# UNIT-3 (TRANSFORMER AND INDUCTION MOTORS)

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## TRANSFORMER

The **equivalent circuit of a transformer** is a simplified diagram that represents the transformer's electrical characteristics using basic components like resistors and inductors. Instead of dealing with the complex internal workings, engineers use this circuit to easily analyze the transformer's behavior, like how much voltage drops or how much energy is lost. It's like a simplified road map that shows you the main routes and key intersections without all the minor streets.

### Components of the Equivalent Circuit 🤓

An equivalent circuit accounts for the imperfections of a real-world (practical) transformer. It includes components that model the various losses and effects:

- **Primary Winding Resistance (R1):** A resistor in the primary side that accounts for the energy lost as heat in the primary coil's wire.
- **Primary Leakage Reactance (X1):** An inductor that models the magnetic flux that "leaks" out and doesn't link with the secondary coil.
- **Magnetizing Reactance (Xm):** An inductor connected in parallel that represents the current needed to create the magnetic field in the core.

This current is required even when no load is connected.

- **Core Loss Resistance (Rc or R0):** A resistor in parallel that represents the energy losses in the core due to hysteresis and eddy currents.
- **Secondary Winding Resistance (R2):** A resistor in the secondary side that accounts for the heat loss in the secondary coil's wire.
- **Secondary Leakage Reactance (X2):** An inductor that models the magnetic flux that leaks from the secondary coil.

These components are typically arranged to show the transformer as an ideal transformer connected to these "lossy" elements.

### Referred to Primary or Secondary Side ⬅ ➡

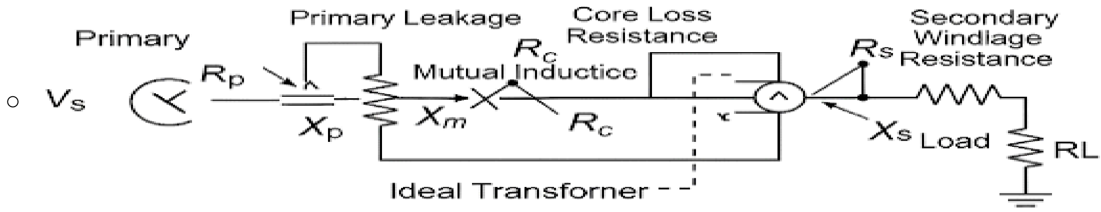
A transformer has a primary and a secondary side, which are electrically isolated. To simplify the equivalent circuit even further, engineers "refer" all the components from one side to the other.

- **Referred to the Primary:** All the resistances and reactances from the secondary side are mathematically converted and moved to the primary side. This eliminates the need to consider the ideal transformer in the circuit, making calculations much simpler.
- **Referred to the Secondary:** Similarly, all components from the primary side can be converted and moved to the secondary side.

When you refer an impedance (like resistance or reactance) from one side to another, you multiply or divide by the square of the **turns ratio** ($K = N2/N1$). For example, a secondary resistance R2 referred to the primary side becomes $R2' = R2/K2$.

### Real-Life Example & Memory Tip 🌐

- **Real-Life Example:** Imagine you're building a video game character. The **actual character** is the real transformer with all its complex internal workings. The **equivalent circuit** is the simplified, low-poly model of that character used in the game to save processing power. It's not a perfect representation, but it's good enough to make the game work smoothly and accurately for its purpose.
- **Memory Tip:**
  - **Equivalent Circuit = Simplified Map.** It's not the real thing, but it's a useful tool for getting around and understanding the main characteristics.
  - Think of the components as representing the **flaws** of a real transformer:
    - **Resistors (R)** = **Heat Loss** 🔥
    - **Inductors (X)** = **Magnetic Leakage** 🧲
  - **"Referring"** is just **re-labeling** the components so they're all on one side, making the map easier to read.




Imagine you have a new car, and you want to know how it performs without taking it on a long road trip. You'd perform two simple tests:

1. **A test to see how much gas it uses just idling.** This would tell you about its "no-load" losses.
2. **A test to see how powerful the engine is when you're trying to move a heavy load.** This would tell you about its "full-load" power and losses.

The **Open Circuit (OC)** and **Short Circuit (SC)** tests are the transformer's equivalent of these checks.[1] They are clever, simple, and safe ways to find out all the important characteristics of a transformer without having to actually connect a full load, which would be expensive and potentially dangerous.

