

Title

# **Electrical Transformer**

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## **Content :-**

- + Define transformer.**
  
- + How does a transformer work?**
  
- + Transformer design.**
  
- + Transformer construction.**
  
- + Transformer equations.**
  
- + Transformer losses, Efficiency and Regulation.**
  
- + Parts of transformer.**
  
- + Basic operation of a transformer.**
  
- + Kind of transformer.**
  
- + Guide for Testing Power Transformers**
  
- + References.**

## Define transformer:

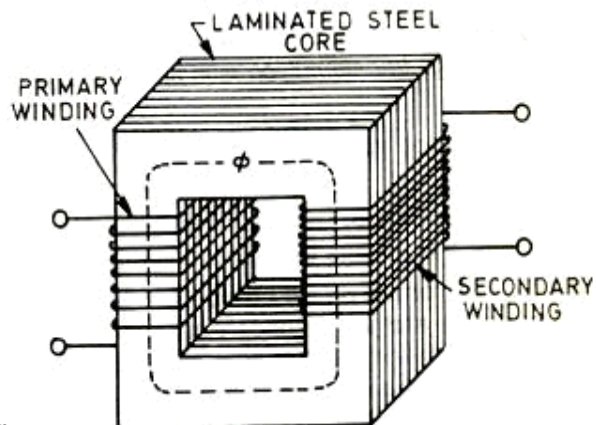
A transformer is a device that transfers electrical energy from one circuit to another through inductively coupled conductors—the transformer's coils. A varying current in the first or primary winding creates a varying magnetic flux in the transformer's core, and thus a varying magnetic field through the secondary winding. This varying magnetic field induces a varying electromotive force (EMF) or "voltage" in the secondary winding. This effect is called mutual induction.

If a load is connected to the secondary, an electric current will flow in the secondary winding and electrical energy will be transferred from the primary circuit through the transformer to the load. In an ideal transformer, the induced voltage in the secondary winding ( $V_S$ ) is in proportion to the primary voltage ( $V_P$ ), and is given by the ratio of the number of turns in the secondary ( $N_S$ ) to the number of turns in the primary ( $N_P$ ) as follows:

By appropriate selection of the ratio of turns, a transformer thus allows an alternating current (AC) voltage to be "stepped up" by making  $N_S$  greater than  $N_P$ , or "stepped down" by making  $N_S$  less than  $N_P$ .

In the vast majority of transformers, the windings are coils wound around a ferromagnetic core, air-core transformers being a notable exception.

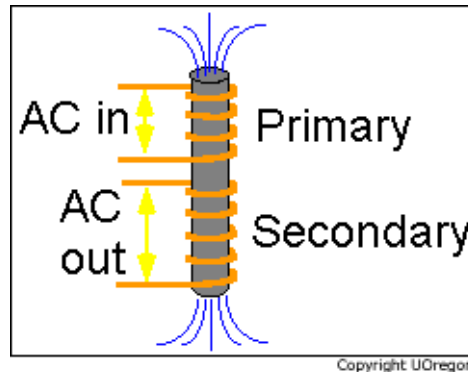
Transformers range in size from a thumbnail-sized coupling transformer hidden inside a stage microphone to huge units weighing hundreds of tons used to interconnect portions of power grids. All operate with the same basic principles, although the range of designs is wide. While new technologies have eliminated the need for transformers in some electronic circuits, transformers are still found in nearly all electronic devices designed for household ("mains") voltage. Transformers are essential for high voltage power transmission, which makes long distance transmission economically practical.



Simple Transformer

## How does a transformer work?

Transformer is an electrical device used to convert AC power at a certain voltage level to AC power at a different voltage, but at the same frequency.



The construction of a transformer includes a ferromagnetic core around which multiple coils, or windings, of wire are wrapped. The input line connects to the 'primary' coil, while the output lines connect to 'secondary' coils. The **alternating current in the primary coil induces an alternating magnetic flux that 'flows' around the ferromagnetic core, changing direction during each electrical cycle. The alternating flux in the core in turn induces an alternating current in each of the secondary coils. The voltage at each of the secondary coils is directly related to the primary voltage by the turns ratio, or the number of turns in the primary coil divided by the number turns in the secondary coil. For instance, if the primary coil consists of 100 turns and carries 480 volts and a secondary coil consists of 25 turns, the secondary voltage is then:**

$$\text{secondary voltage} = (480 \text{ volts}) * (25/100) = 120 \text{ volts}$$



**A transformer may have multiple secondary coils to feed a number of electrical loads; however, power must be conserved, so the sum of the output power must equal the sum of the input power minus losses. Energy losses in transformers are due to a number of factors: these are copper losses in the coils themselves due to material resistance, core**

