2. TRANSFORMERS

Transformers are commonly used in applications which require the conversion of AC voltage from one voltage level to another. There are two broad categories of transformers: *electronic* transformers, which operate at very low power levels, and *power* transformers, which process thousands of watts of power. Electronic transformers are used in consumer electronic equipment like television sets, VCRs, CD players, personal computers, and many other devices, to reduce the level of voltage from 220V (available from the AC mains) to the desired level at which the device operates. Power transformers are used in power generation, transmission and distribution systems to raise or lower the level of voltage to the desired levels. The basic principle of operation of both types of transformers is the same.

In this chapter, we will first review some of the basic concepts of magnetic circuits, which are fundamental building blocks in transformers and electric machinery. In order to understand how a transformer operates, we will examine two inductors that are placed in close proximity to one another. The concepts of such magnetic coupled circuits will be extended to the development of transformers. After understating the relationships between voltages and currents, we will look at some practical considerations regarding the use of transformers.

The main learning objectives for this chapter are listed below.

Learning Objectives:

- Understand concept of mutual inductance
- Understand operation of ideal transformers.
- Use equivalent circuits to determine voltages and currents.
- Analyze the operation of transformer for different transformation ratios.
- Understand the concept of a reflected load in a transformer, and its application in impedance matching.
- Study the application of transformers in electrical energy distribution and power supplies.

Recommended text for this section of the course:

(i) Allan R. Hambley, *Electrical Engineering Principles and Applications*, Chapter 15.

(ii) Giorgio Rizzoni, *Principles and Applications of Electrical Engineering*, Chapter 16.

Magnetic Field and Mutual Inductance: Review of basic concepts

(Please note that these concepts are covered in detail in the Physics module, and therefore will not be discussed in detail in EG1108. The basic terminology is, however, briefly reviewed here.)

2.1 Magnetic field

Magnetic fields are created due to movement of electrical charge, and are present around permanent magnets and wires carrying current (electromagnet), as shown in figure 1.

- In permanent magnets, spinning electrons produce a net external field.
- If a current carrying wire is wound in the form of a coil of many turns, the net magnetic field is stronger than that of a single wire. This field of the electromagnet is further intensified if this coil is wound on an iron core.

In many applications, we need to vary the strength of magnetic fields. Electromagnets are very commonly used in such applications.

- The magnetic field is represented by "*lines of flux*".
- These lines of flux help us to visualize the magnetic field of any magnet even though they only represent an invisible phenomena.
- Magnetic field forms an essential link between transfer of energy from mechanical to electrical form and vice-versa (as we will see later).

Magnetic fields form the basis for the operation of transformers, generators, and motors.

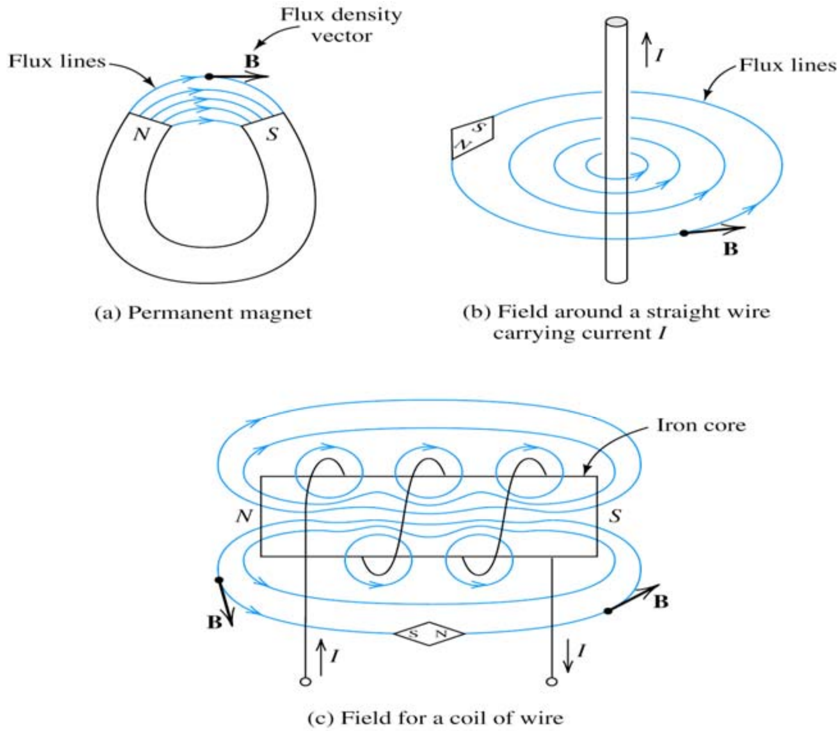


Figure 1: Magnetic field created by (a) permanent magnet, (b) straight wire, (c) coil of wire wound on an iron core

- The direction of this magentic field can be determined using the right hand rule.
- This rule states that if you point the thumb of your right hand in the direction of the current, your fingers will point in the direction of the magnetic field.

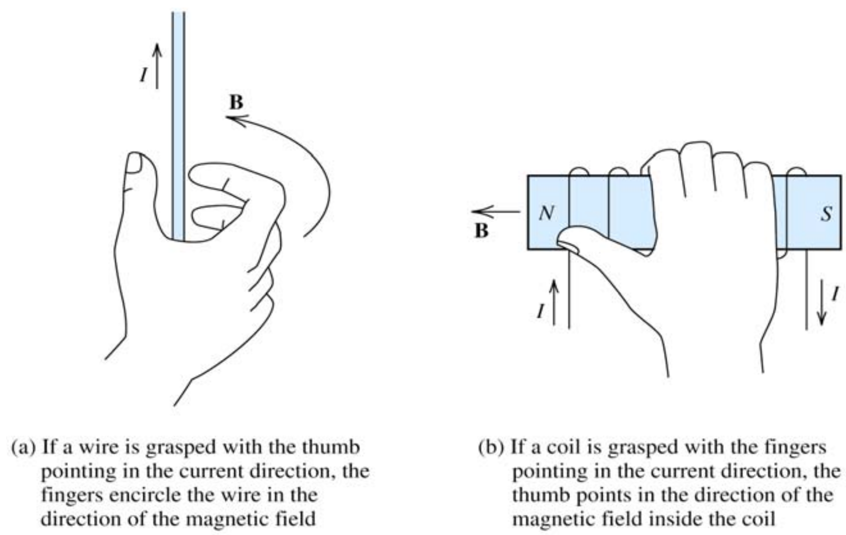


Figure 2: Right hand rule

2.2 Magnetic Flux, Φ

Magnetic field can be visualized as lines of ***magnetic flux*** that form closed paths (see Figure 1). Magnetic flux emanates from the north pole and returns through the south pole.

