Transformers: Introduction and Basics

Introduction

Figure 1 Picture of a Transformer

The transformer (Figure 1) is one of the principal reasons behind the adoption of AC power systems. Its ability to provide a low cost and reliable means of converting AC voltage levels results in high efficiency AC power transmission. Figure 2 shows where a transformer is used in a modern AC power distribution system. A transformer is designed to convert alternating current from one voltage to another. It can be designed to "step up" or "step down" voltages and works on the magnetic induction principle. A transformer has no moving parts and is a completely static solid-state device, which insures, under normal operating conditions, a long and trouble-free life.

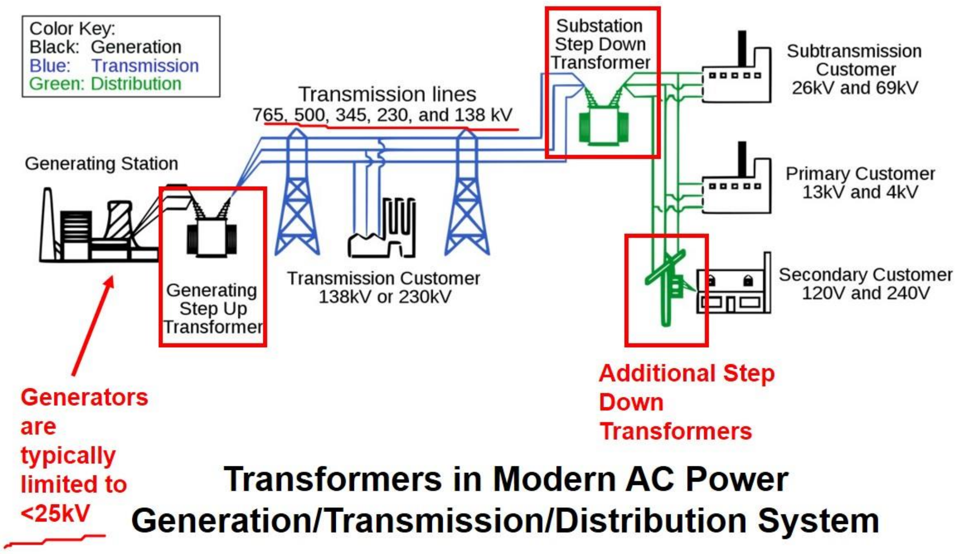

Figure 2. Depiction of Transformers in Power Distribution System

The Ideal Transformer

In its simplest form a transformer consists of two or more coils of insulated wire wound on a laminated iron core. When voltage is introduced to one coil, called the primary, it magnetizes the iron core. A voltage is then induced in the other coil, called the secondary or output coil. The change of voltage (or voltage ratio) between the primary and secondary depends on the turns ratio of the two coils.

The Ideal Transformer (Figure 3) consists of a Primary winding of NP turns and a Secondary Winding of NS turns, wound round a common Iron Core. An AC Voltage Source is connected to the Primary Winding, and this results in an AC Magnetic Flux (Φ) in the Iron Core.

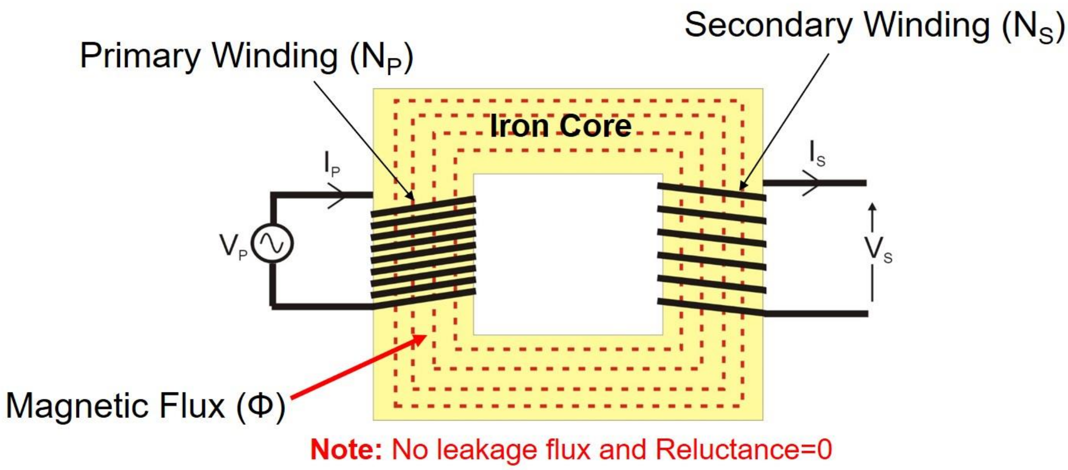

Figure 3. An Ideal Transformer

We can now determine an ideal transformer equation. If we consider the primary side then:

$$V_P = N_P \frac{d\phi}{dt} \tag{1}$$

Whilst on the secondary side:

$$\frac{d\phi}{dt} N_S = V_S \tag{2}$$

From (1) and (2):

$$\frac{V_P}{V_S} = \frac{N_P}{N_S} \tag{3}$$

If we assume our ideal transformer is 100% efficient then Primary power must equal secondary power, so:

$$V_S . I_S = V_P . I_P \tag{4}$$

Then we can get the transformer equation:

$$\frac{I_P}{I_S} = \frac{V_S}{V_P} = \frac{N_S}{N_P} \tag{5}$$

Non-Ideal Transformers

Unfortunately, transformers are not ideal. Initially it is useful to look at basic Electromagnetic Theory, as some of the transformer 'imperfections' and limitations are as a result of the electromagnetic coupling between the primary and secondary electric circuits.

Electromagnetics

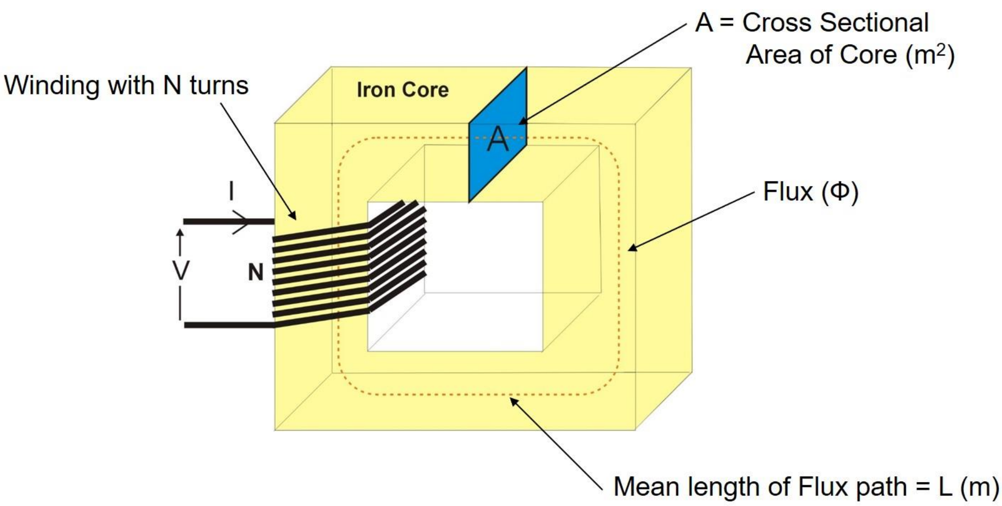

Figure 4. Flux induced in Magnetic Core due to Primary Windings

Referring to Figure 4, the current (I) in the windings produces a Magnetomotive Force (mmf), denoted by $\mathbb{F}$, where:

$$\mathbb{F} = N \cdot I \tag{6}$$

[Note: The units are Ampere turns]

And the magnetic field intensity, H, is:

$$H = \frac{NI}{L} \tag{7}$$

[Note the units is Amps/m]

The mmf produces a magnetic flux, **ϕ**, in the core. We can consider mmf to be a voltage and the magnetic flux to be a current, so there must be an equivalent magnetic "resistance" that limits the magnetic flux. This is termed the reluctance, $\mathbb{R}$, so now we can write an equivalent magnetic Ohm's Law:

$$\Phi = \frac{\mathbb{F}}{\mathbb{R}} \tag{8}$$

[Note: the unit for flux is the Weber and for reluctance it is Amperes/Weber]

We can also define the magnetic flux density in the core:

$$B = \frac{\Phi}{A} \tag{9}$$

[Note the unit is the Tesla or Webers/m^2]

The other thing we need to think about is what material the core is made of and how we can represent it. There are a lot of books and internet resources that discuss the theory of magnetic materials. If you are interested you can do some private research, but we just need to know that the magnetic property is called permeability, µ. There is a permeability of free space which is given by $\mu_o = 4.\pi \times 10^{-7}$ H/m (henries/meter). The permeability of the core is given by:

$$\mu = \mu_r . \mu_o \text{ H/m} \tag{10}$$

Where μ_r is the relative permeability of the material with respect to free space.