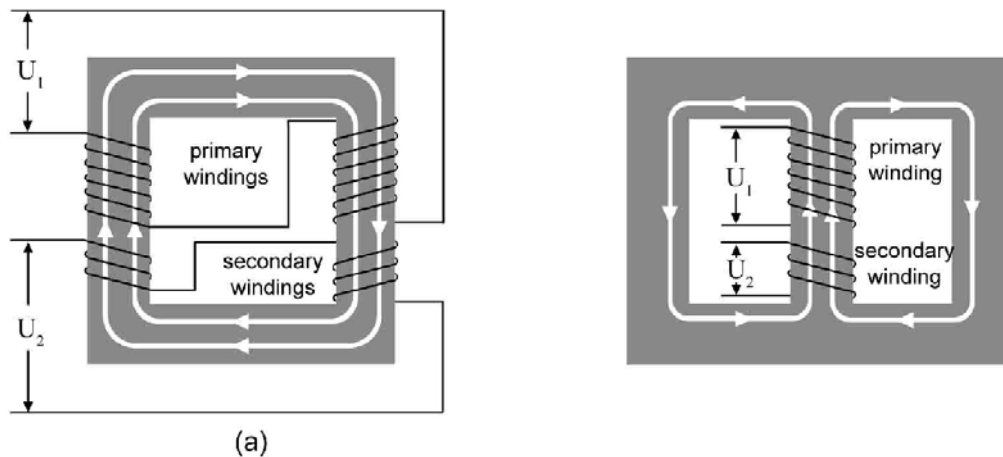
losses due to hysteresis (the reluctance of the magnetic domains to reverse during each electrical cycle)

## Transformer Design

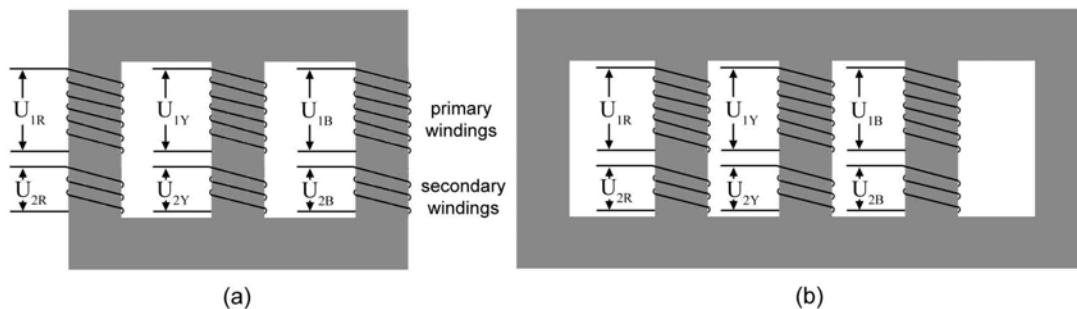
A transformer has primary and secondary coils, each connected to a separate circuit. The primary coil converts an alternating current into an alternating magnetic field. An iron core guides the field into a secondary coil, which produces an alternating current from the magnetic field. Each coil has a number of turns of wire. If the secondary has fewer turns than the primary, it reduces the voltage; this is a step-down voltage transformer. In a step-up voltage transformer, the secondary has more turns, increasing the voltage.

## Transformer Construction

If a transformer was constructed like the one shown in figure 15.1a. with the primary and secondary windings on separate limbs, a proportion of the magnetic flux produced by the primary core would not link to the secondary core. A better arrangement, called a *core-type* transformer is shown in figure 15.5a. If weight and cost are not issues, an even better arrangement called a *shell-type* transformer can be made and is illustrated in figure 15.5b.



**Figure 15.5:** single-phase transformer construction: (a) a core-type transformer and; (b) a shell-type transformer. The magnetic flux path through the core is shown in white



**Figure 15.6:** three-phase transformer construction: (a) core-type, three limb transformer and; (b) a shell-type five limb transformer. Core-type and shell-type transformers can also be constructed for three-phase transformers (figure

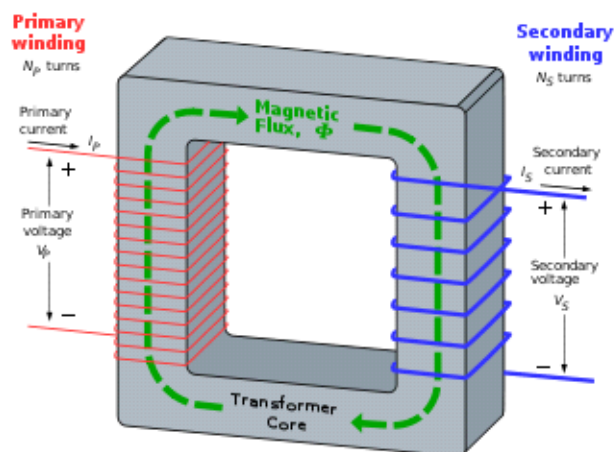
15.6). The advantages of each type are:

- ✚ core-type (or three limb) is the most commonly used method of construction, the smaller core means less weight and expense.
- ✚ shell-type (or five limb) is used for larger transformers because they can be made with a reduced height.

## Transformer Equations

The amount of power at the transformer's primary and secondary coils is nearly the same. The ratio of the turns of wire in the secondary to the primary determines how it alters voltage and current. The formula " $N_s/N_p = V_s/V_p$ " relates the number of turns in the secondary, called " $N_s$ ," and the primary, called " $N_p$ ," to the voltage in the secondary, called " $V_s$ ," and primary, called " $V_p$ ."