- Magnetic flux describes the total amount of magnetic field in a given region.
- Magnetic flux is imperceptible to the five senses and thus hard to describe.
- Flux is known only through its effects.
- It is measured in Webers (Wb)

2.3 Magnetic Flux Density, *B*

If we examine the cross-sectional area of the magnet shown in Figure 1(a) and assume that the flux is uniformly distributed over the area, the magnetic flux density is defined as the magnetic Flux per cross-sectional area.

i.e., $$B = \frac{\phi}{A} \qquad (1)$$

where A is the cross sectional area.

- Flux density is a vector quantity
- Its units are Weber per sq meter or Teslas (*T*)

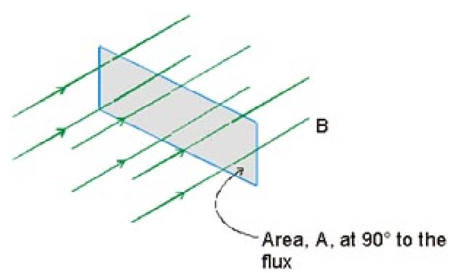


Figure 3: Magnetic flux density

2.4 Flux Linkage, λ

- The flux passing through the surface bounded by a coil is said to ***link*** the coil (refer to figure 1(c)).
- For a coil of wire, the flux passing through the coil is the product of the number of turns, *N*, and the flux passing through a single turn, ϕ.
- This product is called the magnetic flux linkage of the coil, λ.

i.e., $\lambda = N\phi$ weber-turns. (2)

2.5 Faraday's Law

Michael Faraday discovered that whenever a conductor is moved through a magnetic field, or whenever the magnetic field near a conductor is changed, currents flow in the conductor. This effect is called **electromagnetic induction**.

Voltage induced in ***a single coil***, due to sinusoidally varying flux ϕ is:

$$e_t = \frac{d\phi}{dt} \quad volts \tag{3}$$

For a coil with N number of turns, the total induced voltage can be calculated by adding the voltages induced in all the turns,

$$e = Ne_t = N\frac{d\phi}{dt} \quad \text{volts} \tag{4}$$

Substituting from equation (2), $\lambda = N\,\phi$

$$e = \frac{d\lambda}{dt} \quad \text{volts} \tag{5}$$

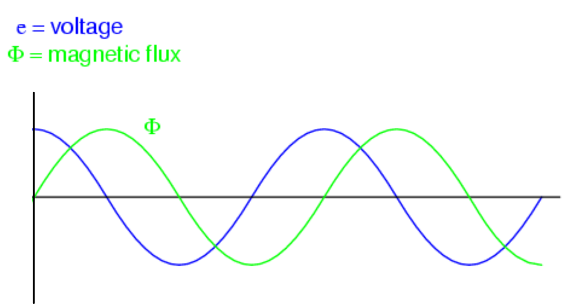


Figure 4: Voltage induced in a coil due to sinusoidally varying flux

In summary,

- The magnetic flux induces voltage in a coil if the flux linkages are changing with respect to time.

What will happen if the conductor is moving, while the flux lines are stationary?

Example 1:

A 10-turn circular coil has a radius of 5cm.

(i) A flux density of 0.5 T is directed perpendicular to the plane of the coil. Evaluate the flux linking the coil and the flux linakges.

(ii) Suppose that the flux is reduced to zero at a uniform rate during an interval of 1 milli second. Determine the voltage induced in the coil.

Solution:

(i) Using the equation for flux density ($\mathbf{B} = \phi/A$):

$$\text{flux } \phi = B\,A = B\,\pi\,r^2$$

$$= 0.5\,\pi\,(0.05)^2 \text{ Wb}$$

$$= 0.003927 \text{ Wb}$$

Flux linkage, $\lambda = N\,\phi = 10 \times 0.003927 = 0.03927$ Wb-turns

(ii) If the flux is reduced from this value to zero in $dt = 0.001$ seconds,

$$\text{Induced voltage, } e = d\lambda/dt = -\frac{0.03927}{0.001}$$

$$= -39.27 \text{ V}$$

Note that, here the flux is being reduced from a positive value to zero, hence the negative sign. However, more information is needed to determine the polarity of this voltage using Lenz's Law. Thus the minus sign of the result is not meaningful.

2.6 Analogy between Magnetic and Electric Circuits

In circuits that involve multiple coils magnetic circuit concepts, which are analogous to those used for analysis of electric circuits, are used.

- The ***magnetomotive force*** (mmf) of an N-turn current carrying coil is given by:

  $$\mathcal{F} = N\,i \qquad (6)$$

The magnetomotive force in magnetic circuits is analogous to a source voltage of an electric circuit.

- The ***reluctance*** of a magnetic circuit is analogous to the resistance of an electric circuit, and is given by:

  $$\Re = l\,/\mu A \qquad (7)$$

  where l is the length of the path, A is the cross-sectional area, and μ is the permeability of the material.

- The ***magnetic flux*** ϕ in a magnetic circuit is analogous to current in electric circuits.

