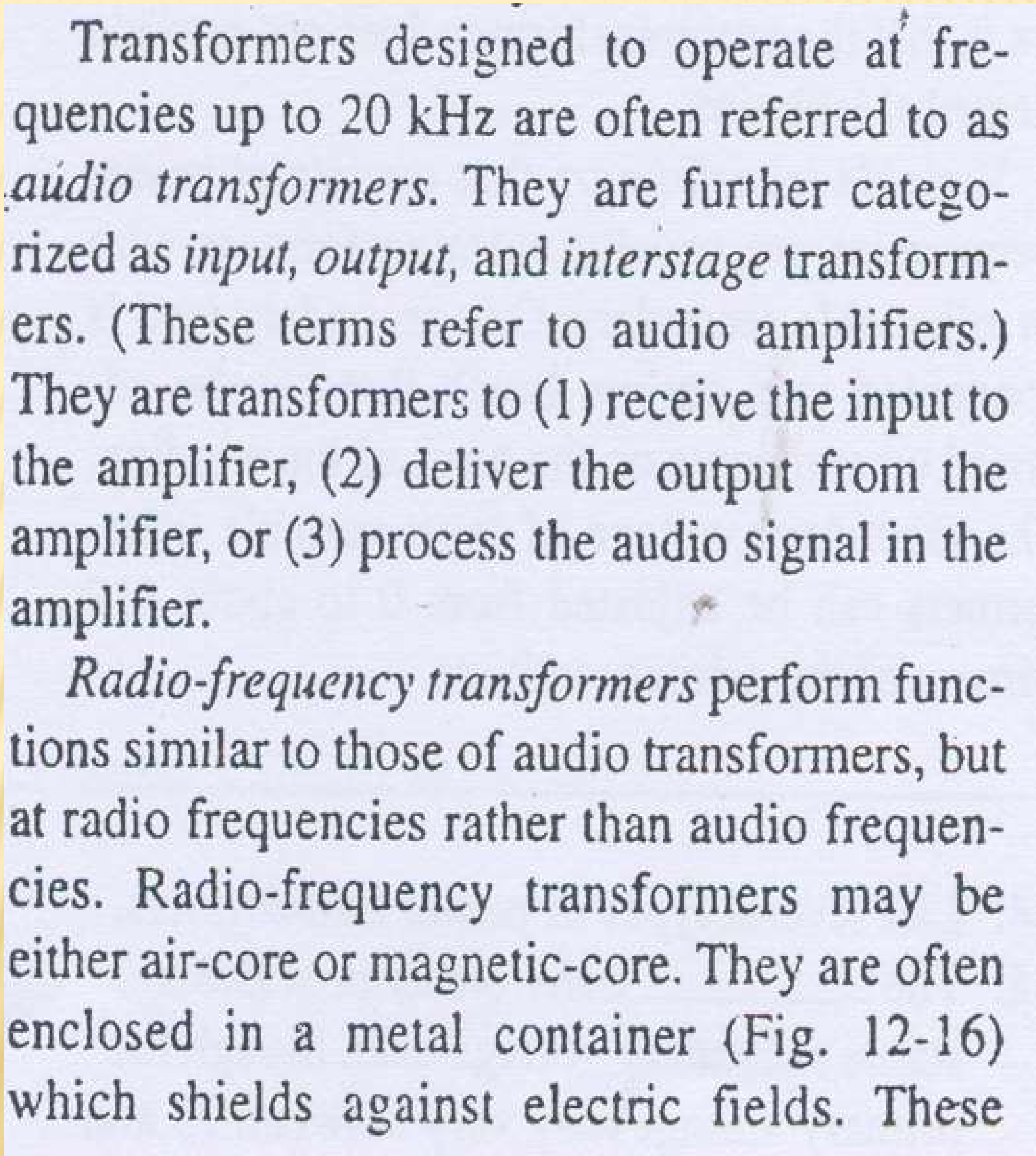
Transformers



Power transformers are designed to operate at power-line frequencies and voltages (usually 60 Hz and from 115 to several thousand volts). The larger transformers are for power distribution and lighting. Smaller transformers are used for rectifier or control circuits in electronic systems. Rectifier transformers are used for providing low-voltage alternating current for rectification into direct current. These transformers are also used for providing low-voltage alternating current for control circuits (relays, solenoids, etc.). Therefore, they are also called *control transformers*.

12-5 Types of Transformers

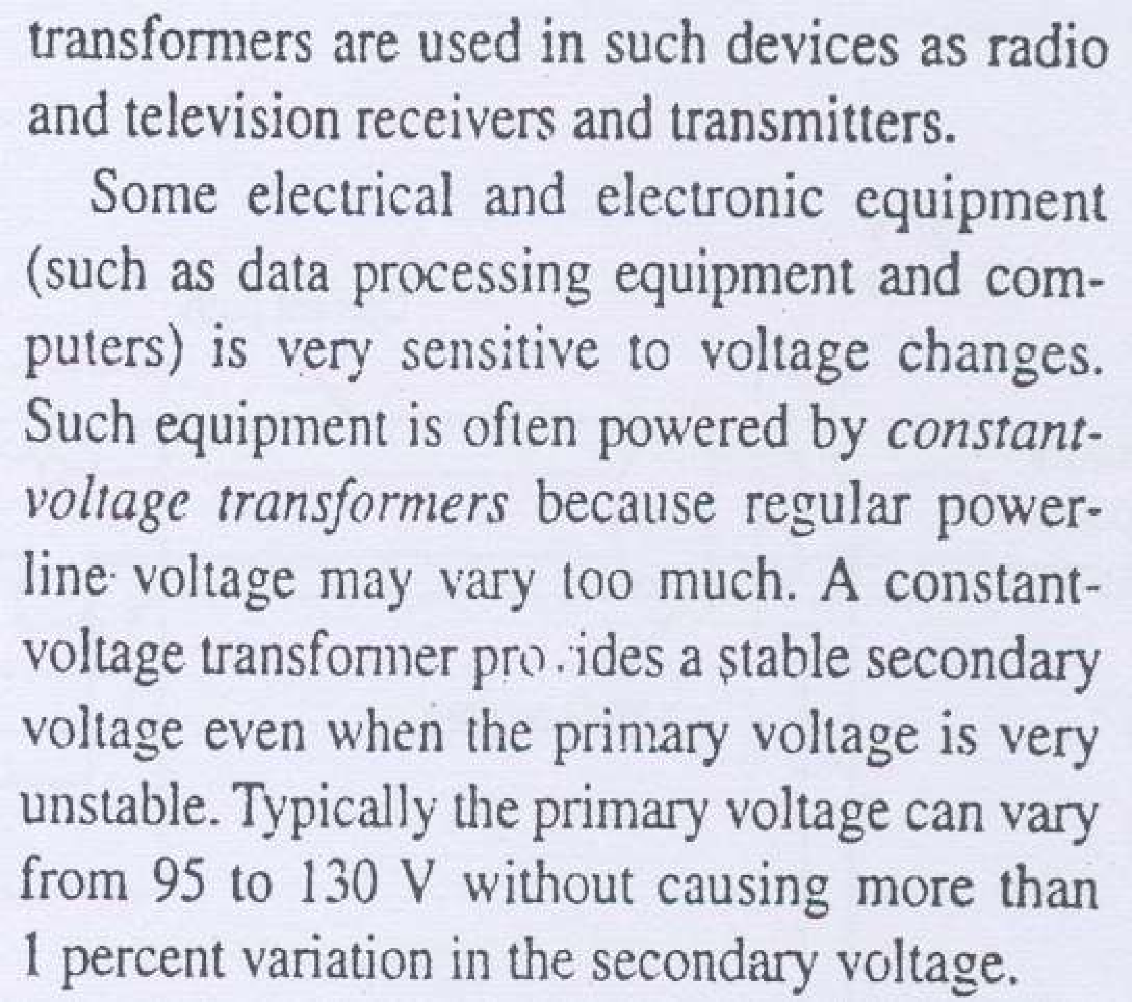
Transformers



Transformers designed to operate at frequencies up to 20 kHz are often referred to as *audio transformers*. They are further categorized as *input*, *output*, and *interstage* transformers. (These terms refer to audio amplifiers.) They are transformers to (1) receive the input to the amplifier, (2) deliver the output from the amplifier, or (3) process the audio signal in the amplifier.

Radio-frequency transformers perform functions similar to those of audio transformers, but at radio frequencies rather than audio frequencies. Radio-frequency transformers may be either air-core or magnetic-core. They are often enclosed in a metal container (Fig. 12-16) which shields against electric fields. These

Transformers

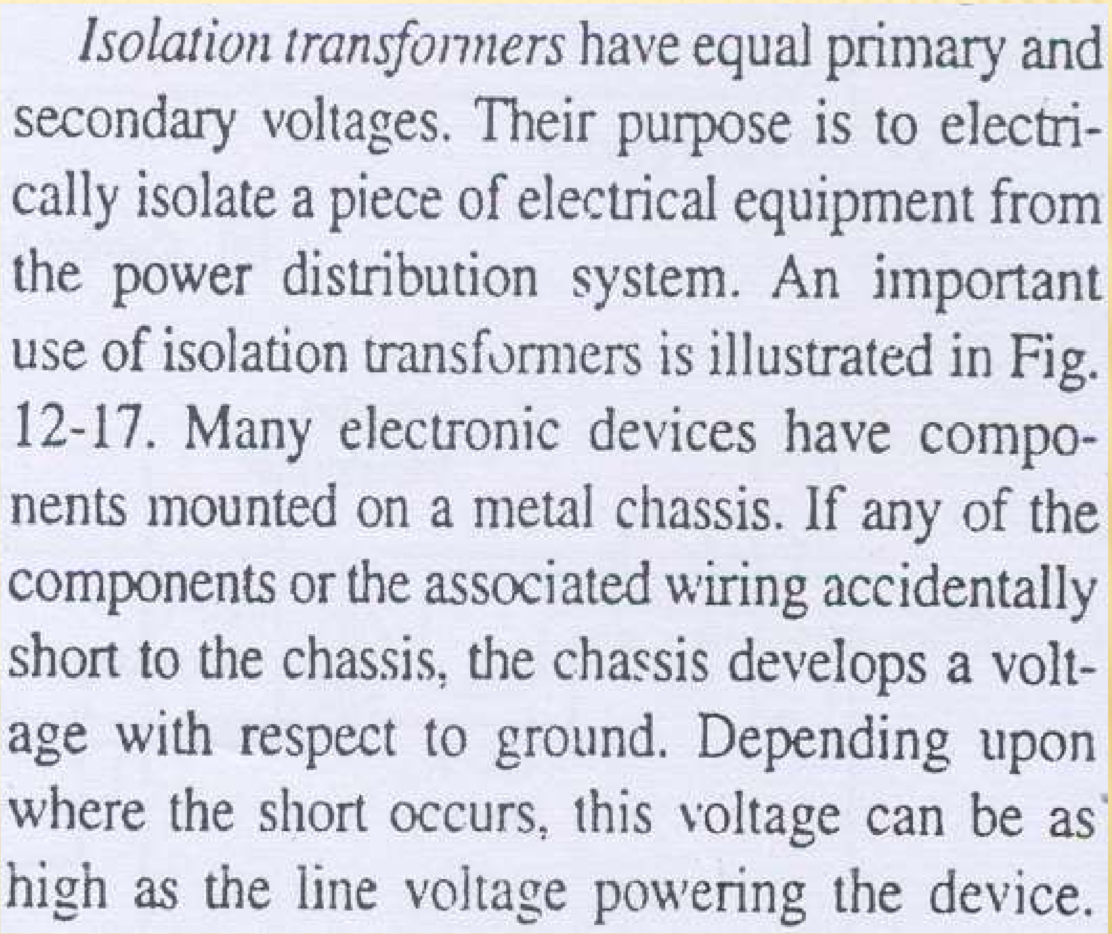


transformers are used in such devices as radio and television receivers and transmitters.