The equation " $P_p = V_p I_p = V_s I_s = P_s$ " states primary power equals primary voltage times primary current. This equals secondary voltage times secondary current, and they all equal secondary power. A transformer can reduce voltage and increase current, or increase voltage and reduce current, as long as the product of voltage and current remains the same.



## Transformer Losses, Efficiency And Regulation

### Iron Losses:

Iron losses were covered in section 5.3 and 5.4. Since iron losses are dependent on the frequency of the supply they are assumed to remain constant and not depend on the transformer's loading.

### Copper Losses:

These are due to the resistance of the wire from which the windings are made. If the secondary winding of a transformer is connected to an open circuit, so that no current flows, the primary winding will still carry a small current which provides the ampere-turns necessary to set up the magnetic flux in the core. Since this magnetising current is very small it is normally assumed to be zero. When the secondary winding is connected to a closed circuit a current will flow in it, the power loss in a conductor is  $P = I^2R$ , therefore the copper losses will be proportional to the square of the current. Thus, a transformer operating on half load will have only one quarter of the copper loss it has when providing full load. We can say:

copper loss  $P_C = (\text{actual load}/\text{full load})^2 \times \text{full-load copper loss}$

### **Efficiency:**

As well as providing for the output power, input to a transformer must supply the transformer losses. Thus:

input power = output power + power losses

efficiency = output power / input power \* 100%

efficiency = (input power - power losses) / input power \* 100%

efficiency = output power / (output power + power losses) \* 100%

### **Regulation**

The resistance and inductance reactance of a transformer winding provide an impedance through which output current must pass. A voltage drop thus occurs in the windings of the transformer, its value depending on the effective impedance and on the current ( $U = IZ$ ). As the current drawn increases, the voltage drop increases and since the EMF induced in the secondary windings is constant (not depending on load current) the output voltage must drop. The difference between the no-load output voltage and the full-load output voltage, expressed as a percentage of no-load voltage, is called the *voltage regulation*:

regulation = (no-load voltage - full-load voltage) / no-load voltage \* 100%

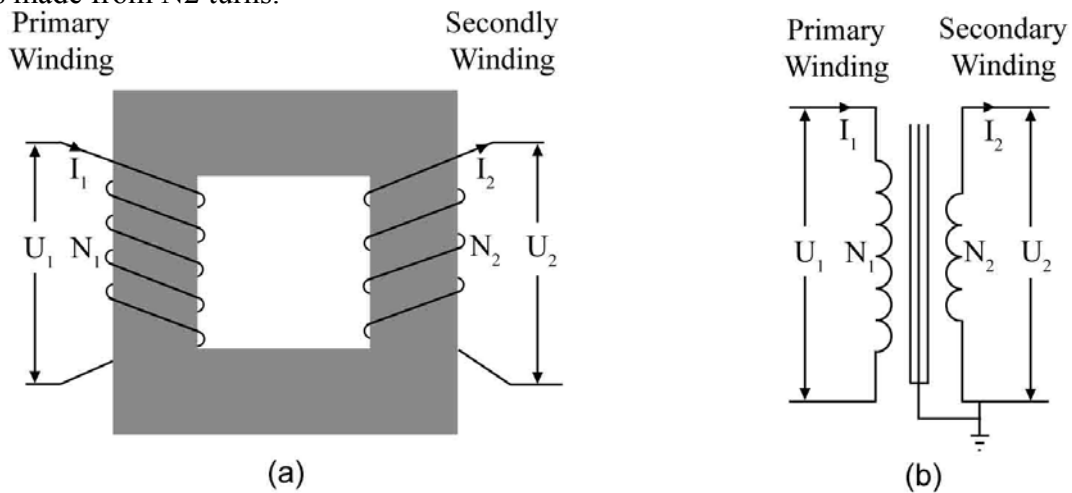
The value of voltage regulation is normally a few percent

## **Parts of transformer:**

### **1 -Single-Phase Transformers**

Transformers are made up from *primary* and *secondary* coils (called windings) that are made from turns of insulated wire. The coils are arranged on a core of magnetic material that increases the

amount of magnetic flux set up by one coil and will make sure that most of it links with the other coil; in this way mutual inductance is increased. A simple transformer is illustrated in figure 15.1a and the corresponding circuit diagram is shown in figure 15.1b. The primary winding has a voltage of  $U_1$  across it and is made of  $N_1$  turns of wire. The secondary coil has a voltage of  $U_2$  across it and is made from  $N_2$  turns.