**Open Circuit (OC) Test** 🔌

This test is performed to find the **core losses** (also called no-load losses) and the parameters of the **magnetizing branch** of the equivalent circuit.[2]

**How it's done:**

1. The transformer's **high voltage (HV)** side is left **open** (nothing is connected to it).[3]
2. A low voltage (LV) AC source, typically at the transformer's rated voltage, is connected to the **low voltage (LV)** side.[4]
3. A voltmeter, ammeter, and wattmeter are connected on the LV side to measure voltage, current, and power.[5]

Because the secondary side is open, no current flows in the secondary winding.[6] This means very little current is drawn from the source on the primary side—just enough to create the magnetic field in the core.[7] This tiny current is not enough to cause any significant copper losses, so the wattmeter reading in this test almost exclusively measures the **core losses** (hysteresis and eddy current losses).

**Real-Life Example:**

This is like measuring the power consumption of a fan when it's spinning with no one in the room. The fan is running, but it's not actually doing any work. The power it uses is just to overcome internal friction and resistance, which is like the core losses of the transformer.

**Memory Tip:**

**OC = O**pen **C**ircuit. Think of the letter **'O'** for **Core losses**, which are the losses that happen all the time, even when the transformer is just "on" but not doing anything.[8]

### Short Circuit (SC) Test ⚡

This test is performed to find the **full-load copper losses** and the parameters of the **series branch** (winding resistances and leakage reactances).[9]

**How it's done:**

1. The transformer's **low voltage (LV)** side is **shorted** using a thick wire.[10]
2. A very small AC voltage (typically just 5-10% of the rated voltage) is applied to the **high voltage (HV)** side.
3. The voltage is slowly increased until the ammeter shows the **rated current** flowing through the windings.
4. A voltmeter, ammeter, and wattmeter are connected on the HV side to measure these values.[11]

Because the applied voltage is so low, the magnetic field in the core is very weak, which means the core losses are negligible.[12] However, since the rated current is flowing through the windings, the **copper losses** (due to the resistance of the wires) are at their maximum. Therefore, the wattmeter reading in this test almost exclusively measures the **full-load copper losses**.

**Real-Life Example:**

This is like a tug-of-war where both teams are pulling with full force but the rope isn't moving. The teams are working hard (full-load current is flowing), but no useful work is being done. The energy is all being lost as heat and muscle strain (copper losses).

**Memory Tip:**

**SC = S**hort **C**ircuit. Think of the letter **'S'** for **Series** components and **'S'** for **Squaring** the current (since copper loss is [13] I2R). [14] The test is all about measuring the effects of a large current.

When we talk about **losses** in a transformer, we're simply talking about wasted energy. A transformer's job is to transfer electrical power from one circuit to another, but it's not a perfect machine. Some of the electrical energy that goes in is converted into heat instead of useful output. The main goal of a good transformer design is to minimize these losses.

There are two main types of losses that account for almost all the wasted energy.

### 1. Core Losses (Iron Losses)

These are losses that happen in the transformer's iron core. They occur whenever the transformer is connected to an AC source, regardless of whether a load is connected or not. This is why they are often called "no-load losses" or "constant losses."

There are two types of core losses:

- **Hysteresis Loss:** The alternating current in the primary winding repeatedly magnetizes and demagnetizes the core. This constant reversal of the magnetic field requires energy, which is dissipated as heat. Think of it like bending a piece of metal back and forth; it gets hot.
- **Eddy Current Loss:** The changing magnetic field in the core also induces small circulating electrical currents, called eddy currents, within the core itself. These currents flow through the resistance of the core material, generating heat. To reduce this, the core is made of thin, insulated plates (laminations) instead of a single solid block.

**Real-Life Example:** Imagine a car engine idling. Even though the car isn't moving (no useful work is being done), the engine is running and consuming fuel to overcome internal friction and resistance. That energy is a "loss" in this context. The core losses in a transformer are similar—they are present just by having the transformer "on."

### 2. Copper Losses ♨️

These are losses that happen in the transformer's copper windings (the coils of wire). They are caused by the natural electrical resistance of the wire. As current flows through the windings, it encounters this resistance and generates heat.

The key thing about copper losses is that they are **variable**. The amount of heat generated depends on the amount of current flowing through the windings, which is determined by the **load** connected to the transformer. When there's no load, there's very little current, and therefore very little copper loss. When the transformer is supplying full power, the current is high, and the copper loss is at its maximum.

**Real-Life Example:** Think of a phone charger. When you're charging your phone, the charging brick and the cable get a little warm. That heat is wasted energy, which is a copper loss. The more demanding the task your phone is doing while charging (i.e., the higher the current), the hotter the cable gets.

**Memory Tips:**

- **Core Losses:** Think of the **C**ore. **C**ore is **C**onstant. These losses are always there.
- **Copper Losses:** Think of **C**opper. **C**opper losses depend on the **C**urrent, and the current changes with the **C**onnected load.

## Efficiency ⚙️

**Efficiency** is a measure of how well a transformer converts the electrical power it takes in to the electrical power it sends out. In simple terms, it tells you how much useful work you get for the energy you put in.