It can be shown that these three are related by:

$$F = \Re\phi \qquad (8)$$

Which is the magnetic circuit equivalent of Ohm's Law ($V = i\,R$).

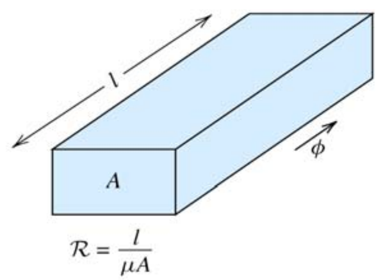


Figure 5: Magnetic circuit

In summary, when an N-turn coil carrying a current *i* is wound around a magnetic core, the magnetomotive force generated by the coil produces a flux within the core. Assuming that this flux is uniformly distributed across the cross-section, then the magnetic circuit is analogous to a resistive electric circuit.

2.7 Mutual Inductance

Consider the situation illustrated in figure 6 where two coils are placed close to each other. To keep our discussion simple, let's assume that the resistance of the coils is negligible. When AC current flows through the first coil, it produces a time-varying flux. When the second coil is placed in its vicinity, some of this flux links the other coil. According to Faraday's law, this flux in turn induces voltage in the other coil. The magnetic coupling between the coils due to this flux is described by a quantity called ***mutual inductance***. The magnetic flux produced by one coil can either aid or oppose the flux produced by the other coil.

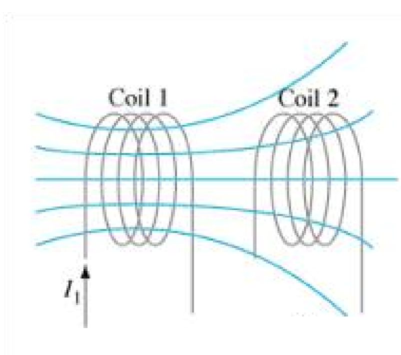


Figure 6: mutually coupled coils

Next we will study a very useful electrical device (transformer) that exploits the concept of mutual coupling to transform voltage and current from one circuit to another.

Transformer

A transformer is a very common magnetic structure found in many everyday applications.

- AC circuits are very commonly connected to each other by means of transformers.
- A transformer couples two circuits magnetically rather than through any direct connection.
- It is used to raise or lower voltage and current between one circuit and the other, and plays a major role in almost all AC circuits.

Application Example: Transformers are a necessary part of all power supplies.

Figure 7: Small power supply

Application Example: Electric power systems

Transformers find many applications in electric power distribution where they are employed for increasing or decreasing voltage levels.

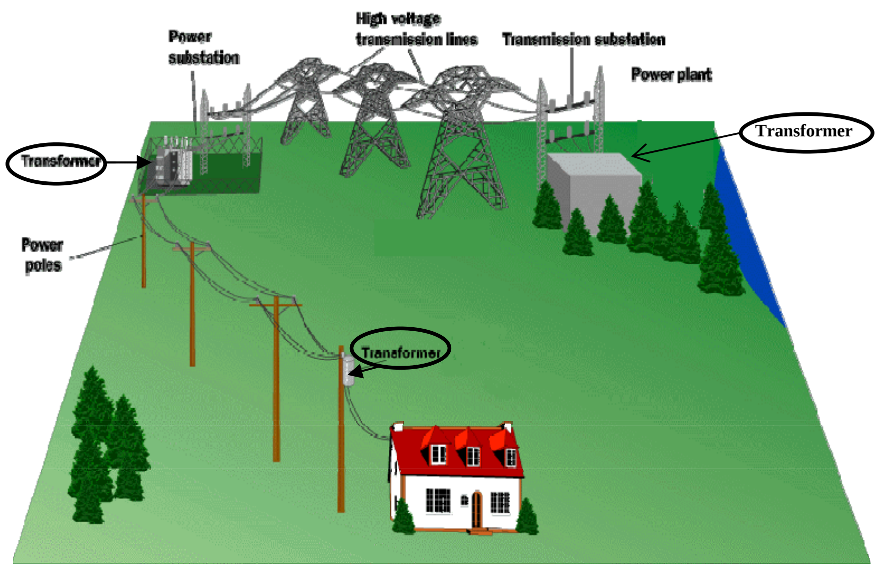


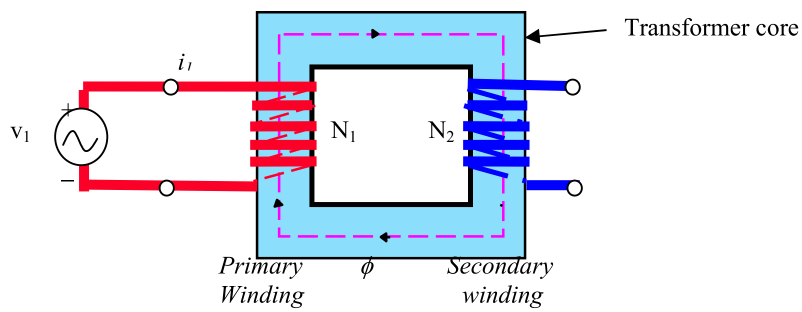
Figure 8: Transformers in Power Systems

2.8 Ideal Transformer

An ideal transformer consists of two conducting coils wound on a common core, made of high grade iron.

- There is no electrical connection between the coils, they are connected to each other through magnetic flux.
- The coil on input side is called the ***primary*** winding (coil) and that on the output side the ***secondary***.

When an AC voltage is applied to the primary winding, a time-varying current flows in the primary winding and causes an AC magnetic flux to appear in the transformer core. The arrangement of primary and secondary windings on the transformer core is shown in figure 9 below. The voltage, current and flux due to the current in the primary winding is also shown.