**Figure 1:** (a) a simple transformer; (b) the circuit diagram for a simple transformer.

An alternating current in the primary coil will set up an alternating magnetic flux in the core and the primary's self inductance induces an EMF which opposes the supply voltage that is driving the current (sections 6.5 and 9.5). The induced EMF will almost be the same magnitude as the supply voltage and although there will be a small difference, this is normally ignored. The changing EMF from the primary coil links with the second coil and mutual inductance causes an EMF to be induced (section 6.4). It is normally assumed that all of the flux from the primary links with the secondary, and although this is not strictly true it is a good approximation and the induced EMF per turn in the primary is taken to be the same as the induced EMF per turn in the secondary. Thus

$$\text{primary volts per turn} = \text{primary volts} / \text{primary turns} - U_1/N_1$$

$$\text{secondary volts per turn} = \text{secondary volts} / \text{secondary turns} - U_2/N_2$$

$$U_1/N_1 = U_2/N_2 \text{ and } U_1/U_2 = N_1/N_2$$

If 100% efficiency is assumed:

$$\text{power in} = \text{power out} \quad U_1 I_1 \cos \theta_1 = U_2 I_2 \cos \theta_2$$

Where  $I_1$  and  $I_2$  are the primary and secondary currents, and  $\cos \theta_1$  and  $\cos \theta_2$  are the primary and secondary power factors. If the two power factors are assumed to be the same, they cancel and:

$$U_1 I_1 = U_2 I_2$$

$$\text{Therefore: } U_1/U_2 = N_1/N_2 = I_1/I_2$$

For a transformer with more turns in the primary than the secondary  $U_1 > U_2$ , such a transformer is

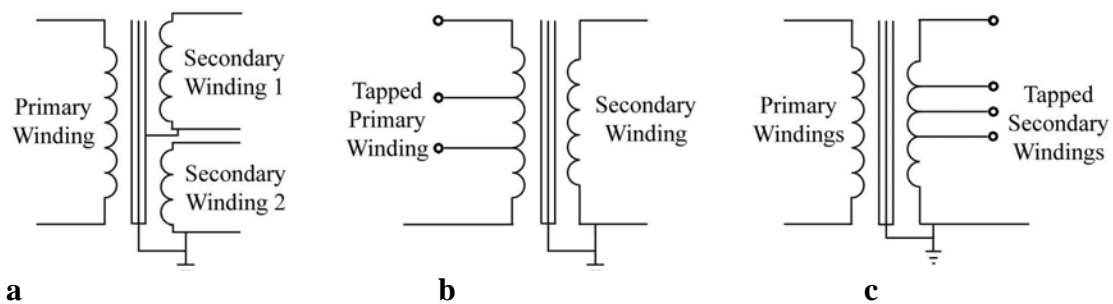


called a *step-down* transformer. For a transformer with more turns in the secondary than the primary  $U_1 < U_2$ , such a transformer is called a *step-up* transformer.

- **Tapped Windings**

The voltage ratio depends on the ratio of the number turns in the primary to the number of turns in the secondary. If more than one secondary voltage is needed from one transformer a number of secondary windings can be provided. All of the windings are placed on the same magnetic core and this arrangement is shown in figure 15.2a.

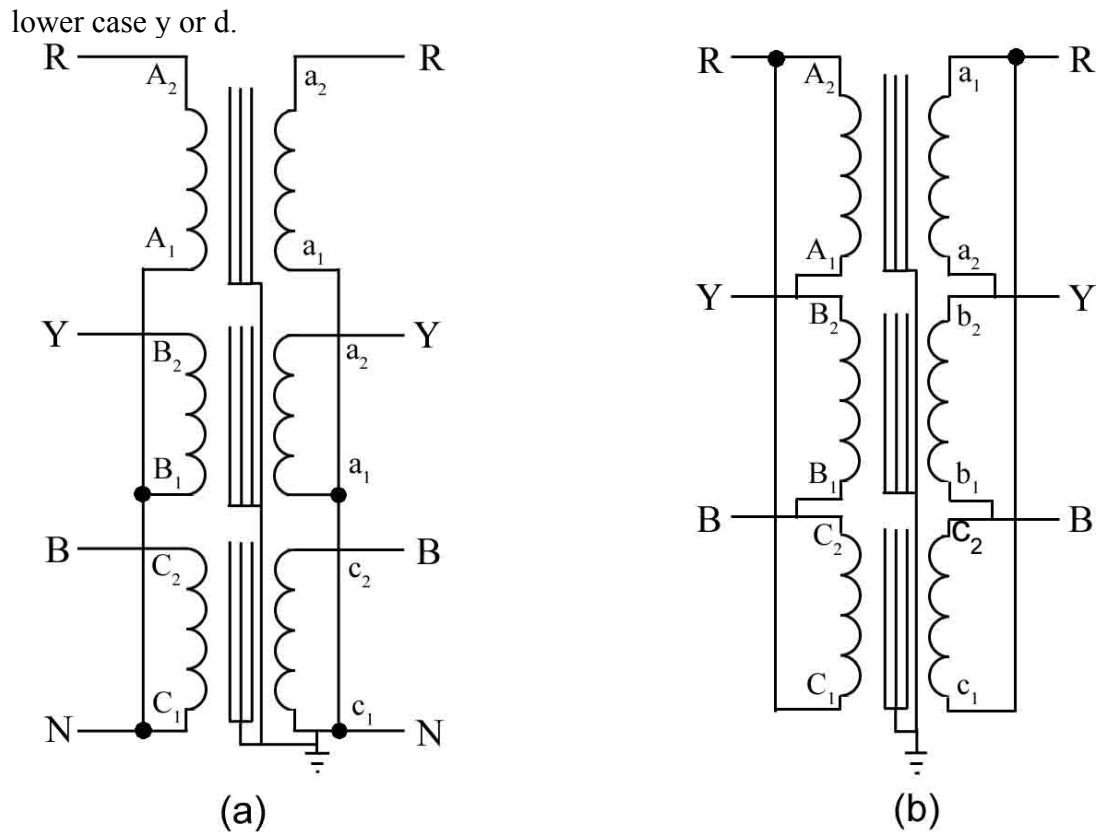
In some cases a single adjustable voltage is needed, and this can be accomplished by tapping the primary or secondary winding. Figure 15.2b and c show tapped windings, where the number of coils in winding that has been tapped can be changed by switching between terminals. It is unusual to tap both the primary and secondary windings, transformers with small outputs are usually tapped on the secondary winding.