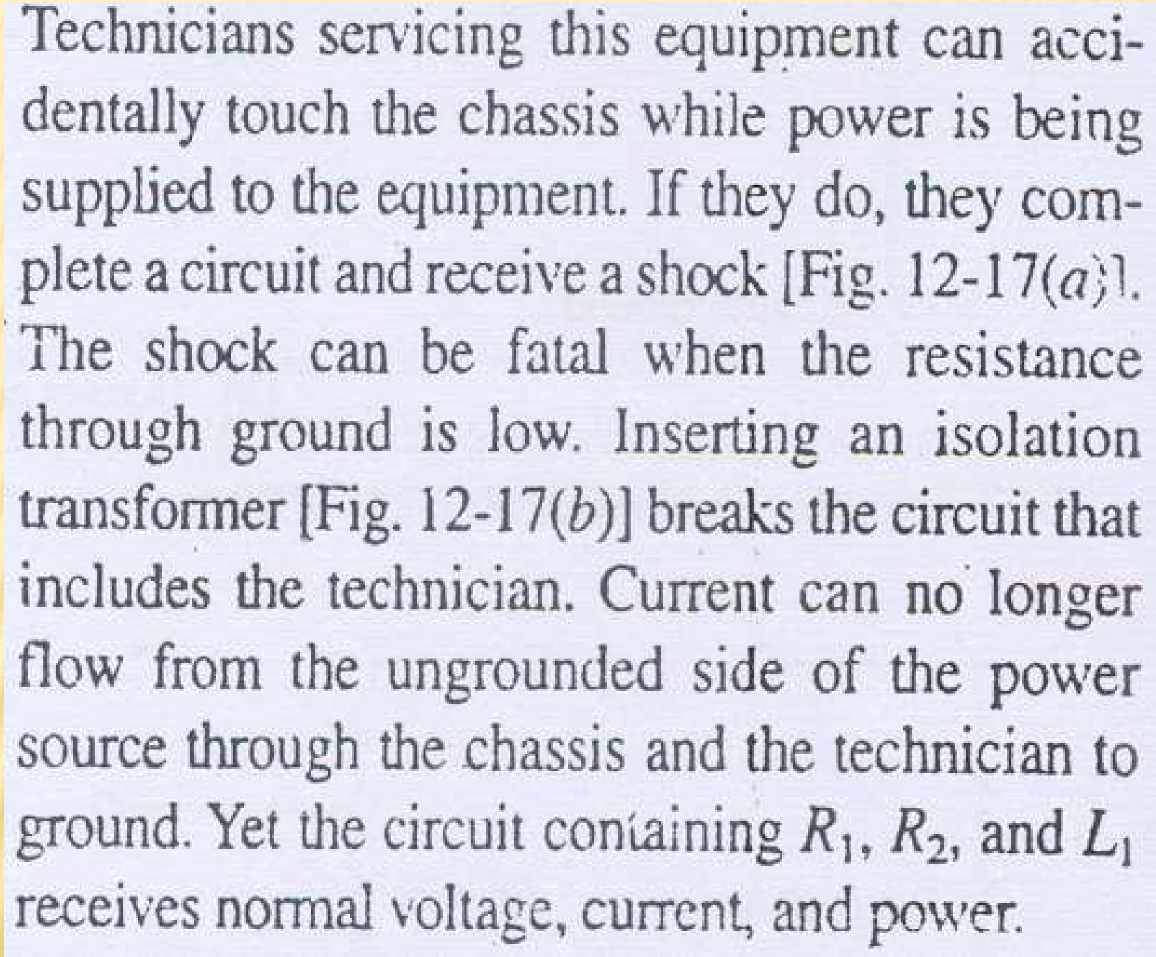
Some electrical and electronic equipment (such as data processing equipment and computers) is very sensitive to voltage changes. Such equipment is often powered by *constant-voltage transformers* because regular power-line voltage may vary too much. A constant-voltage transformer provides a stable secondary voltage even when the primary voltage is very unstable. Typically the primary voltage can vary from 95 to 130 V without causing more than 1 percent variation in the secondary voltage.

12-5 Types of Transformers

Transformers


Isolation transformers have equal primary and secondary voltages. Their purpose is to electrically isolate a piece of electrical equipment from the power distribution system. An important use of isolation transformers is illustrated in Fig. 12-17. Many electronic devices have components mounted on a metal chassis. If any of the components or the associated wiring accidentally short to the chassis, the chassis develops a voltage with respect to ground. Depending upon where the short occurs, this voltage can be as high as the line voltage powering the device.

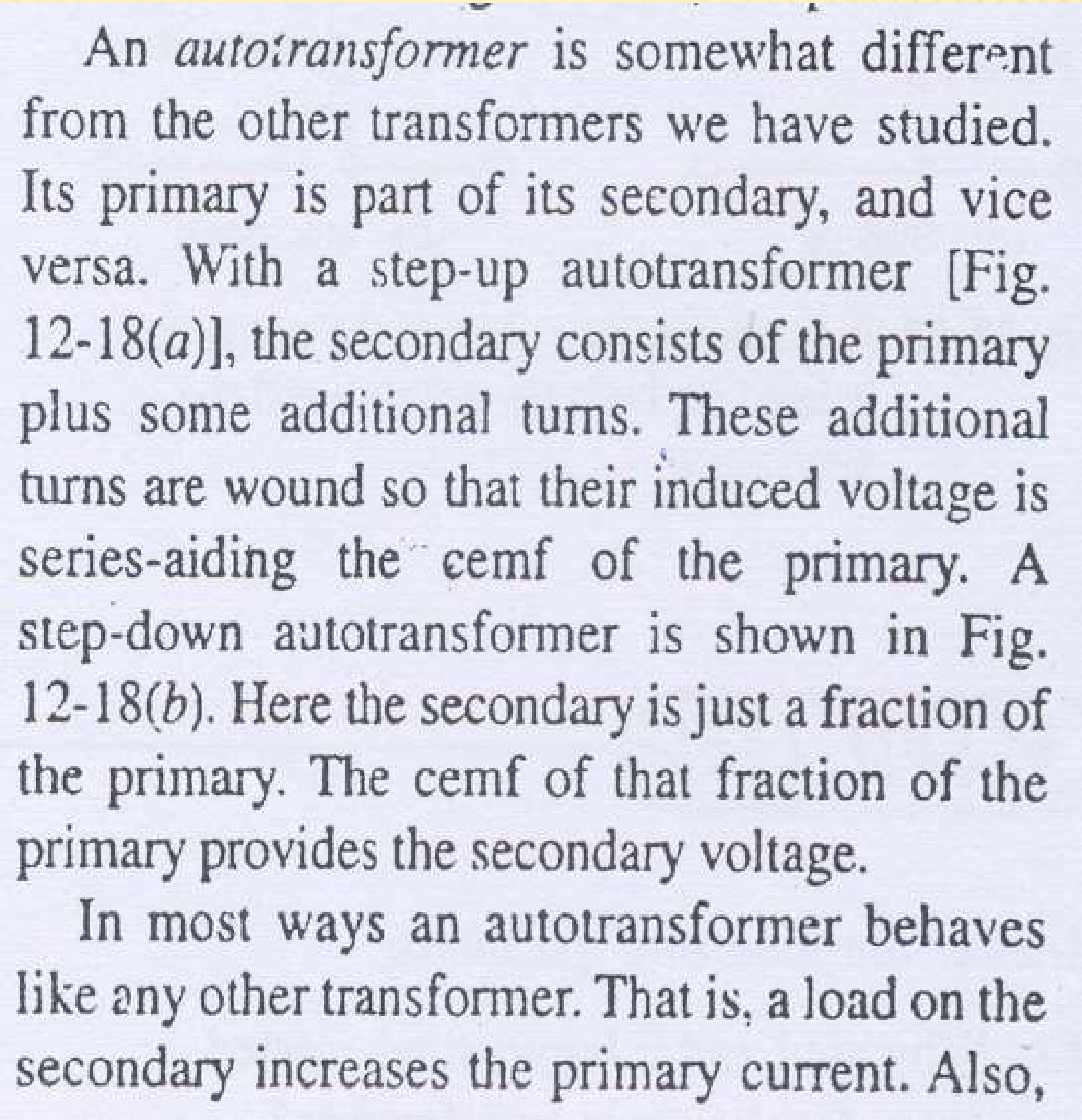
Transformers



Technicians servicing this equipment can accidentally touch the chassis while power is being supplied to the equipment. If they do, they complete a circuit and receive a shock [Fig. 12-17(*a*)]. The shock can be fatal when the resistance through ground is low. Inserting an isolation transformer [Fig. 12-17(*b*)] breaks the circuit that includes the technician. Current can no longer flow from the ungrounded side of the power source through the chassis and the technician to ground. Yet the circuit containing R_1, R_2, and L_1 receives normal voltage, current, and power.