A transformer's efficiency is never 100% because, as we discussed, there are always some losses (core and copper losses). The goal of a well-designed transformer is to be as efficient as possible, wasting as little energy as heat.

The formula for efficiency is a simple ratio:

$$\text{Efficiency } (\eta) = \frac{\text{Output Power}}{\text{Input Power}} \times 100\%$$

Since Input Power is equal to Output Power plus Losses, the formula can also be written as:

$$\text{Efficiency } (\eta) = \frac{\text{Output Power}}{\text{Output Power} + \text{Losses}} \times 100\%$$

ingredients. The **output** is the finished cake. The **losses** are the ingredients that spill on the floor, the batter left in the bowl, or the heat that escapes the oven. The more efficient the chef, the less is wasted, and the more cake you get for the ingredients you bought. A transformer is like a highly efficient chef, wasting very little.

**Memory Tip:** **E**fficiency is all about getting the most **E**nergy out.

## Voltage Regulation 🧮

**Voltage regulation** is a measure of how much the output voltage of a transformer changes when you connect a load. An ideal transformer would have an output voltage that stays perfectly constant, regardless of the load. A practical transformer's output voltage drops slightly as the load increases.

We want the voltage regulation to be as low as possible, ideally close to 0%. This indicates that the output voltage is stable and doesn't change much from its "no-load" value to its "full-load" value.

The formula for voltage regulation is:

$$\text{Voltage Regulation} = \frac{(\text{No-Load Voltage}) - (\text{Full-Load Voltage})}{\text{Full-Load Voltage}} \times 100\%$$

- **No-Load Voltage:** The voltage at the secondary terminals when nothing is connected.
- **Full-Load Voltage:** The voltage at the secondary terminals when the transformer is supplying its maximum rated load.

**Real-Life Example:** Imagine a water faucet. When there's no one else using water in the house (no-load), the water pressure is high. But when someone flushes a toilet or runs a washing machine (full-load), the water pressure at your faucet might drop slightly. The amount that the pressure drops is the "voltage regulation." A good plumbing system would have very little drop in pressure, just like a good transformer has very little voltage regulation.

**Memory Tip:** **V**oltage **R**egulation tells you if the **V**oltage **R**emains constant.

## Autotransformer

An **autotransformer** is a special type of transformer that has only **one winding** shared by both the primary and secondary circuits.[1] Unlike a conventional transformer where the primary and secondary windings are separate and magnetically isolated, an autotransformer has a single winding with a tap point.[2] The input voltage is applied across the entire winding, and the output voltage is taken from a portion of the winding.[3]

**How it Works:**

- **Step-Down:** If you connect the load to a portion of the winding, the output voltage will be less than the input.[4]
- **Step-Up:** If you connect the input to a portion of the winding and the load to the entire winding, the output voltage will be greater than the input.[5]

This direct electrical connection means that autotransformers are more efficient, smaller, and cheaper than two-winding transformers, especially when the voltage difference between the primary and secondary is small. However, a major disadvantage is that there is no electrical isolation between the primary and secondary circuits.

**Real-Life Example:** Autotransformers are often used as **dimmer switches** for lights. The knob you turn simply moves the tap point on the single winding, changing the output voltage to the light bulb.[6] They are also used in laboratories to get a variable AC voltage supply.[7]

**Memory Tip:** Think of "auto" as "self" or "single." An **auto**transformer is a **single-winding** transformer.[8]

## Three-Phase Transformer Connections

Three-phase power is the standard for generating and transmitting large amounts of electrical power. It consists of three separate AC power waves, each offset by 120 degrees from the others. A three-phase transformer is used to change the voltage of this power. This can be done either by using three separate single-phase transformers or by using a single transformer with a three-limbed core.

The way the three windings are connected determines the relationship between the input (primary) and output (secondary) voltages and currents. The two most common connections are **Delta** (Δ) and **Wye** (Y).

### 1. Delta Connection (Δ)

In a delta connection, the ends of the three windings are connected to form a closed loop, like the Greek letter delta (Δ). The three-phase lines are connected to the corners of this loop.

- **Voltage:** The line voltage is **equal** to the phase voltage.
- **Current:** The line current is 3

  times the phase current.

- **Key Feature:** This connection provides a closed path for circulating harmonic currents, which helps prevent unwanted voltages. It also allows the system to continue operating even if one winding fails, albeit at reduced capacity.

**Real-Life Example:** Delta connections are often used for high-voltage transmission lines because they can be more reliable. They are also common in industrial and commercial buildings.

**Memory Tip:** Think of the **triangle** shape of the Delta connection. The lines are connected at the corners of the triangle, and the voltage is the same across the sides.

**2. Wye Connection (Y) or Star Connection**

In a wye connection, one end of each of the three windings is connected to a common point, called the **neutral point**. The other ends of the windings are connected to the three-phase lines.