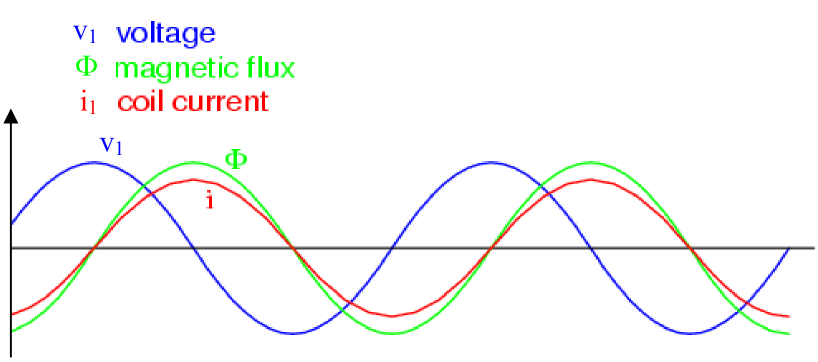


Figure 9: Voltage, current and flux in the primary winding

This flux links with the secondary winding due to the mutual magnetic coupling, and induces a voltage in secondary winding (Faraday's Law).

Depending on the ratio of turns in the primary and secondary winding, the RMS secondary voltage can be greater or less than the RMS primary voltage.

For analyzing an ideal transformer, we make the following assumptions:

- The resistances of the windings can be neglected.
- All the magnetic flux is linked by all the turns of the coil and there is no leakage of flux.
- The reluctance of the core is negligible.

We can write the equations for sinusoidal voltage in this ideal transformer as follows.

- The primary winding of turns N_1 is supplied by a sinusoidal voltage v_1.

  $v_1 = V_{1m} \cos(\omega t)$ (9)

  here, v_1 is the time-varying (also called instantaneous) voltage applied to the primary winding, with the maximum value V_{1m} and RMS value of V_1 $(=V_{1m}/\sqrt{2})$.

From Faraday's Law, the voltage across the primary winding terminals can be written as:

$v_1 = N_1 (d\phi/dt)$

From these two equations, $N_1 (d\phi/dt) = V_{1m} \cos(\omega t)$

Rearranging and integrating, the equation for common flux can be written as:

$$\phi = \frac{V_{1m}}{N_1 \omega} \sin(\omega t) \qquad (10)$$

This common flux passes through both the windings.

2.9 Voltage Relationships

This common flux flows through the transformer core and links with the secondary winding. According to Faraday's law, a voltage is induced across the terminals of the secondary winding.

- Assuming that all of the flux links all of the turns in each coil, when the common flux changes ($d\phi/dt$), a sinusoidal voltage v_2 is induced in the secondary winding, the voltages are given by:

$$v_1 = N_1 \frac{d\phi}{dt} \quad \text{and} \quad v_2 = N_2 \frac{d\phi}{dt} \qquad (11)$$

- The polarities of the induced voltages are given by *Lenz*'s *law*; i.e. the induced voltages (also called *emf*) produce currents that tend to oppose the flux change.
- From the above equations, $\frac{v_1}{v_2} = \frac{N_1}{N_2}$ (12)
- In terms of RMS values,

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = a \quad \text{(turns ratio)} \qquad (13)$$

- The "*turns ratio*" determines the amount the voltage is changed

2.10 Current Relationships

If we now connect a load across the terminals of the secondary winding (figure 10), the circuit on the secondary side of the transformer is complete, and a current i_2 starts to flow through it.

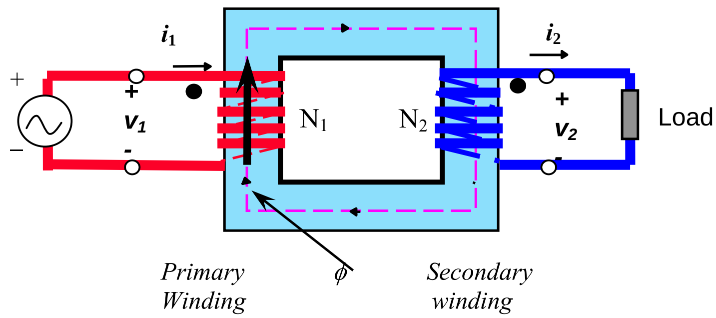


Figure 10: Ideal transformer connected to a load

- The magnetomotive force corresponding to the current in the secondary winding is given by:

  $mmf = N_2\, i_2$

- The input coil is forced to generate a counter *mmf* to oppose this *mmf*.
- This results in current i_1 such that the total mmf applied to the core is:

  $F = N_1\, i_1\; - N_2\, i_2$ (14)

The mmf is related to the flux and reluctance by:

$F = \Re\phi$

- In a well designed transformer, the core reluctance is very small.
- In the ideal case, this reluctance $\Re$ is zero, and therefore the mmf required to establish flux in the core is zero.

  Therefore, $F = N_1\, i_1\; - N_2\, i_2 = 0$ (15)

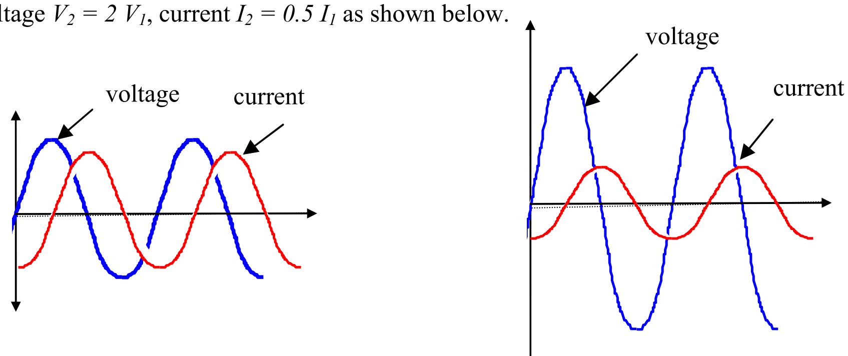
- Expressing currents in terms of RMS values, and rearranging the terms in equation (15),

  $$\frac{I_2}{I_1} = \frac{N_1}{N_2} = a\ (turns\ ratio) \quad (16)$$

In summary,

- **An ideal transformer divides a sinusoidal input voltage by a factor of *a* and multiplies a sinusoidal input current by *a* to obtain secondary voltage and current.**

For example, if the transformer has a turns ratio $a = 1/2$,
the voltage $V_2 = 2\ V_1$, current $I_2 = 0.5\ I_1$ as shown below.