12-5 Types of Transformers

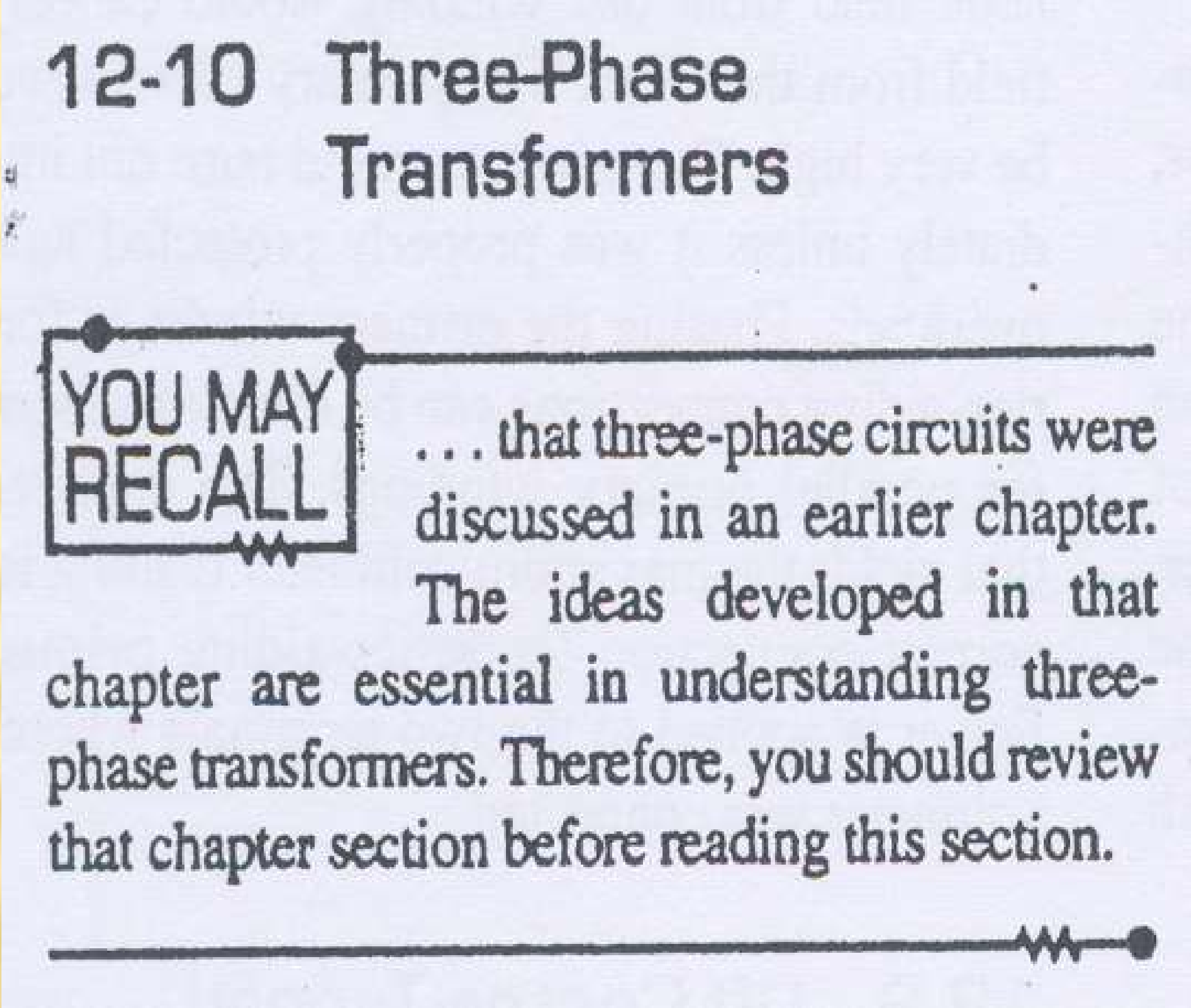
Transformers



An *autotransformer* is somewhat different from the other transformers we have studied. Its primary is part of its secondary, and vice versa. With a step-up autotransformer [Fig. 12-18(*a*)], the secondary consists of the primary plus some additional turns. These additional turns are wound so that their induced voltage is series-aiding the cemf of the primary. A step-down autotransformer is shown in Fig. 12-18(*b*). Here the secondary is just a fraction of the primary. The cemf of that fraction of the primary provides the secondary voltage.

In most ways an autotransformer behaves like any other transformer. That is, a load on the secondary increases the primary current. Also,

Transformers



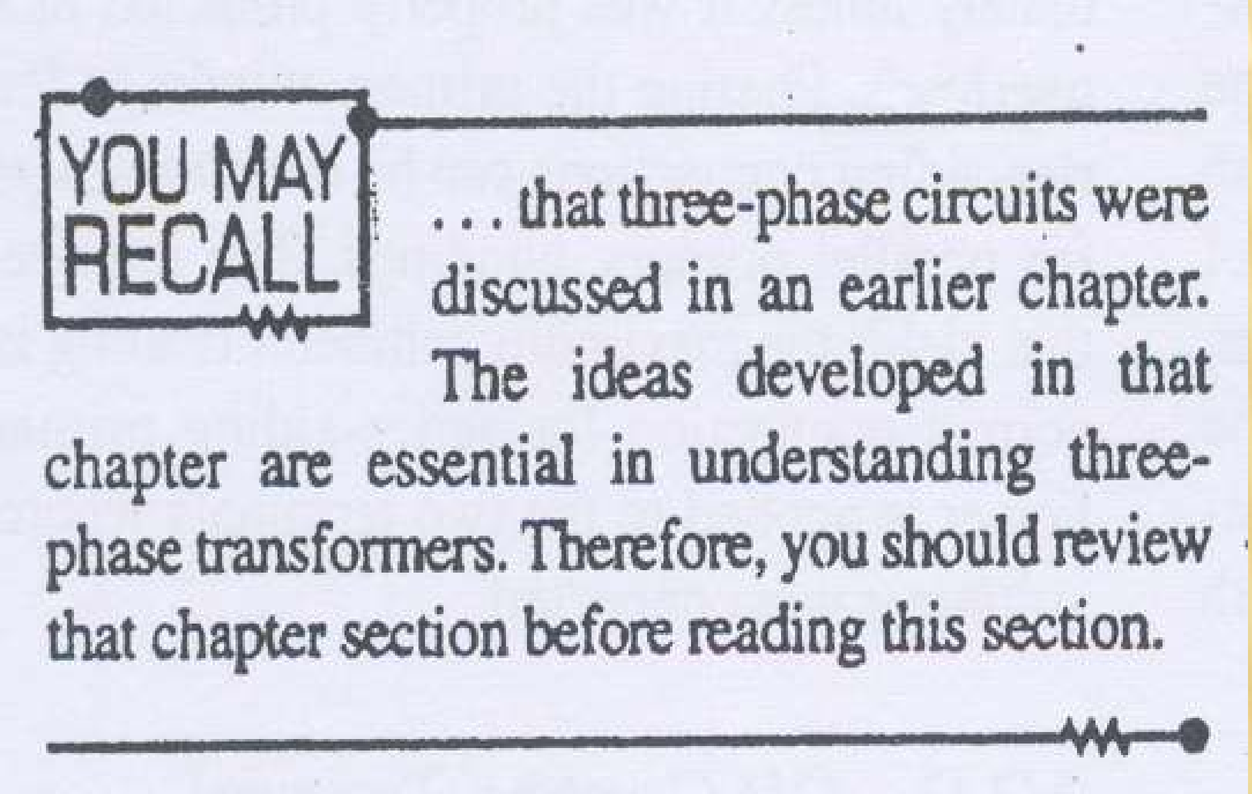
12-10 Three-Phase Transformers

YOU MAY RECALL

. . . that three-phase circuits were discussed in an earlier chapter. The ideas developed in that chapter are essential in understanding three-phase transformers. Therefore, you should review that chapter section before reading this section.

12-10 Three-Phase Transformers

Transformers



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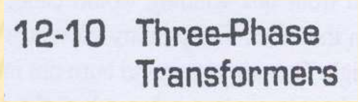
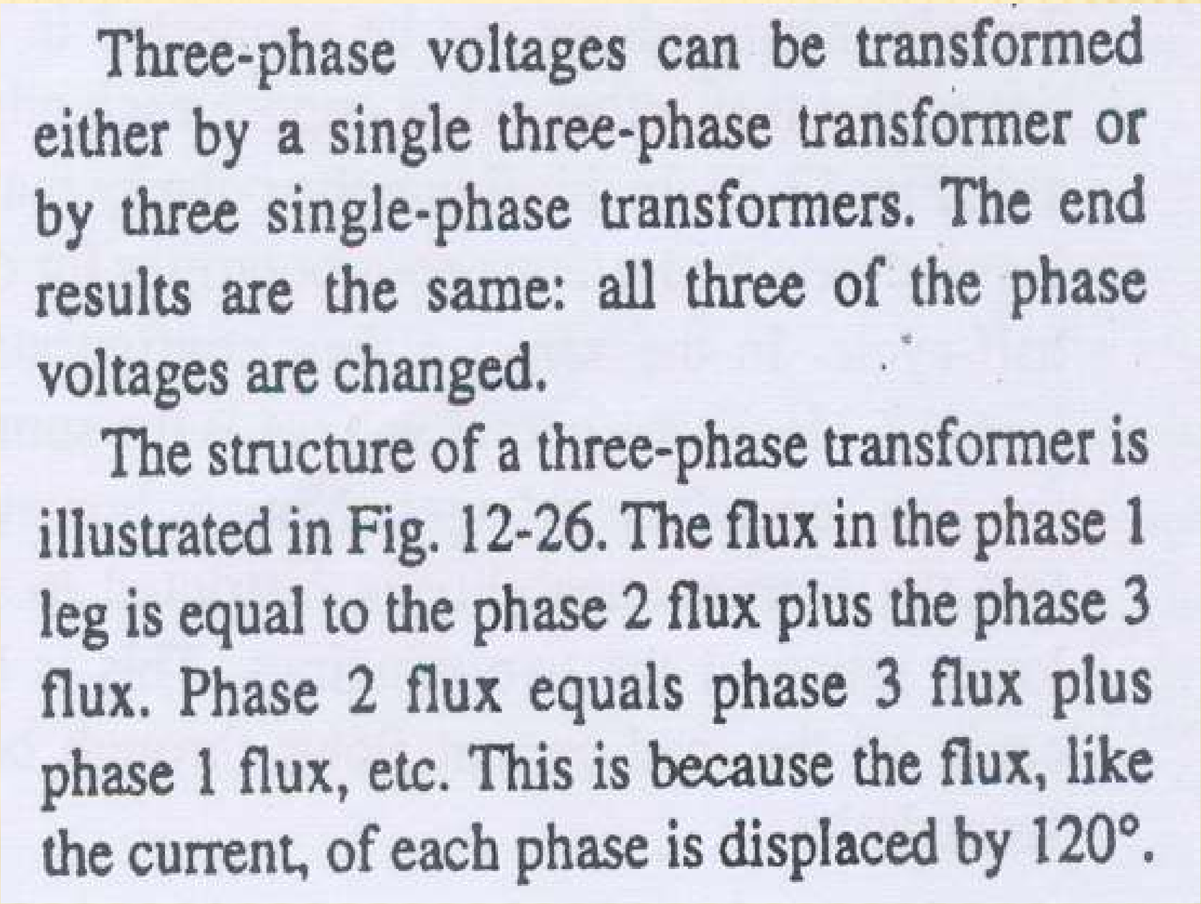

12-10 Three-Phase Transformers

Transformers


Three-phase voltages can be transformed either by a single three-phase transformer or by three single-phase transformers. The end results are the same: all three of the phase voltages are changed.

The structure of a three-phase transformer is illustrated in Fig. 12-26. The flux in the phase 1 leg is equal to the phase 2 flux plus the phase 3 flux. Phase 2 flux equals phase 3 flux plus phase 1 flux, etc. This is because the flux, like the current, of each phase is displaced by 120°.