**Figure 2:** Methods for obtaining multiple voltages from a single transformer: (a) multiple secondary windings; (b) tapped primary winding; (c) tapped secondary winding.

## 2- Three-phase Transformers

A three phase transformer is effectively the same as three single-phase transformers connected in a three-phase arrangement and it is possible to use three separate single-phase transformers, although it is far more usual to have all the windings on the same core. Three-phase transformers have six windings, three primary and three secondary, that can be connected in star (Y) or delta (D) configurations. The primary winding is commonly denoted by a capital Y or D and the secondary windings are denoted by



**Figure 3:** Three-phase transformers similarly connected: (a) star-star - for the primary and secondary one end from each winding is connected together forming a neutral; (b) delta-delta – one end of each winding

connected to the next winding.

Figure 15.3a shows a transformer where both primary and secondary windings are star connected,

**Figure 15.2:** Methods for obtaining multiple voltages from a single transformer: (a) multiple secondary windings; (d) tapped primary winding; (c) tapped secondary winding.

**Figure 15.3:** Three-phase transformers similarly connected: (a) star-star - for the primary and secondary one end from each winding is connected together forming a neutral; (b) delta-delta – one end of each winding connected to the next winding.

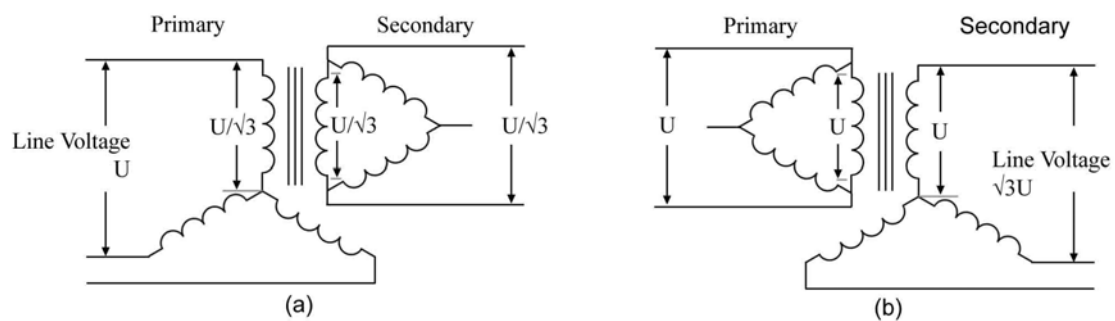
such a transformer is called a *star-star*, *wye-wye* or *Yy* transformer. Figure 15.3b shows a *deltadelta*, *mesh-mesh* or *Dd* transformer, where both primary and secondary cores are delta connected.

The secondary and primary coils need not be connected in the same configuration so that star-delta

(Yd) and delta-star (Dy) are also possible and are shown in figure 15.4. Transformers with delta connected secondaries are seldom used to supply consumer's loads because there is no position for a neutral wire, such transformers are used for high voltage transmission between substations.

Figure 15.3 shows the standard method for marking three-phase transformer windings. The three primary windings are labelled with a capital A, B and C. The three secondary windings are labelled with a lower case a, b and c. Each winding has two ends and labelled 1 and 2 so that the ends of the primary on the second winding are labelled B1 and B2. If the primary and secondary windings are connected similarly (i.e. star-star or delta-delta), calculations are the same as those for single phase transformers, as long as the system is balanced (section 13.4). When the primary and secondary have different types of connection, the overall turns ratio of the transformer is more complicated. For example, consider a single-phase transformer with a 1:1 turns ratio, the input and output voltages from the windings are the same. This will also be true for a three-phase transformer with the primary and secondary windings connected similarly. However, if the three-phase transformer is connected in star-delta (figure 15.4a), and has a primary line voltage of  $U$ , each of the star connected primaries will have the phase voltage across it, which is  $U/\sqrt{3}$  (the voltage between any line and the neutral point). Each of the secondary windings will then have this same voltage induced in it, and since these windings are delta-connected, the voltage  $U/\sqrt{3}$  will be the secondary. Thus, a star-delta transformer with a turns ratio of 1:1 provides a  $\sqrt{3}:1$  stepdown. For figure 15.a:

$$N_1/N_2 = U_1/U_2 \sqrt{3}$$



**Figure 15.4:** Three-phase transformers with primary and secondary windings connected differently: (a) star-delta; (b) delta-star.