Primary voltage and current *Secondary voltage and current*

Figure 11: Voltage and current waveforms

- Is there any limit to the magnitude of voltage increase/decrease in a transformer?
- What changes will have to be made if we wanted to switch primary and secondary sides, i.e., apply the supply voltage on the right hand side in figure 10, while the load is connected on the left hand side?

2.11 Ideal Transformer – Equivalent Circuit

The equivalent circuit (i.e., without the magnetic core) of an ideal transformer can be drawn as follows. The equivalent circuit is used for determining the performance characteristics of the transformer.

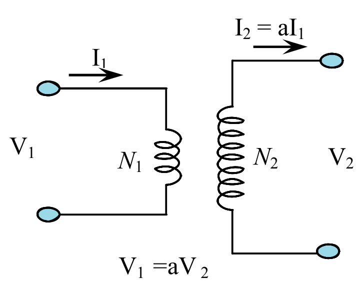


Figure. 12: Ideal transformer equivalent circuit

[Note that the voltage and current relationships remain the same whether they are shown in their instantaneous values or RMS values.]

Let's consider some cases. The transformer equivalent circuits for these cases are shown in figure 13.

- If $a < 1$, i.e. $N_1 < N_2$

  The output voltage is greater than the input voltage and the transformer is called a **step-up** transformer (figure 13(a)).

- If $a > 1$, i.e. $N_1 > N_2$

  The output voltage is smaller than the input voltage and the transformer is called a **step-down** transformer (figure 13(b)).

- If a = 1, i.e. $N_1 = N_2$

  The output voltage is the same as the input voltage and the transformer is called an **isolation** transformer (figure 13(c)).

  These transformers perform a very useful function for applications where two circuits need to be *electrically* isolated from each other.

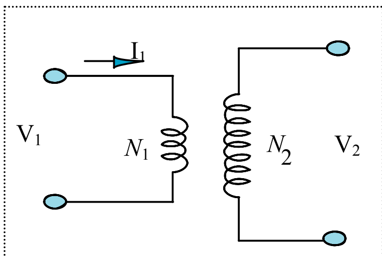


Figure 13(a): Step-up transformer

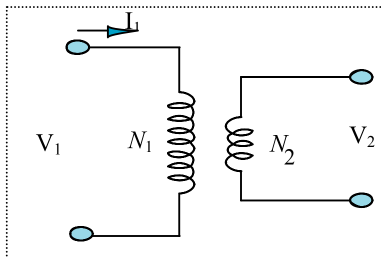


Figure 13(b): Step-down transformer

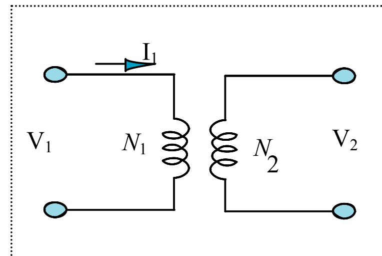
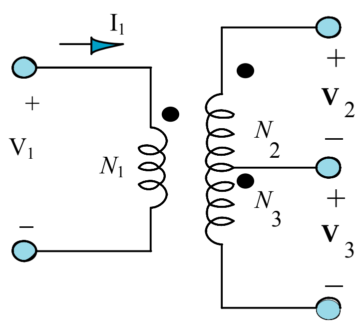


Figure 13(c): Isolation transformer

In many applications, the secondary winding is tapped at two different points, giving rise to two output circuits (see figure 14). The most common configuration is **centre-tapped** transformer which splits the secondary voltage into two equal voltages.



$$\mathbf{V}_2 = \frac{N_2}{N_1}\mathbf{V}_1$$

$$\mathbf{V}_3 = \frac{N_3}{N_1}\mathbf{V}_1$$

Figure 14: Centre-tapped transformer

- Can you think of some specific applications where there is a need to use an isolation transformer?
- What applications use centre-tapped transformers?

<u>Example 2:</u>

A transformer is required to deliver 1A current at 12 V from a 240 V RMS supply voltage. The number of turns in the primary winding is 2000.
(i) How many turns are required in the secondary winding?
(ii) what is the current in the primary winding?

Solution:

Here, $V_1 = 240$ V; $V_2 = 12$ V;
$I_2 = 1$ A; $N_1 = 2000$

(i) Using equation (13), the number of turns in the secondary winding:

$$N_2 = N_1 \frac{V_2}{V_1} = 2000 \times \frac{12}{240} = 100 \ turns$$

The turns ratio, a = 20 (i.e., this is a step-down transformer)

(ii) From equation (16), the primary current:

$$I_1 = \frac{N_2}{N_1} I_2 = \frac{100}{2000} \times 1 = 50 \text{ mA}$$

2.12 Power in an Ideal Transformer

The power delivered to the load by the secondary winding:

$$p_2 = v_2 . i_2 \tag{17}$$

(Note that the lower case letter (e.g. p, v, or i) refers to the time-varying instantaneous value of an ac wave.)

Using equations for v_2 and i_2 and substituting in the above equation,

$$v_2 = \frac{1}{a} v_1 \quad and \quad i_2 = a\, i_1,$$

$$\therefore \ p_2 = \left(\frac{1}{a}\right) v_1 .(a\, i_1) = v_1 . i_1 \tag{18}$$

However, the power delivered to the primary winding by the source is :

$$p_1 = v_1 . i_1 \tag{19}$$

Therefore, $p_1 = p_2$ (20)

i.e., *Power input = Power output*

In terms of RMS values, $\boldsymbol{P_1 = P_2}$

In summary,

- **The net power is neither generated nor consumed by an ideal transformer.**
- The losses are zero in an ideal transformer.
- If a transformer increases the voltage, the current decreases and vice versa.