12-10 Three-Phase Transformers

Transformers

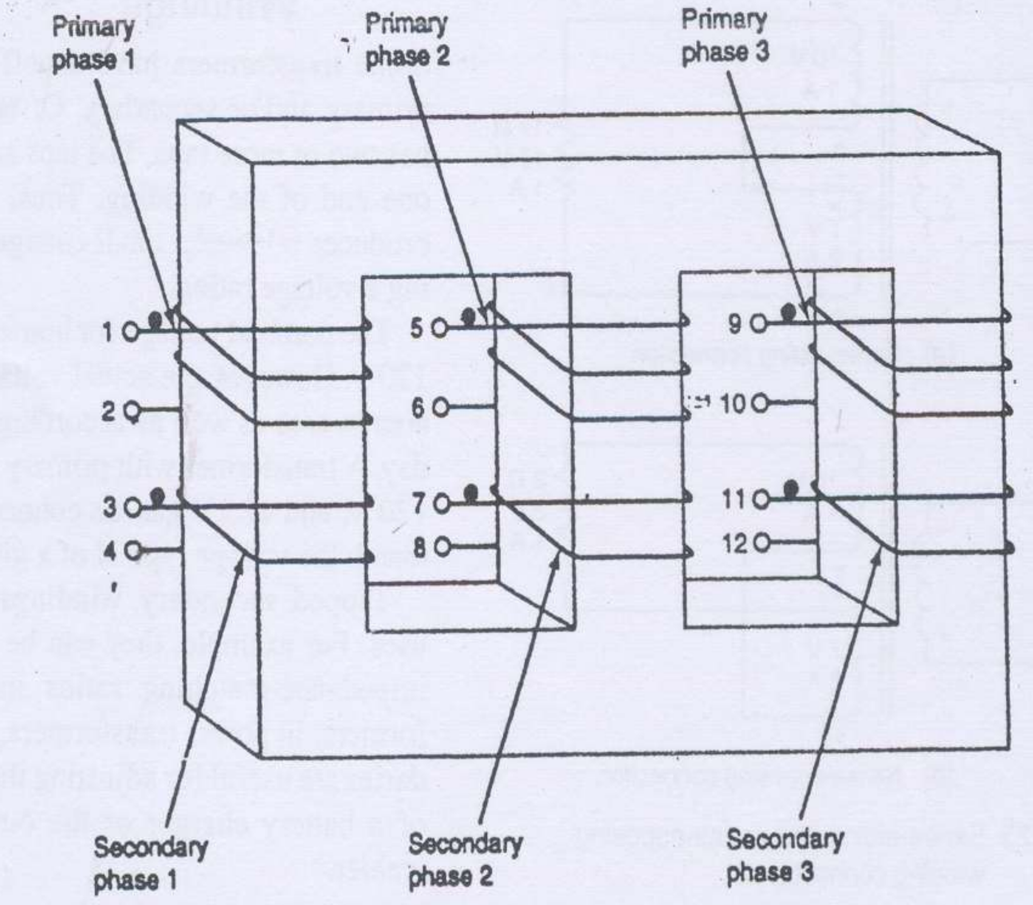
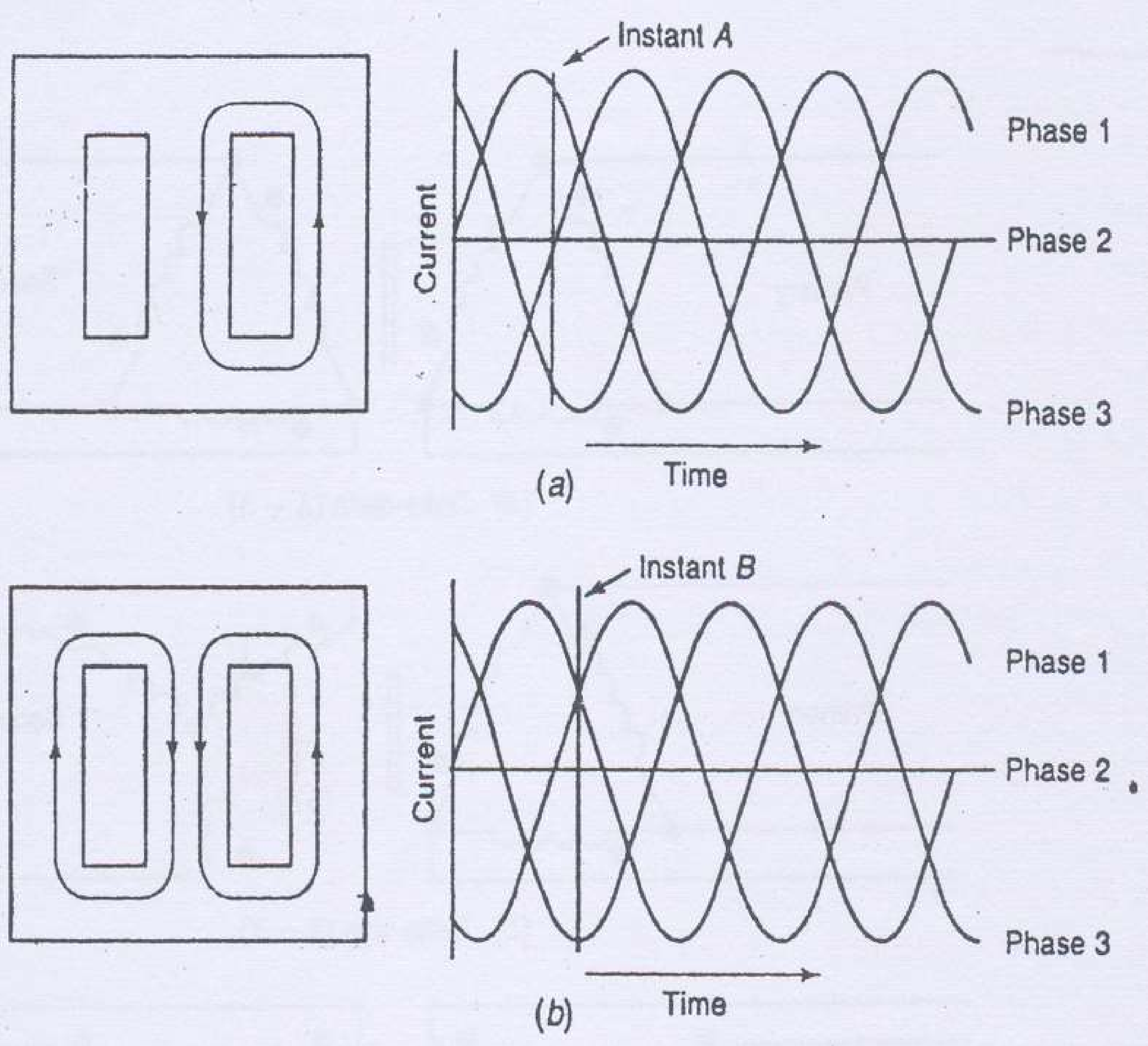


Fig. 12-26 Three-phase transformer. One phase is wound on each leg of the transformer.

12-10 Three-Phase Transformers

Transformers



12-10 Three-Phase Transformers

Transformers

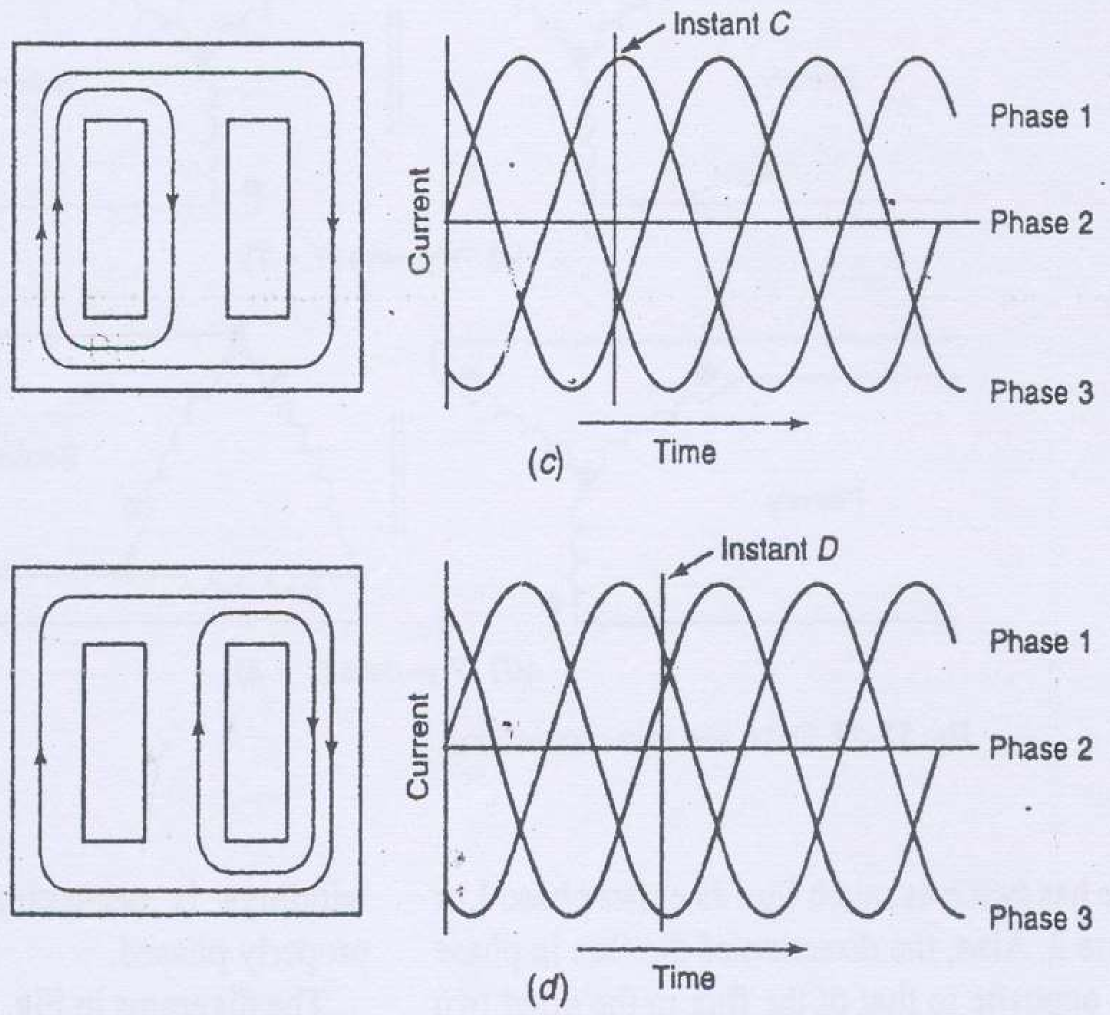


Fig. 12-27 Core flux in a three-phase transformer core.