For a delta-star transformer a similar effect happens but there is a 1: step-up for line voltage in addition to the effect of the turns. Thus, from figure 15.4b:

$$N_1/N_2 = U_1 \sqrt{3} / U_2$$

Only identical transformers should ever be connected in parallel. Transformers are identical when their turn ratios are the same and when the primary and secondary windings are connected in the same way

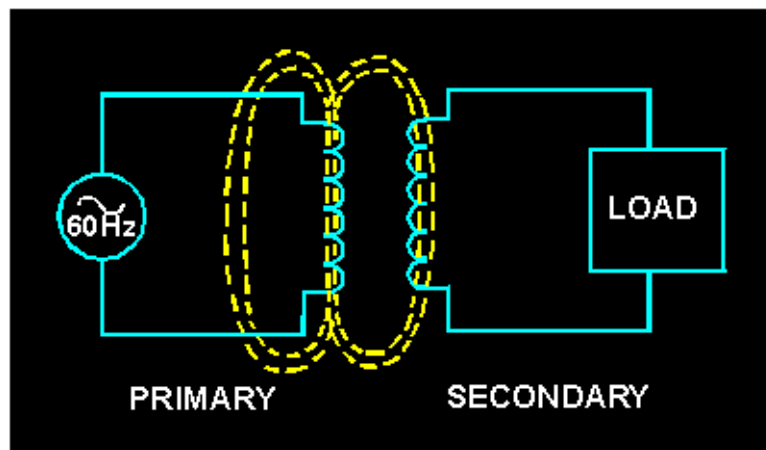
## BASIC OPERATION OF A TRANSFORMER:

In its most basic form a transformer consists of:

1. A primary coil or winding.
2. A secondary coil or winding.
3. A core that supports the coils or windings.

Refer to the transformer circuit in figure 5-1 as you read the following explanation: The primary winding is connected to a 60 hertz ac voltage source. The magnetic field (flux) builds up (expands) and collapses (contracts) about the primary winding. The expanding and contracting magnetic field around the primary winding cuts the secondary winding and induces an alternating voltage into the winding. This voltage causes alternating current to flow through the load. The voltage may be stepped up or down depending on the design of the primary and secondary windings.

Figure 5-1. - Basic transformer action.



Q.2 What are, the three basic parts of a transformer?

### THE COMPONENTS OF A TRANSFORMER

Two coils of wire (called windings) are wound on some type of core material. In some cases the coils of wire are wound on a cylindrical or rectangular cardboard form. In effect, the core material is air and the transformer is called an AIR-CORE TRANSFORMER. Transformers used at low frequencies, such as 60 hertz and 400 hertz, require a core of low-reluctance magnetic material, usually iron. This type of transformer is called an IRON-CORE TRANSFORMER. Most power transformers are of the iron-core type. The principle parts of a transformer and their functions are:

The CORE, which provides a path for the magnetic lines of flux.

The PRIMARY WINDING, which receives energy from the ac source.

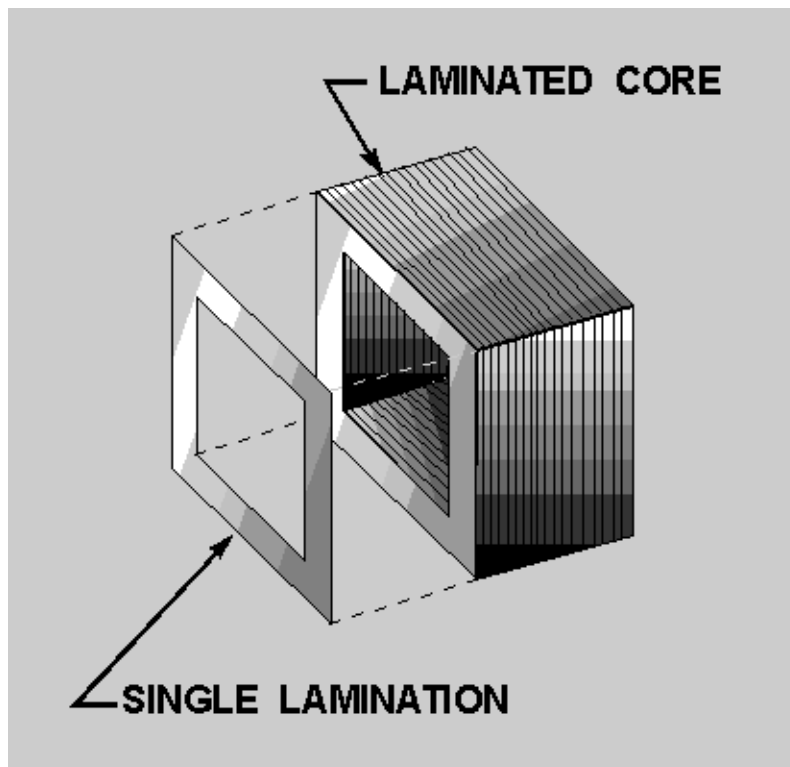
The SECONDARY WINDING, which receives energy from the primary winding and delivers it to the load.