Application Example: Power distribution systems

AC electricity is generated in power stations at medium voltage levels (*i.e.*, something like 11kV), and is consumed by the domestic user at an RMS voltage of 220V (in Singapore). The electricity generated at the power station is fed into a step-up transformer which boosts its peak voltage from a few kilo volts to many tens of kilovolts. The output from the step-up transformer is fed into a high tension transmission line, which typically transports the electricity over many tens of kilometers, and, once the electricity has reached its point of consumption, it is fed through a series of step-down transformers until, by the time it emerges from a domestic plug, its RMS voltage is only 220V. The process can be shown using a simple block diagram as follows:

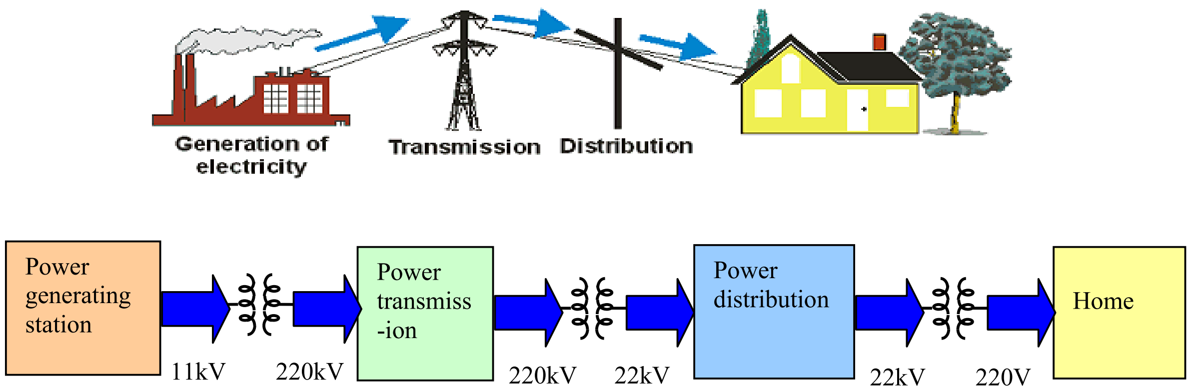


Figure15: Transformers raise/lower voltages in electrical energy distribution

- But, if AC electricity is generated and consumed at comparatively low voltages, why go to the trouble of stepping up the voltage to a very high value at the power station and then stepping down the voltage again once the electricity has reached its point of consumption? Why not generate, transmit, and distribute the electricity at 220V?
- Why is AC more widely used compared to DC?

2.13 Transformer rating

The transformer is usually rated in terms of its input and output voltages and apparent power that it is designed to safely deliver.

For example, if a transformer carries the following information on its name-plate:

10kVA, 1100/110volts

What are the meanings of these ratings?

The **voltage ratio** indicates that the transformer has two windings, the *high-voltage* winding is rated for 1100 Volts and the *low-voltage* winding for 110 volts.

These voltages are proportional to their respective number of turns. Therefore, the voltage ratio also represents the turns ratio a. (e.g., $a = 10$ here)

The **kVA rating** (i.e., apparent power) means that each winding is designed for 10 kVA.

Therefore the **current rating** for the high-voltage winding = 10000/1100 = 9.09A

Current rating for low voltage winding = 10000/110 = 90.9 A

The term "**rated load**" for a device refers to the load it is designed to carry for (theoretically) indefinite period of time. **Rated load** for the transformer refers to the apparent power specified as above, and shown in the name-plate information.

Note that during actual operation, the transformer may be required to operate at less power than its rated power.

2.14 Impedance transformation

Consider the following circuit, where a load impedance Z_L is connected in the secondary winding. The RMS values of current and voltage in the secondary winding are related to the impedance by:

$$Z_L = \frac{V_2}{I_2} \tag{23}$$

Substituting for V_2 and I_2,

$$Z_L = \frac{(N_2/N_1)V_1}{(N_1/N_2)I_1} = \left(\frac{N_2}{N_1}\right)^2 \frac{V_1}{I_1} \tag{24}$$

Rearranging this equation, and substituting $a = N_1/N_2$, the impedance *seen* by the source, Z'_L is given by:

$$Z'_L = \frac{V_1}{I_1} = a^2 Z_L \tag{25}$$

i.e., When a load impedance Z_L is connected across the secondary winding terminals, the AC source connected on the input side *sees* the load impedance magnified by the factor a^2.

We say that the load impedance is *reflected* or *referred* to the primary side by the square of the turns ratio *a*.

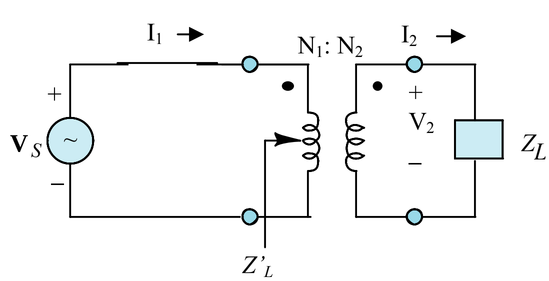


*Figure 16: Load impedance as **seen** by the source*

This circuit can be simplified as follows:

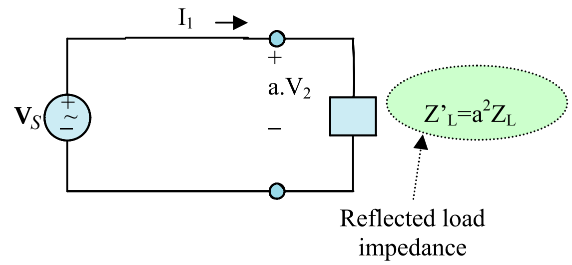


Figure 17: Simplified circuit

In a similar manner, it can be shown that if an impedance is connected on the source side of the circuit (as shown below), the load *sees* it changed by a factor of ($1/a^2$).