12-10 Three-Phase Transformers

Transformers

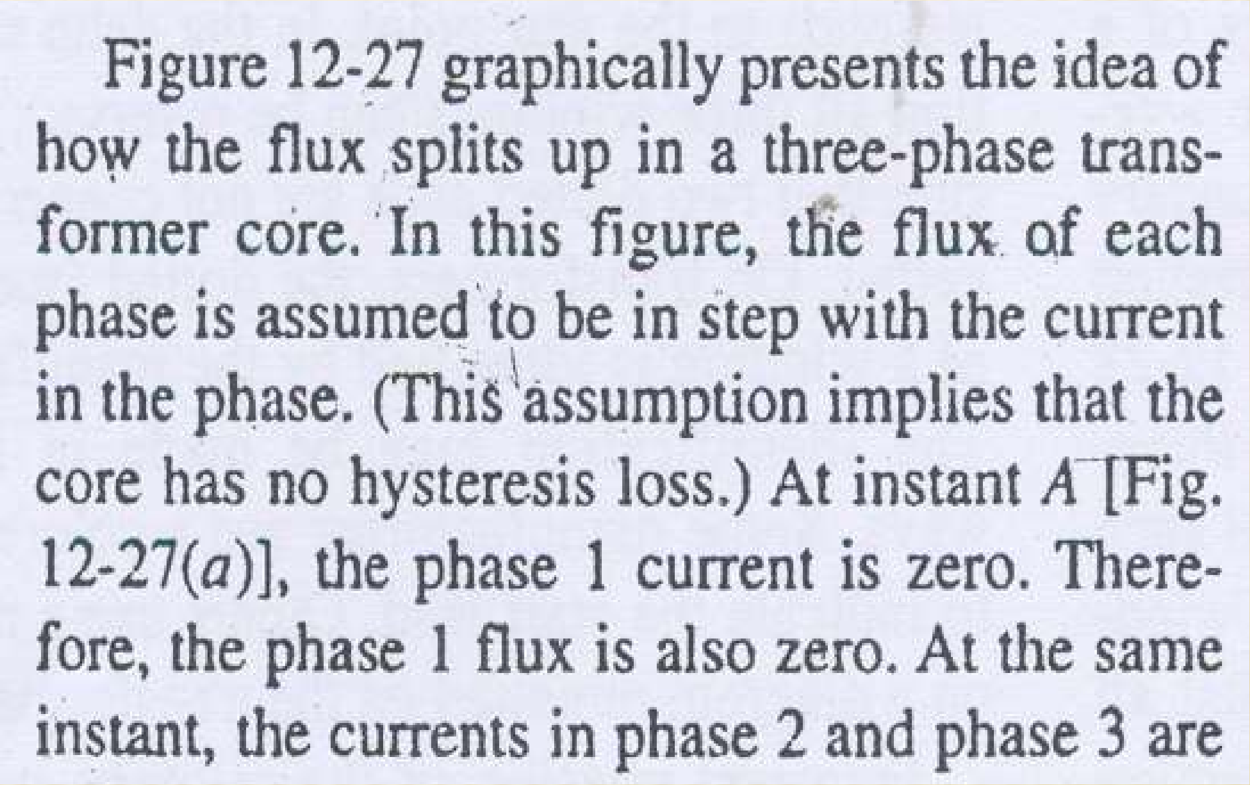
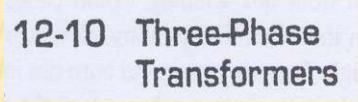
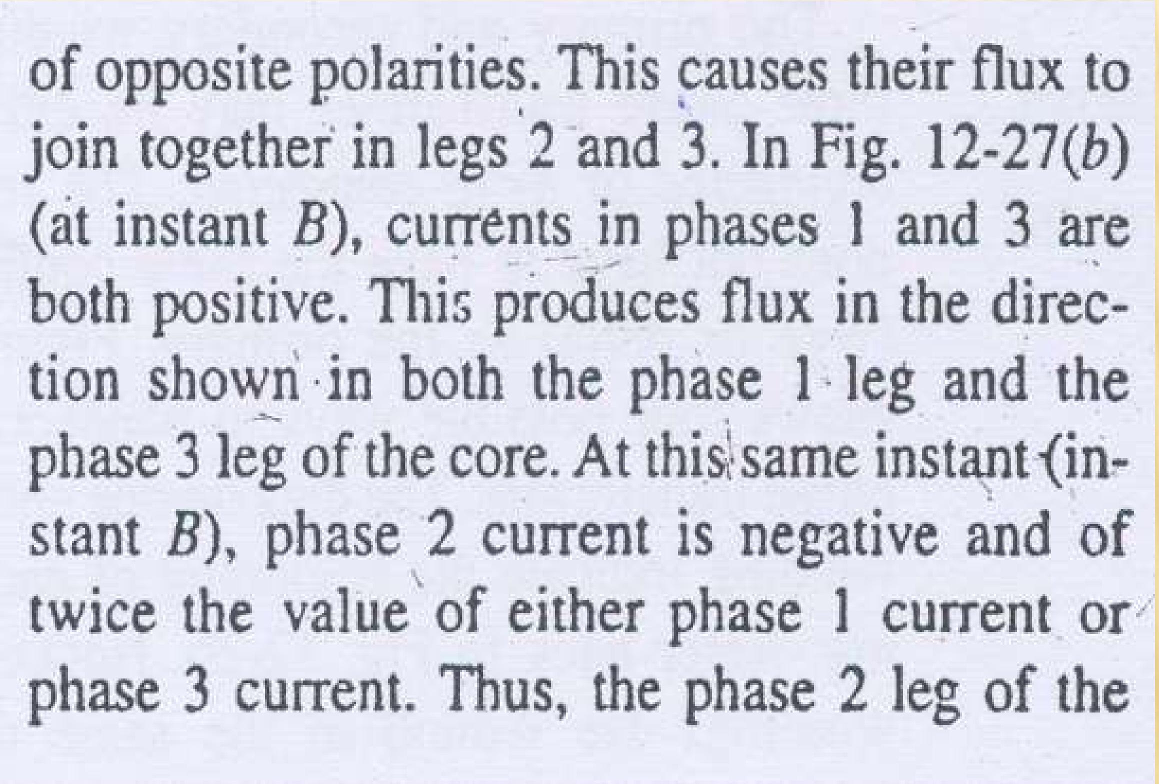


Figure 12-27 graphically presents the idea of how the flux splits up in a three-phase transformer core. In this figure, the flux of each phase is assumed to be in step with the current in the phase. (This assumption implies that the core has no hysteresis loss.) At instant *A* [Fig. 12-27(*a*)], the phase 1 current is zero. Therefore, the phase 1 flux is also zero. At the same instant, the currents in phase 2 and phase 3 are

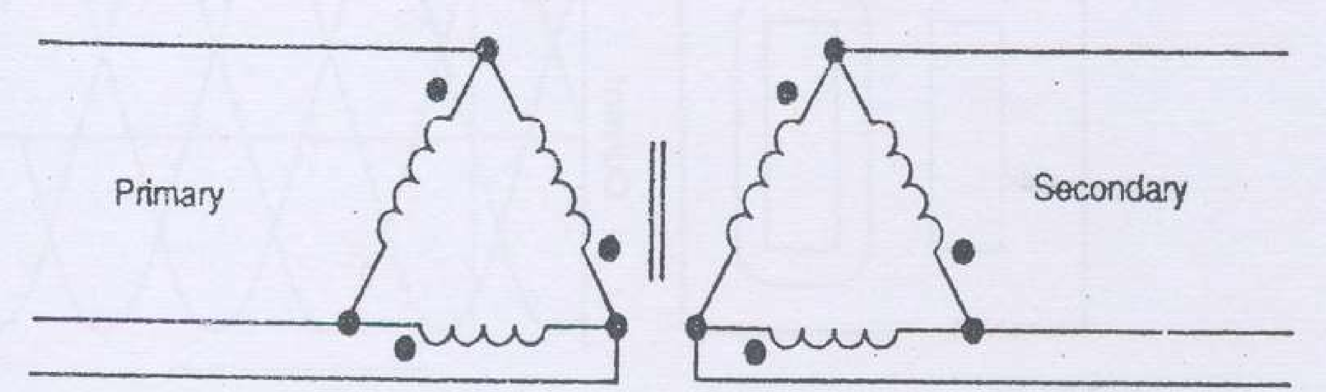

12-10 Three-Phase Transformers

Transformers

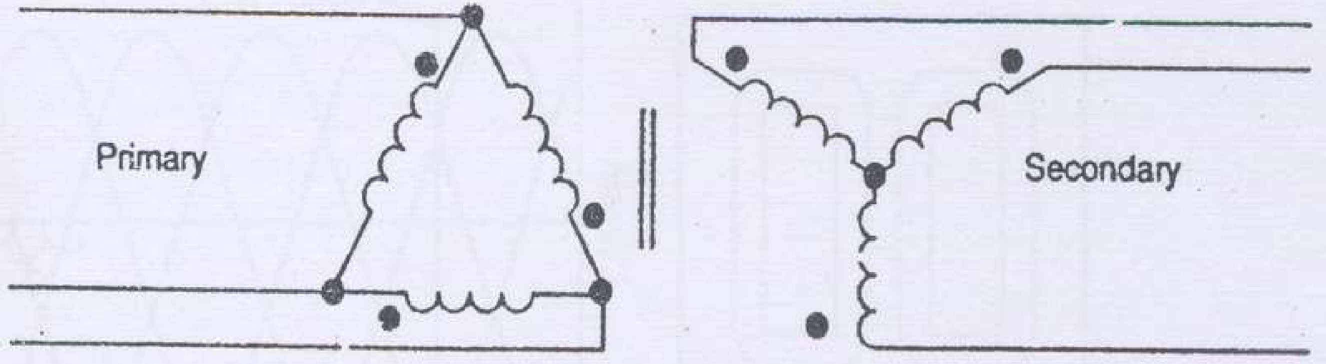

of opposite polarities. This causes their flux to join together in legs 2 and 3. In Fig. 12-27(*b*) (at instant *B*), currents in phases 1 and 3 are both positive. This produces flux in the direction shown in both the phase 1 leg and the phase 3 leg of the core. At this same instant (instant *B*), phase 2 current is negative and of twice the value of either phase 1 current or phase 3 current. Thus, the phase 2 leg of the

12-10 Three-Phase Transformers

Transformers



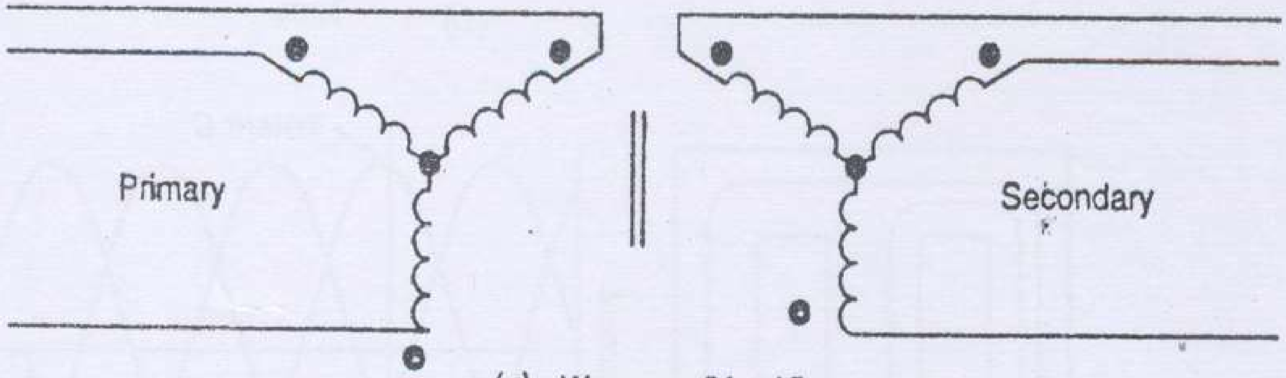
(a) Delta-delta (Δ – Δ)



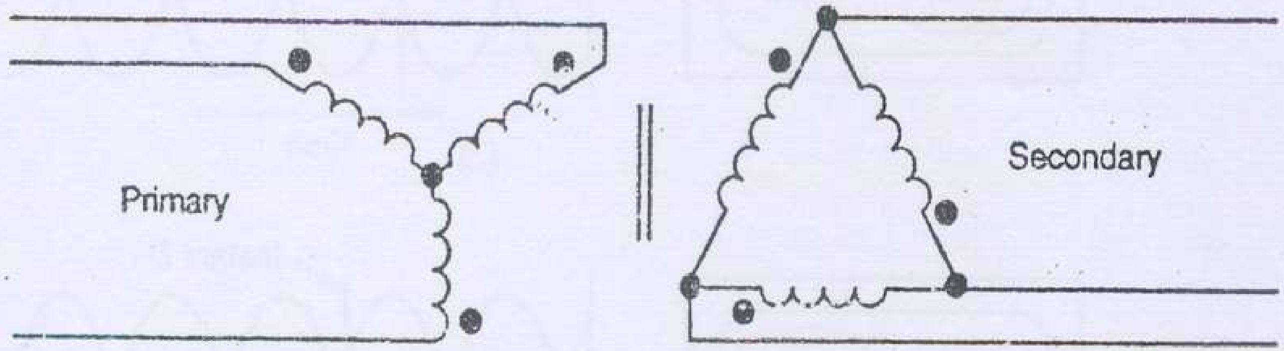
(b) Delta-wye (Δ – Y)