The ENCLOSURE, which protects the above components from dirt, moisture, and mechanical damage.

## CORE CHARACTERISTICS

The composition of a transformer core depends on such factors as voltage, current, and frequency. Size limitations and construction costs are also factors to be considered. Commonly used core materials are air, soft iron, and steel. Each of these materials is suitable for particular applications and unsuitable for others. Generally, air-core transformers are used when the voltage source has a high frequency (above 20 kHz). Iron-core transformers are usually used when the source frequency is low (below 20 kHz). A soft-iron-core transformer is very useful where the transformer must be physically small, yet efficient. The iron-core transformer provides better power transfer than does the air-core transformer. A transformer whose core is constructed of laminated sheets of steel dissipates heat readily; thus it provides for the efficient transfer of power. The majority of transformers you will encounter in Navy equipment contain laminated-steel cores. These steel laminations (see figure 5-2) are insulated with a non-conducting material, such as varnish, and then formed into a core. It takes about 50 such laminations to make a core an inch thick. The purpose of the laminations is to reduce certain losses which will be discussed later in this chapter. An important point to remember is that the most efficient transformer core is one that offers the best path for the most lines of flux with the least loss in magnetic and electrical energy.

Figure 5-2. - Hollow-core construction.



## kind of transformer:

### Voltage Transformer

A typical voltage transformer reduces the 110-volt household alternating current to some lower amount, such as 12 volts. As small electronic devices use between 3 and 24 volts, they need transformers to reduce the voltage to the correct amount. High-voltage equipment, such as neon signs, use step-up transformers to increase voltage to thousands of volts.

### Current Transformer

It is difficult to directly measure the thousands of amps of current that flow in commercial and industrial equipment. A current transformer having its primary connected to large currents has its secondary connected to a meter. The transformer reduces the current going to the meter, making measurements safe and practical

**Power Transformer:** Power transformer is an electric machine with a useful life cycle of some 30 years. This doesn't mean to say that cannot be used above this time, in fact, a great part of the electric and industrial fleet is being operated with reliable machines above this time. The really important fact is to know the status and evolution of the transformer to be in conditions to operate it with the maximum security and know if it is appropriate to continue it's use, know overload capacity, limit load, refurbish it or either take it out from active service. There is a group of maintenance techniques that from an electric point of view and through some field tests are going to allow us to trace the transformer status as indicated and in the case of breakdown diligently detect the real problem and perform the required actions.

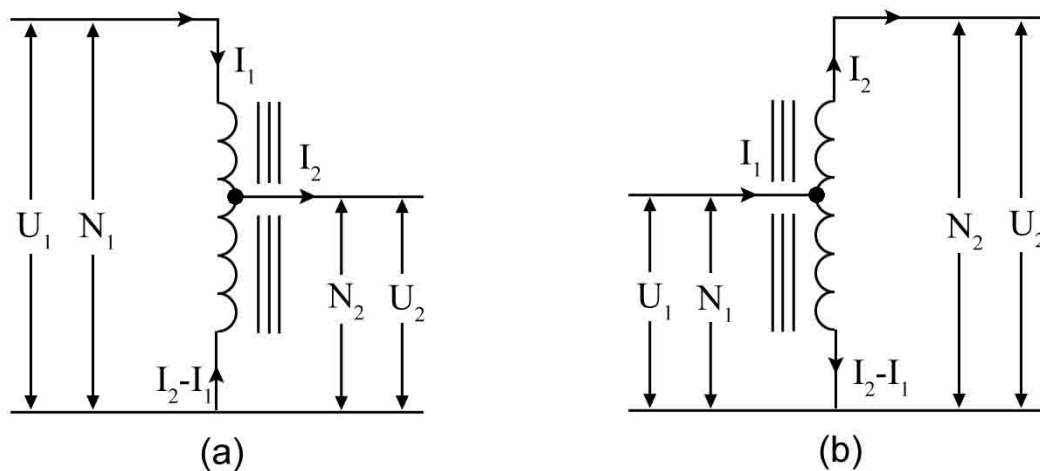


FIG 2. Field testing of a power transformer before putting into service (50MVA).

**POWER TRANSFORMERS FIELD TESTING.** As a result of the owner company, the importance of the machine and the outage possibilities, it is necessary to perform on each transformer a fitted maintenance program with a test protocol previously accorded. Next will be indicated a series of test that can set up this program and that are something like a continuation of validation tests performed when manufacturing the transformer but adapted to field testing. We have to take under account that in the field, in transformer installations, is not usually possible to have bulky equipments, what states certain limitations to field test with respect to manufacturing ones. Described tests are chosen from the commercially available ones, standardized and usual into test programs.