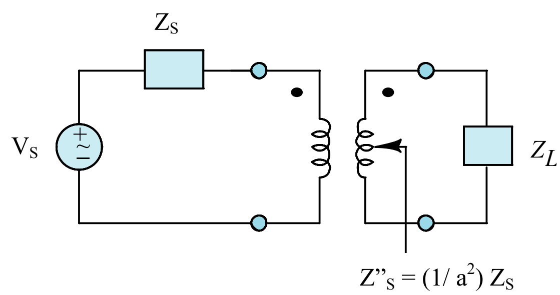


Figure 18: Source impedance as ***seen*** *by the load*

If we look at this circuit from the load side (i.e., as seen by the load), the voltage of the source and the impedance appear changed as shown below.

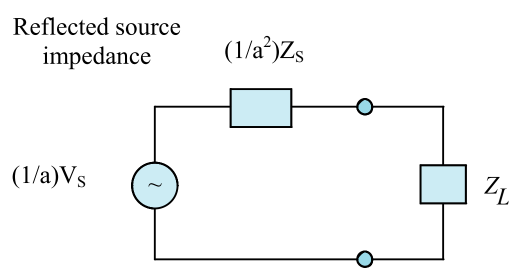


Figure 19: Simplified circuit

Application Example: Impedance Matching

A very important application of transformers is as an impedance matching device using the concept of "reflected load".

Recall that the maximum power transfer theorem states that a power source delivers maximum power to the load when the load resistance is equal to the internal resistance of the source. This can be accomplished by using a transformer to match the two resistances.

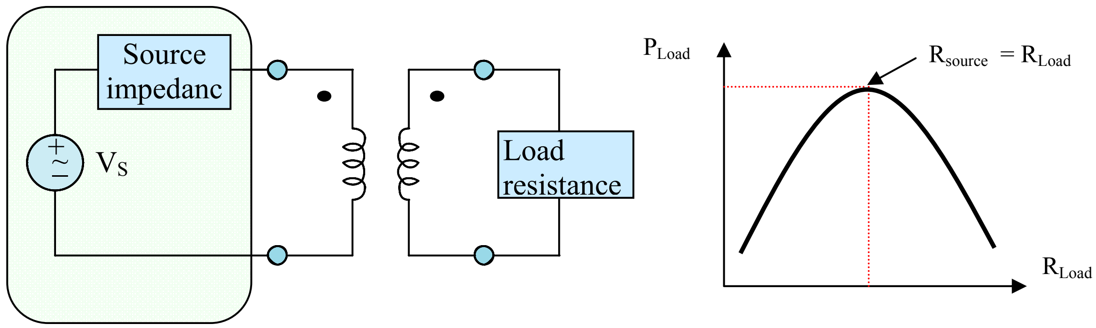


Figure 20: Transformer application for impedance matching

Thus, by choosing the appropriate turns ratio for the transformer in equation (25), the effective load resistance R'_L can be made equal to the internal resistance of the source, no matter what value the actual load resistance R_L takes. This process is called *impedance matching*. A practical example of impedance matching in given below.

Example 3:

For example, if the internal resistance of the source is 75Ω, and the resistance of the load is 300Ω, a transformer with turns ratio of 1:2 can be used for impedance matching as shown below.

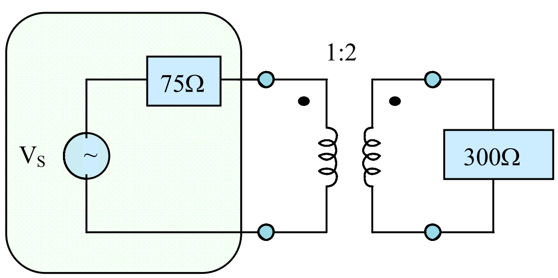


Figure 21: Impedance matching

The maximum power transfer from an active device like an amplifier to an external device like a speaker will occur when the impedance of the external device matches that of the source. Transformers are used for this purpose. Improper impedance matching can lead to excessive power use, distortion, and noise problems.

Example 4:

For the circuit shown below, find the phasor currents and voltages, and the power delivered to the load.

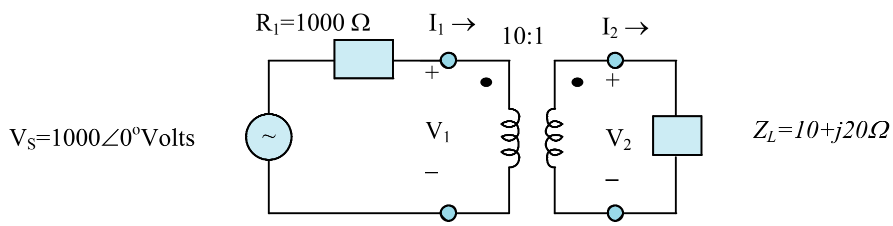


Figure 22: Transformer equivalent circuit for example 4

The load impedance reflected to (i.e., seen by) the primary side:

$$Z'_L = \left(\frac{N_1}{N_2}\right)^2 Z_L = (10)^2(10 + j20)ohms$$

The total impedance seen by the source is:

$$Z_S = R_1 + Z'_L = 1000 + 1000 + j2000 = 2828\angle 45^o \text{ ohms}$$

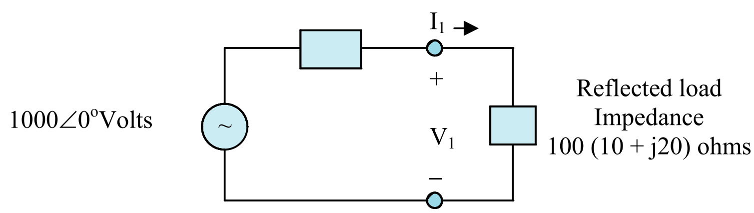


Figure 23: Simplified circuit

The primary current and voltage can be calculated as:

$$I_1 = \frac{V_s}{Z_s} = \frac{1000\angle 0^0}{2828\angle 45^0} = 0.3536\angle -45^0\, A$$

$$V_1 = I_1 Z'_L = 0.3536\angle\text{-}45^o \text{x } (1000 + j2000)$$

$$= 790.6\angle 18.43^o V$$

Using the turns ratio, we can calculate secondary side voltage and current as follows:

$$I_2 = \left(\frac{N_1}{N_2}\right) I_1 = \frac{10}{1} 0.3536\angle -45^0 = 3.536\angle -45^0\, A$$

$$V_2 = \left(\frac{N_2}{N_1}\right) V_1 = \frac{1}{10}(790.6\angle 18.43^0) = 79.06\angle 18.43^0\, V$$