12-10 Three-Phase Transformers

Transformers



(c) Wye-wye (Y − Y)

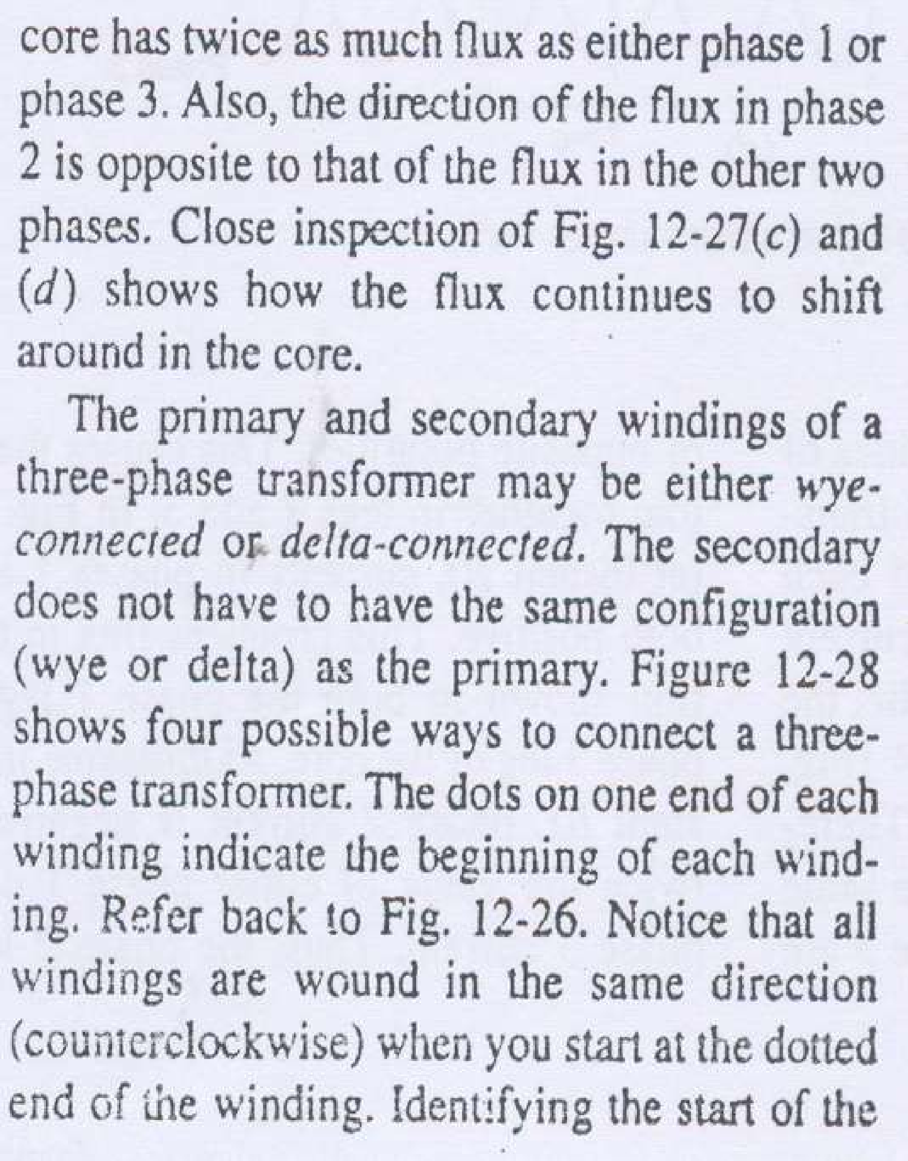


(d) Wye-delta (Y − Δ)

Fig. 12-28 Delta and wye connections.

12-10 Three-Phase Transformers

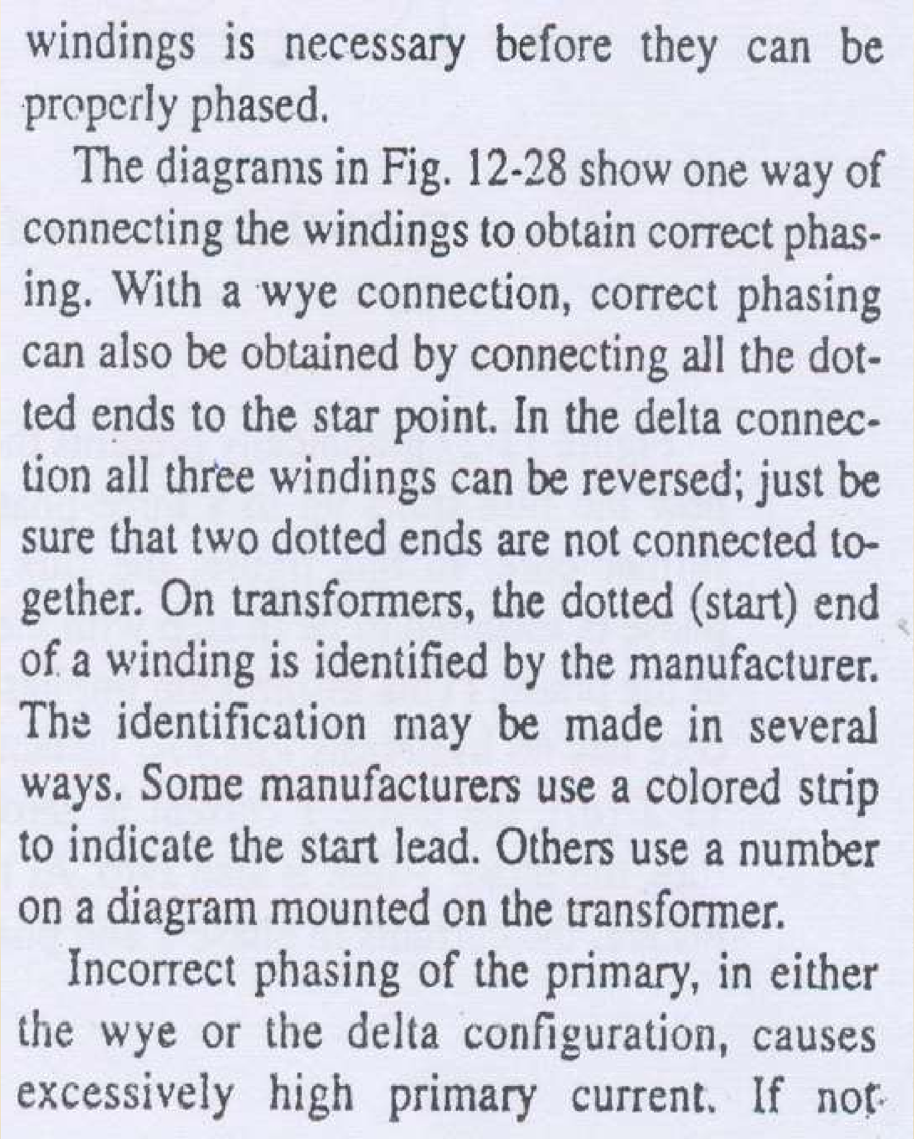
Transformers



core has twice as much flux as either phase 1 or phase 3. Also, the direction of the flux in phase 2 is opposite to that of the flux in the other two phases. Close inspection of Fig. 12-27(*c*) and (*d*) shows how the flux continues to shift around in the core.

The primary and secondary windings of a three-phase transformer may be either *wye-connected* or *delta-connected*. The secondary does not have to have the same configuration (wye or delta) as the primary. Figure 12-28 shows four possible ways to connect a three-phase transformer. The dots on one end of each winding indicate the beginning of each winding. Refer back to Fig. 12-26. Notice that all windings are wound in the same direction (counterclockwise) when you start at the dotted end of the winding. Identifying the start of the

Transformers



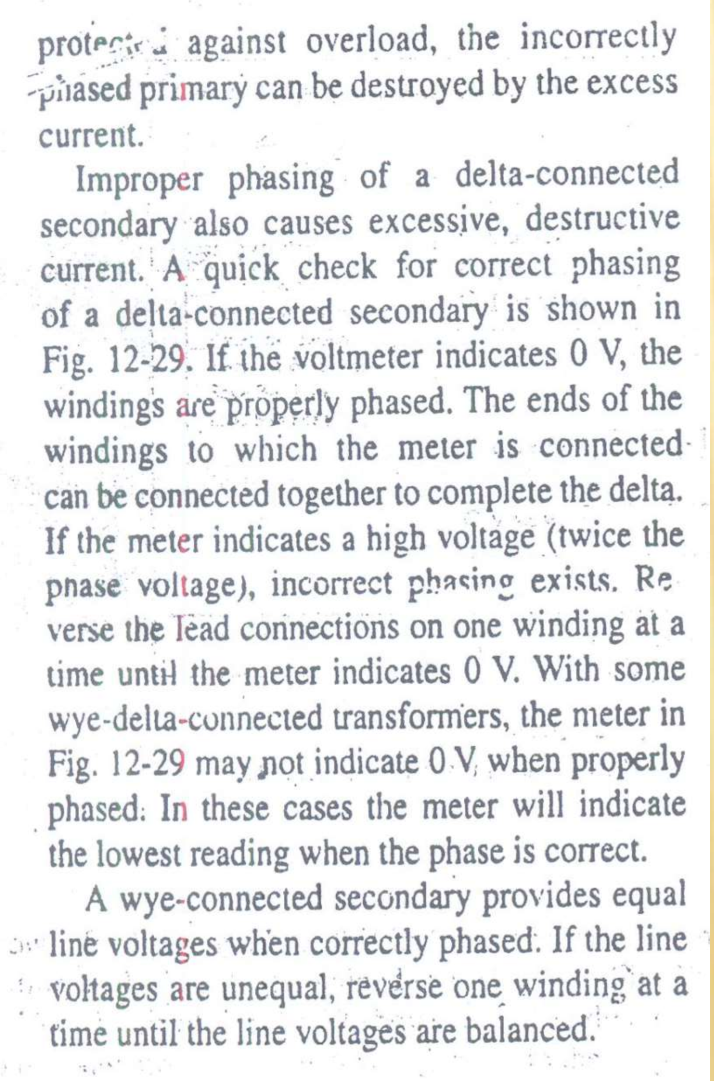
windings is necessary before they can be properly phased.

The diagrams in Fig. 12-28 show one way of connecting the windings to obtain correct phasing. With a wye connection, correct phasing can also be obtained by connecting all the dotted ends to the star point. In the delta connection all three windings can be reversed; just be sure that two dotted ends are not connected together. On transformers, the dotted (start) end of a winding is identified by the manufacturer. The identification may be made in several ways. Some manufacturers use a colored strip to indicate the start lead. Others use a number on a diagram mounted on the transformer.

Incorrect phasing of the primary, in either the wye or the delta configuration, causes excessively high primary current. If not

12-10 Three-Phase Transformers

Transformers



protected against overload, the incorrectly phased primary can be destroyed by the excess current.