3

**Auto Transformer:** An autotransformer has only one tapped winding, which is both the primary and the secondary of



**Figure 15.7:** Autotransformers: (a) step-down; (b) step-up.

the machine. Since only one winding is needed the autotransformer is cheaper than a normal transformer. Step-down and step-up transformers are illustrated in figure 15.7. If losses are neglected, turns, voltage and current ratios are the same for double wound transformers, that is :

where:

- N1 = number of turns connected to input voltage
  - N2 = number of turns connected to output voltage
  - U1 = input (primary) voltage
  - U2 = output (secondary) voltage
  - I1 = input (primary) current
  - I2 = output (secondary) current
- The disadvantages of the autotransformer are that:

- ✚ There is a direct metallic connection between the input and the output, whereas the coupling in a double-wound transformer is magnetic only, giving electrical isolation of the two windings.
- ✚ In the event of an open-circuit fault in the common part of the winding, the input voltage of a

# **GUIDE FOR TESTING POWER TRANSFORMERS**

The following routine tests must be carried out on all power transformers :

- separate-source voltage withstand test
- induced voltage test
- voltage ratio measurement and check of polarities and connections
- no-load current and no-load loss measurement
- winding resistance measurement
- short-circuit impedance and load loss measurement
- partial discharge measurement

## ***1- Dielectric tests – Separate-source voltage withstand test***

The single-phase applied voltage wave shape shall be approximately sinusoidal. The test must be

performed at rated frequency. At the end of the test, the test voltage shall be rapidly reduced up

to 1/3 the full voltage before disconnection. The full test voltage shall be applied for 60 seconds

between the winding under test and all the remaining windings, magnetic core, frame and enclosure connected to earth. The test shall be performed on all the windings. The test is successful if no failure occurs at full test voltage.

## ***2- Induced voltage test***

The test voltage shall be twice the value corresponding to the rated voltage; it shall be applied



between the terminals of the secondary windings, by maintaining the primary winding open. The

duration of the test at full voltage shall be 60 s, and the frequency twice the rated value. The test

shall start with a voltage lower than 1/3 the full test voltage, and it shall be quickly increased up to

full value. At the end of the test, the voltage shall be rapidly reduced up to 1/3 the rated value before disconnection. The test is successful if no failure occurs at full test voltage.

### ***3- Voltage ratio measurement and check of polarities and connections***

Voltage ratio measurement and check of polarities and connections shall be performed on all tap changer

positions; the correspondence between the numbers assigned to the tapping's and the

ratings shall also be checked. Voltage ratio measurement shall be performed phase by phase

between the terminals of corresponding windings. Voltage ratio measurement is carried out by

use of potentiometer method.

### ***4- No-load current and no-load loss measurement***

This test is performed by supplying LV windings at rated frequency and rated voltage. The wave

shape shall be as nearly as possible of the sine-wave and the primary windings shall be open

The frequency of the test shall not differ from the rated value more than  $\pm 1\%$ . No-load current

and loss shall be measured as well as the mean value and the effective value of the voltage. If

these two readings are equal, no correction shall be applied on the measurement of no-load

loss; otherwise, no-load loss shall be referred to sine-wave condition in accordance with IEC

Standards 60076-1. No-load current shall result as the average value of three readings performed

by effective value ammeters. Three watt meters shall be used to measure the power, by using instrument transformers and transducers when necessary

### ***5- Winding resistance measurement***

Winding resistance measurement shall be performed when the windings are at ambient temperature without supply for a time long enough to achieve this condition. The measurements

shall be carried out in direct current between terminals according to the sequence U-V; V-W; .WU

Ambient temperature shall also be measured. It shall result as the average value of three .measurements performed by apposite thermal sensors

HV winding resistance measurement

HV winding resistance measurement shall be performed by measuring simultaneously voltage : and current. The voltmeter and ammeter must be connected as follows

‘voltmeter terminals must be connected beyond current cables •

‘the current shall not exceed 10% of winding rated current •

.the measurement shall be carried out after voltage and current are stable •

.Unless otherwise agreed, the HV winding shall be connected on principal tapping

LV winding resistance measurement

LV winding resistance measurement shall be performed by measuring simultaneously voltage and

: current. The voltmeter and ammeter shall be connected as follows

‘voltmeter terminals shall be connected beyond current cables •

‘the current shall not exceed 5% of winding rated current •

..the measurement shall be carried out after voltage and current are stable •

### ***6- Short-circuit impedance and load loss measurement***

Short-circuit impedance and load loss measurement shall be performed at rated frequency, by

applying on the transformer primary windings ( connected on principal tapping) a three – phase

‘sine-wave voltage system. The secondary windings shall be short-circuited. Applied voltage .current and load loss shall be measured

The frequency of the test shall not differ from the rated frequency more than  $\pm 1\%$ . In case the rated power is higher than 1000 kVA, load loss shall be measured by using three wattmeters, in

order to reduce measurement uncertainties. When necessary, instrument transformers and transducers shall be used. The measured values shall be referred to rated current and then calculated at reference temperature. This temperature is the annual average ambient temperature (20°C) increased by the permissible temperature rise in accordance with the temperature class of the windings. IEC 60726 specify the permissible temperature rises on table

no. 4. Beside, IEC 60076-1 give a complete explanation of how to perform the carries at rated .current and at reference temperature

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