The power delivered to the load:

$$P_L = (I_2)^2 R_L = (3.536)^2(10) = 125.0331W$$

What is the power **consumed** in the reactive part of the load?

Application Example: Power Supply Circuits

Transformers are an integral part of all power supplies. A typical application example of AC-DC power supply is shown below, where transformer is used for lowering the voltage to a level more suitable for consumption. This voltage is then rectified and filtered to obtain a DC voltage.

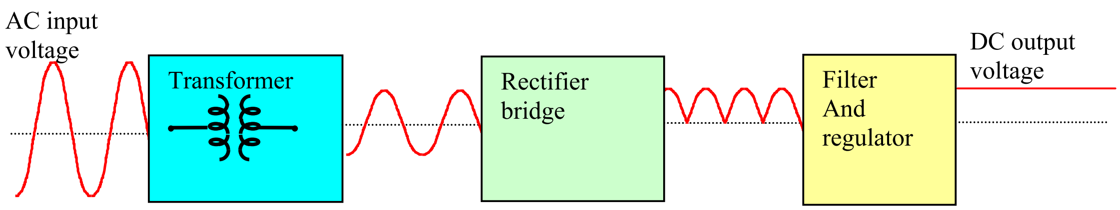


Figure 24: Block diagram of a power supply

Aside from the ability to easily convert between different levels of voltage and current in AC and DC circuits, transformers also provide an extremely useful feature called *isolation*, which is the ability to couple one circuit to another without the use of direct wire connections.

- What type of transformer will result if there is only one winding in the transformer?
- Why does the transformer used in power supplies gets heated after a few hours in operation?
- What would happen if a transformer is connected across DC supply voltage?

2.15 Actual (Non-ideal) Transformer

Recall that we had made several assumptions when analyzing an ideal transformer. An actual transformer differs from an ideal transformer in that is has:

- Resistive (I^2R) losses (also called copper losses) in the primary and secondary windings
- Not all the flux produced by the primary winding links the secondary winding, and vice versa. This gives rise to some leakage of flux.
- The core requires a finite amount of *mmf* for its magnetization.
- Hysteresis and eddy current losses cause power loss in transformer core.

The equivalent circuit of an ideal transformer can be modified to include these effects.

- Resistances R_1 and R_2 can be added on both primary and secondary side to represent the actual winding resistances.
- The effect of leakage flux can be included by adding two inductances L_1 and L_2 respectively, in the primary and secondary winding circuits.

- We had assumed that the core reluctance was zero, however a real transformer has non-zero reluctance. A magnetizing inductance L_m can be added to account for this. The corresponding reactance of the iron core is X_m $(= 2\pi f L_m)$
- We had ignored core losses earlier. However, in actual transformers, hysteresis and eddy currents cause iron losses in the core. A resistance Rc can be added in the transformer equivalent circuit to account for core losses.

Effects of winding resistance, leakage flux and imperfect core are added to the ideal transformer circuit shown below to obtain the circuit for a practical transformer.

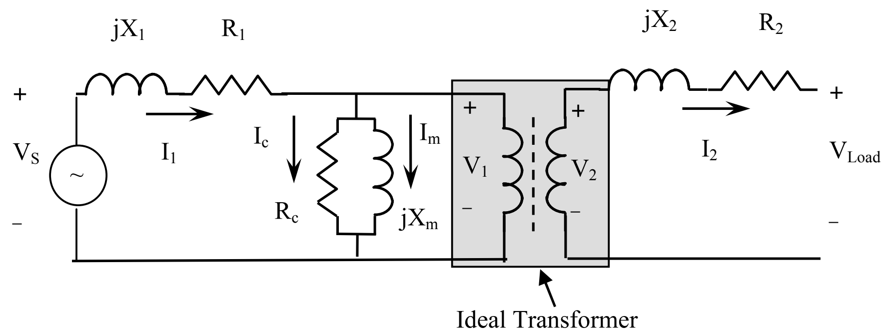


Figure 25: Equivalent circuit of a practical transformer

Here,

R_1, R_2 - Resistances of primary and secondary windings

X_1, X_2 - Leakage reactance of primary and secondary windings

I_m, X_m - Magnetizing current and reactance

I_c, R_c - Current and resistance accounting for core losses

The sum of I_m and I_c is called the exciting current.

The equivalent circuit is useful in determining the characteristics of the transformer.

Voltage Regulation

Because of the elements R_1, R_2, L_1 and L_2, the voltage delivered to the load side of a transformer varies with the load current which is undesirable.

The regulation of an actual transformer is defined as:

$$\text{Percent regulation} = \frac{V_{2\,no\text{-}load} - V_{2\,load}}{V_{2\,load}} \times 100\% \qquad (26)$$

Efficiency

Because of the resistances in the transformer equivalent circuit, not all of the power input to the transformer is delivered to the load. Efficiency is defined as the ratio of output to the input.

Since, *Input power = Output power + Power losses*

$$\therefore \quad Efficiency = \frac{Output\ power}{Output\ power + Losses} \times 100\% \qquad (27)$$