There are two more things we need to know. The first is that we can find the reluctance from the physical properties of the core:

$$\mathbb{R} = \frac{L}{A \cdot \mu} \tag{11}$$

And permeability is the ratio of magnetic flux density to magnetic field intensity:

$$\mu = \mu_r \cdot \mu_o = \frac{B}{H} \tag{12}$$

Permeability can be considered a measure of how easy it is to set up a magnetic flux in a material. The ferroelectric materials used in a transformer core have very larger values of relative permeability. Typically, $\mu_r = 20000 - 80000$.

We can draw a B-H curve based on equation (12) as shown in Figure 5. The figure illustrates that to set up a flux in the iron core we will need a certain value of current, called the magnetizing current.

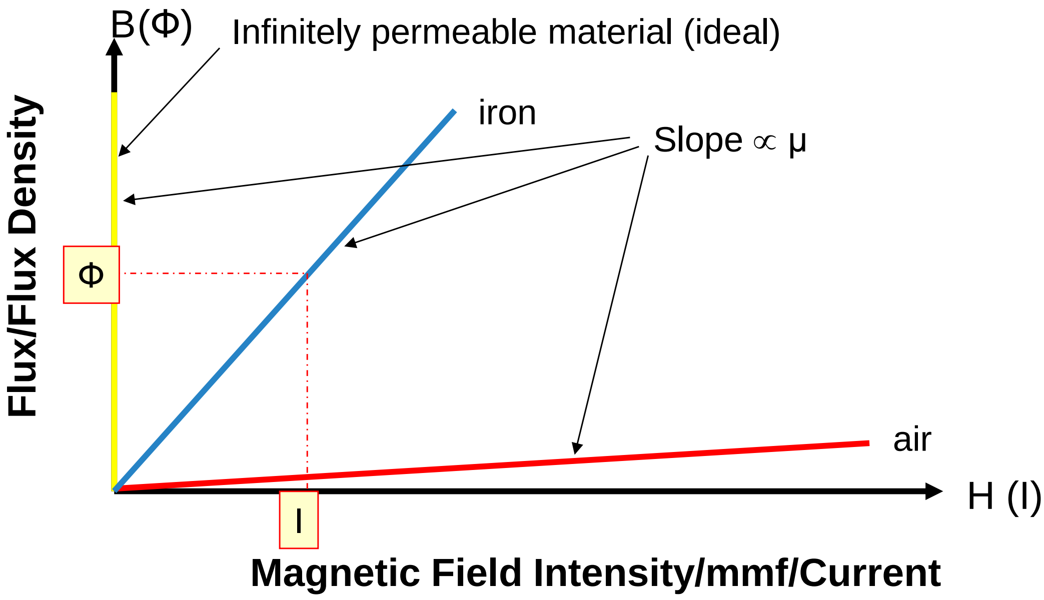

Figure 5. Simplified B-H curve

"Real" B-H curve and Hysteresis Loss

Ferromagnetic material that is used in transformers has a much more complicated **B-H** curve than that shown in Figure 5. A typical **B-H** curve is shown in Figure 6.