Improper phasing of a delta-connected secondary also causes excessive, destructive current. A quick check for correct phasing of a delta-connected secondary is shown in Fig. 12-29. If the voltmeter indicates 0 V, the windings are properly phased. The ends of the windings to which the meter is connected can be connected together to complete the delta. If the meter indicates a high voltage (twice the phase voltage), incorrect phasing exists. Reverse the lead connections on one winding at a time until the meter indicates 0 V. With some wye-delta-connected transformers, the meter in Fig. 12-29 may not indicate 0 V when properly phased. In these cases the meter will indicate the lowest reading when the phase is correct.

A wye-connected secondary provides equal line voltages when correctly phased. If the line voltages are unequal, reverse one winding at a time until the line voltages are balanced.

Transformers

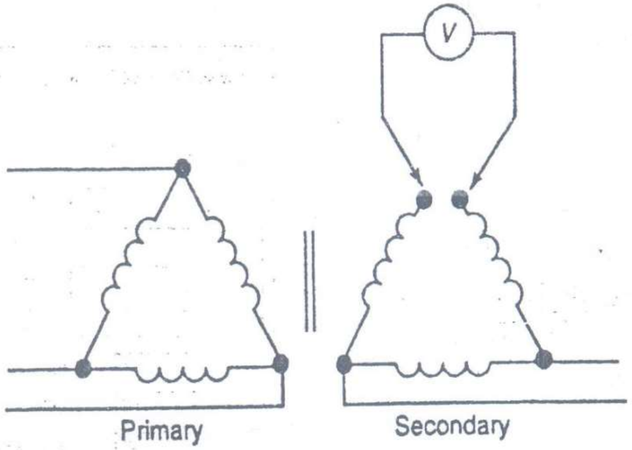
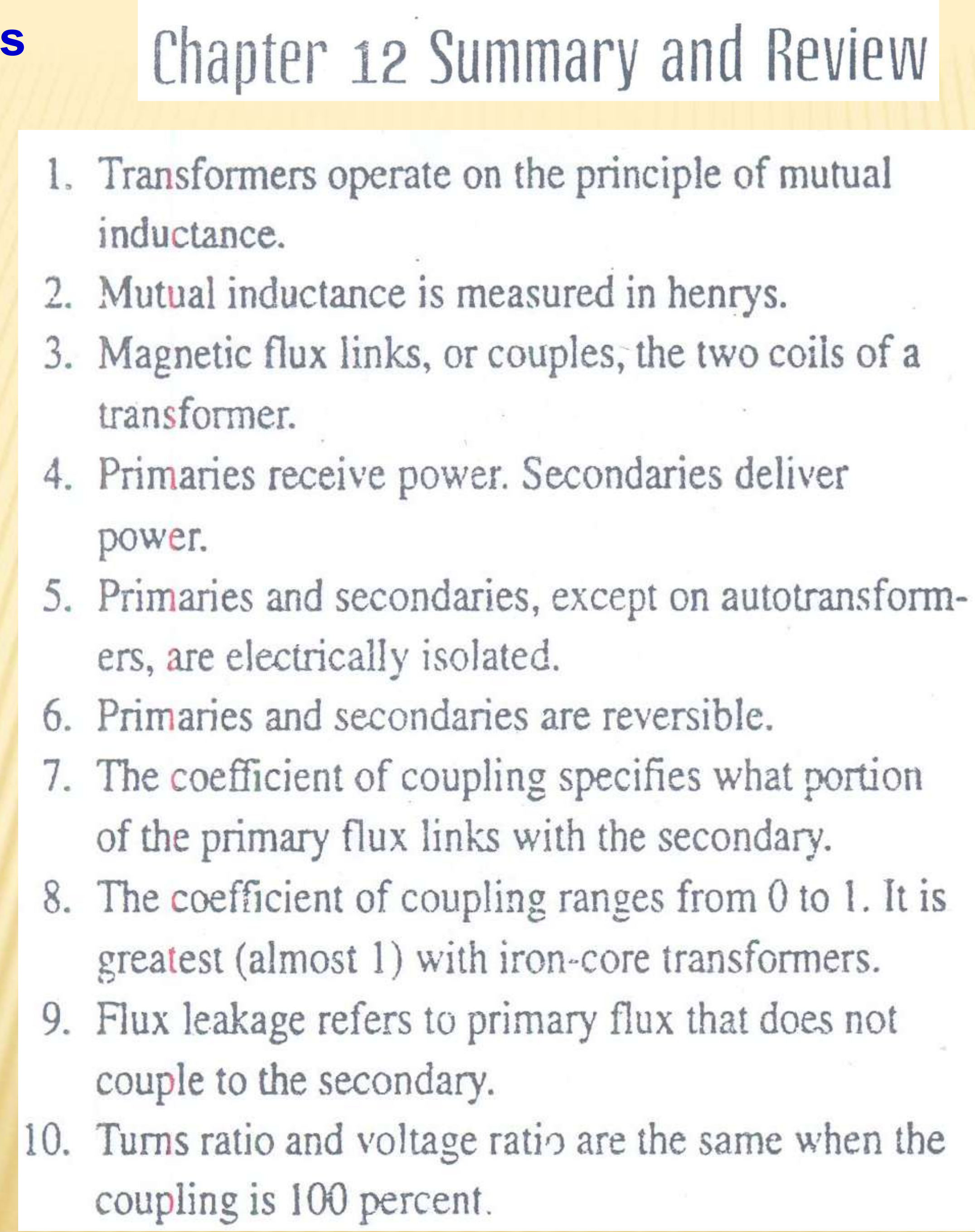


Fig. 12-29 Checking delta phasing. When properly phased, the meter will indicate 0 V.

YOU MAY RECALL

. . . that the relationships between phase and line voltages and phase and line currents were explained in an earlier chapter. These relationships apply to three-phase transformers as well as to three-phase generators.

Transformers

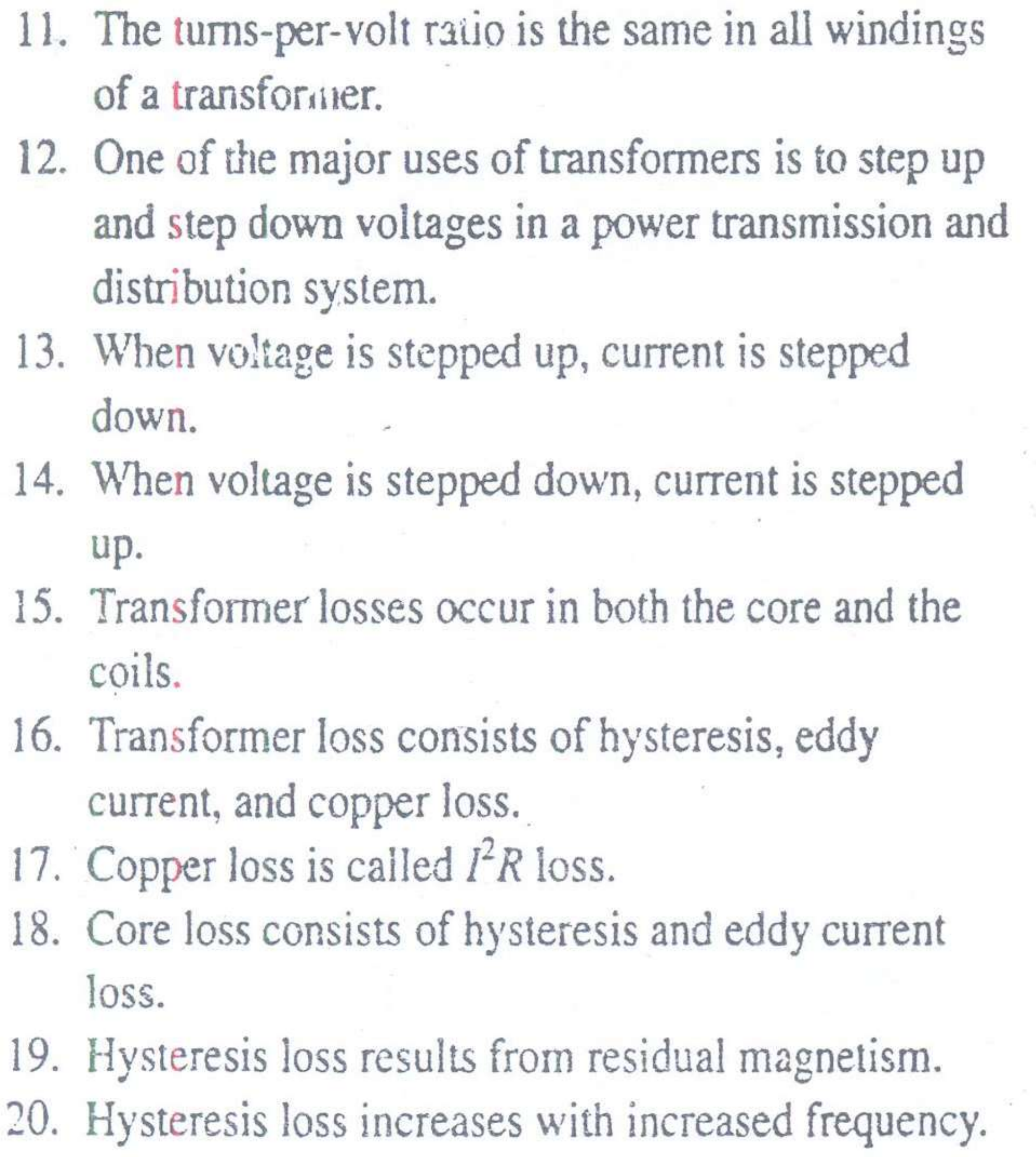


Chapter 12 Summary and Review

1. Transformers operate on the principle of mutual inductance.
2. Mutual inductance is measured in henrys.
3. Magnetic flux links, or couples, the two coils of a transformer.
4. Primaries receive power. Secondaries deliver power.
5. Primaries and secondaries, except on autotransformers, are electrically isolated.
6. Primaries and secondaries are reversible.
7. The coefficient of coupling specifies what portion of the primary flux links with the secondary.
8. The coefficient of coupling ranges from 0 to 1. It is greatest (almost 1) with iron-core transformers.
9. Flux leakage refers to primary flux that does not couple to the secondary.
10. Turns ratio and voltage ratio are the same when the coupling is 100 percent.

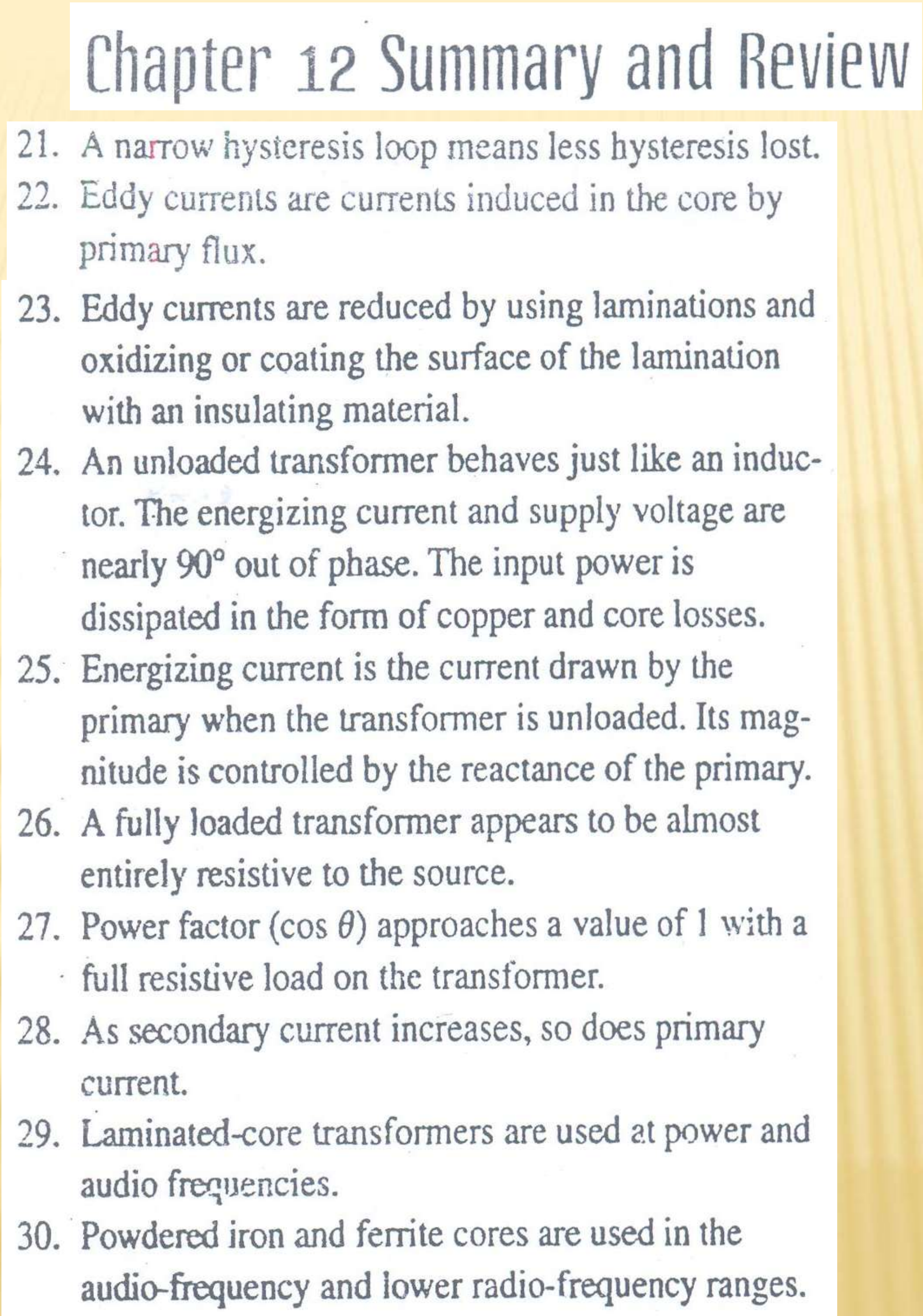
Transformers

Chapter 12 Summary and Review



11. The turns-per-volt ratio is the same in all windings of a transformer.
12. One of the major uses of transformers is to step up and step down voltages in a power transmission and distribution system.
13. When voltage is stepped up, current is stepped down.
14. When voltage is stepped down, current is stepped up.
15. Transformer losses occur in both the core and the coils.
16. Transformer loss consists of hysteresis, eddy current, and copper loss.
17. Copper loss is called I^2R loss.
18. Core loss consists of hysteresis and eddy current loss.
19. Hysteresis loss results from residual magnetism.
20. Hysteresis loss increases with increased frequency.

Transformers

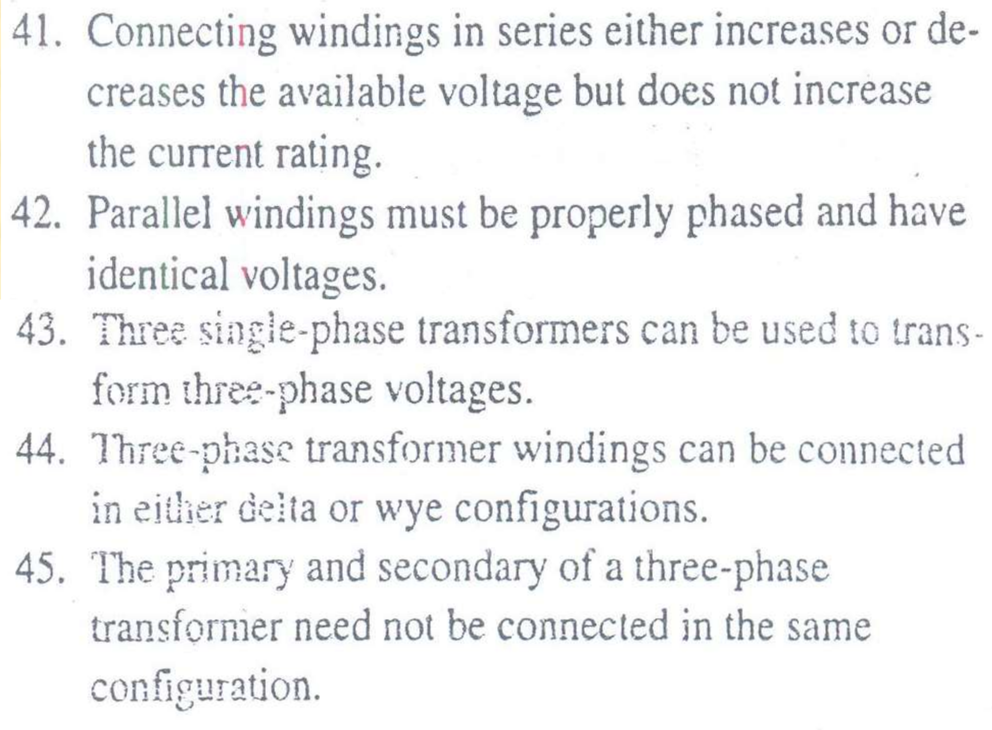


Chapter 12 Summary and Review

21. A narrow hysteresis loop means less hysteresis lost.
22. Eddy currents are currents induced in the core by primary flux.
23. Eddy currents are reduced by using laminations and oxidizing or coating the surface of the lamination with an insulating material.
24. An unloaded transformer behaves just like an inductor. The energizing current and supply voltage are nearly 90° out of phase. The input power is dissipated in the form of copper and core losses.
25. Energizing current is the current drawn by the primary when the transformer is unloaded. Its magnitude is controlled by the reactance of the primary.
26. A fully loaded transformer appears to be almost entirely resistive to the source.
27. Power factor (cos θ) approaches a value of 1 with a full resistive load on the transformer.
28. As secondary current increases, so does primary current.
29. Laminated-core transformers are used at power and audio frequencies.
30. Powdered iron and ferrite cores are used in the audio-frequency and lower radio-frequency ranges.

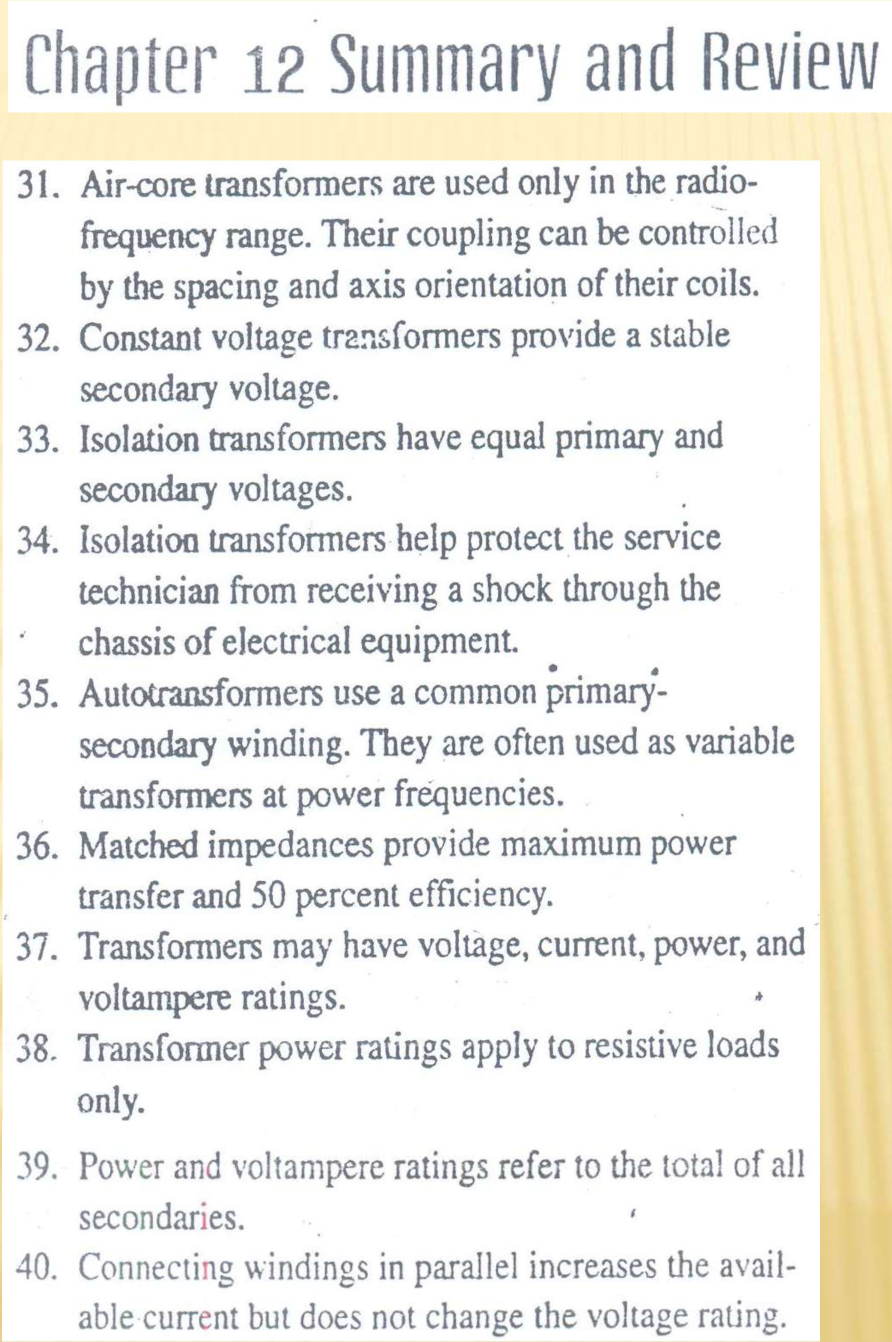
Transformers

Chapter 12 Summary and Review



41. Connecting windings in series either increases or decreases the available voltage but does not increase the current rating.
42. Parallel windings must be properly phased and have identical voltages.
43. Three single-phase transformers can be used to transform three-phase voltages.
44. Three-phase transformer windings can be connected in either delta or wye configurations.
45. The primary and secondary of a three-phase transformer need not be connected in the same configuration.

Transformers



Chapter 12 Summary and Review

31. Air-core transformers are used only in the radio-frequency range. Their coupling can be controlled by the spacing and axis orientation of their coils.
32. Constant voltage transformers provide a stable secondary voltage.
33. Isolation transformers have equal primary and secondary voltages.
34. Isolation transformers help protect the service technician from receiving a shock through the chassis of electrical equipment.
35. Autotransformers use a common primary-secondary winding. They are often used as variable transformers at power frequencies.
36. Matched impedances provide maximum power transfer and 50 percent efficiency.
37. Transformers may have voltage, current, power, and voltampere ratings.
38. Transformer power ratings apply to resistive loads only.
39. Power and voltampere ratings refer to the total of all secondaries.
40. Connecting windings in parallel increases the available current but does not change the voltage rating.