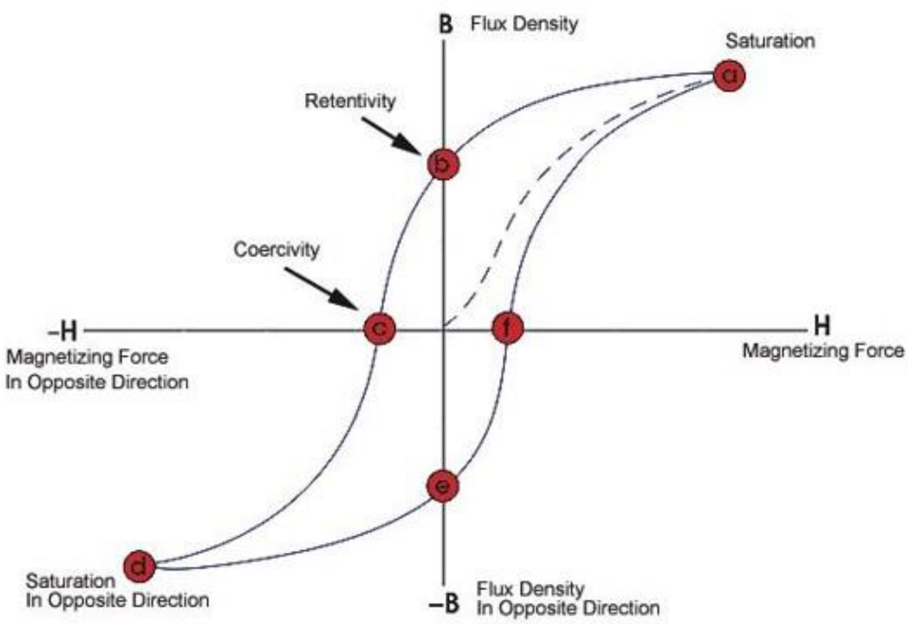

Figure 6 B-H curve for a Ferromagnetic Material

The phenomenon of magnetization lagging the field producing it is called magnetic hysteresis. It is derived from Greek word hysteresis (to lag). Every Ferromagnetic material used in transformer cores exhibits this hysteresis phenomena. By applying an external magnetic field the magnetic material will get magnetized. The extent to which the material gets magnetized depends on the applied field and the permeability of the material (μr). Remember the flux density inside the material is given by $\mathbf{B} = \mu_o\mu_r\mathbf{H}$.

Starting from zero external field: As the external field is increased the magnetization increases until it reaches saturation. After the field inside the material reaches saturation there will not be any further increase in the magnetization, even if the external field is increased.

If we decrease the field the flux density decreases. But at zero external fields (**H**=0) there exists remnant magnetization inside the material. To make the flux density inside the material zero we should apply magnetic field in the direction opposite to the field applied before. The external field that should be applied to make the flux density inside the material zero is called coercive field denoted by Hc.

If we cycle the magnetic field between the two saturation points we will get the Hysteresis loop (B-H curve) shown in figure 6. It is obvious from the B-H curve that magnetization and the flux density inside the material lag the applied field.

The total area inside the hysteresis loop is a measure of hysteresis losses of the core. The work done on the core to neutralize the field inside core appears is the hysteresis loss. The hysteresis losses of a core per, unit volume of core, is given as:

Total hysteresis losses = Total area inside hysteresis loop ×volume of core.

Materials with less area inside the hysteresis loop are preferred for transformer cores.

Eddy Currents

When an alternating magnetic field is applied to a magnetic material an emf is induced in the material itself according to Faraday's Law of Electromagnetic induction. Since the magnetic material is a conducting material, these EMFs circulates currents within the body of the material. These circulating currents are called **Eddy Currents** and will occur when the conductor experiences a changing magnetic field.

As these currents are not responsible for doing any useful work, and it produces an I^2R loss in the magnetic material, known as an Eddy Current Loss. Similar to hysteresis loss, eddy current loss also increases the temperature of the magnetic material. The hysteresis and the eddy current losses in a magnetic material are also known by the name iron losses, or core losses, or magnetic losses.

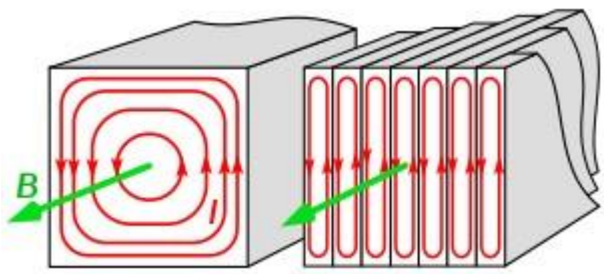

Figure 7. Eddy currents in a Transformer core.

A sectional view of the magnetic core is shown in Figure 7. When the changing flux links with the core itself, it induces emf in the core which in turns sets up the circulating Eddy Currents. If the core is made up of solid iron of larger cross-sectional area, the magnitude of I will be very large, and hence losses will be high. The magnitude of the current can be reduced by splitting the solid core into thin sheets called laminations, in the plane parallel to the magnetic field. Each lamination is insulated from each other by a thin layer of varnish or oxide film. By laminating the core the area of each section is reduced, and hence the induced emf also reduces. As the area through which the current is passed is smaller, the resistance of the eddy current path increases.

Copper (I^2R) losses in the Windings

Current in a transformer winding leads to copper (I^2R) loss which causes the temperature of the winding to increase. If this temperature exceeds the winding insulation limit (Class F insulation has a 155°C limit) then the winding will sustain physical damage. Cooling systems (oil) are used in large transformers to reduce the temperature rise for a given current, and therefore increase the maximum safe operating current. Current limit equates to a Current Density Limit (typical values in range 3 – 20A/mm^2 dependent on cooling)

$$\text{Current Limit} = \frac{\text{Current Density Limit} \times \text{Coil Area} \times \text{Fill Factor}}{\text{Number of Turns}} \tag{13}$$

Fill Factor is the reduction in area since it is not all filled with copper, due to insulation thickness and gaps between turns. Typical values of fill factor are >0.9.

Leakage Flux

In practise not all the flux will be confined to the iron core. There will be some flux in the space surrounding the core. The leakage flux is minimized by the very high μ_r for the magnetic materials used in a transformer core. (typically ~1500).