- **Voltage:** The line voltage is 3

  times the phase voltage.
- **Current:** The line current is **equal** to the phase current.
- **Key Feature:** The neutral point provides a common return path for unbalanced loads. It also provides two different voltages: the line-to-line voltage and the line-to-neutral voltage.

**Real-Life Example:** Wye connections are very common in power distribution systems. This is because they provide a neutral wire, which allows you to get both three-phase power (for motors) and single-phase power (for homes and lighting) from the same transformer. The voltage in your home (e.g., 120 V) is the line-to-neutral voltage, while the line-to-line voltage (e.g., 208 V) is used for bigger appliances.

**Memory Tip:** Think of the letter **'Y'** with the neutral point at the center. The voltage from the center to any point on the Y is the phase voltage, and the voltage between any two outer points is the line voltage. The line current just flows through the arms of the Y.

A single-phase induction motor is a type of electric motor that uses a single-phase alternating current (AC) to produce rotational motion.[1] It's the kind of motor you find in most household appliances.[2] Unlike three-phase motors, which are self-starting, single-phase motors require a bit of extra help to get going.[3]

## Construction 🛠️

A single-phase induction motor has two main parts:[4]

- **Stator:** This is the stationary outer part of the motor.[5] It's made of a steel frame with slots that hold the windings. In a single-phase motor, the stator has two sets of windings:

  - **Main Winding:** A low-resistance, high-inductance winding that creates the primary magnetic field.[6]
  - **Auxiliary Winding (or Starting Winding):** A high-resistance, low-inductance winding that is only used to start the motor.[7] It's often connected in series with a **capacitor** and a **centrifugal switch**.[8]

- **Rotor:** This is the rotating inner part of the motor.[9] It consists of a laminated steel core with copper or aluminum bars embedded in slots. These bars are short-circuited at both ends by end rings, giving it the name "squirrel cage rotor."[10]

### Working Principle 🔄

The working principle is based on **Faraday's Law of Electromagnetic Induction**.[11] Here's a simple breakdown:

1. **The Problem:** When you apply a single-phase AC current to the main winding, it creates a magnetic field that only changes in magnitude, not direction. This pulsating magnetic field cannot produce a rotating force (torque) by itself.[12] It just makes the rotor vibrate, which is why a single-phase motor is **not self-starting**.[13]
2. **The Solution:** To solve this, the **auxiliary winding** is brought in. It is physically placed at 90 degrees to the main winding. A **capacitor** is

added in series with the auxiliary winding.[14] The capacitor causes the current in the auxiliary winding to lead the current in the main winding.

3. **Creating a Rotating Field:** Because the currents in the two windings are now out of phase, they create two magnetic fields that are also out of phase. The combination of these two fields produces a **rotating magnetic field**.[15]
4. **Inducing Current and Rotation:** This rotating magnetic field cuts across the bars of the squirrel cage rotor, inducing a voltage and a current in them (Faraday's Law).[16] The current in the rotor creates its own magnetic field, which interacts with the stator's rotating field.[17] This interaction produces a force that causes the rotor to spin in the same direction as the rotating magnetic field.[18]
5. **Running and Disconnecting:** Once the motor reaches about 75% of its full speed, a **centrifugal switch** automatically disconnects the auxiliary winding and the capacitor.[19] The motor continues to run solely on the main winding.[20] The main winding's pulsating magnetic field is enough to maintain the rotor's rotation once it's already spinning.[21]

### Real-Life Example 🏠

Think about a common household fan. When you turn it on, you hear a hum, and it starts to spin. Inside that fan is a single-phase induction motor.

The capacitor and starting winding get it up to speed, and then they get disconnected.[22] The rest of the time, the fan motor runs on just the main winding.[23] The same principle applies to motors in washing machines, refrigerators, and air conditioners.[24]

## Memory Tips 🧠

- **Single-Phase = Single-Problem:** A single-phase motor has one big problem: it can't start on its own.[25]
- **Two Windings = Two Jobs:** The motor has a **main** winding for running and a **start** winding to solve the starting problem.
- **Capacitor = The Helper:**[26] The capacitor is the **"helper"** that creates the second magnetic field to get the motor spinning.[27]
- **Centrifugal Switch = The Bouncer:** Once the party (the motor) is started, the **bouncer** (centrifugal switch) kicks out the helper (the auxiliary winding) because it's no longer needed

A three-phase induction motor is a type of electric motor that uses three-phase alternating current (AC) to produce powerful and smooth rotational motion.[1] These motors are workhorses in industry because they are simple, rugged, and highly efficient.[2] Unlike their single-phase counterparts, they are **self-starting** and do not require any extra components to get going.[3]

## Construction 🛠️

A three-phase induction motor has two main parts:[4]

- **Stator:** This is the stationary outer part of the motor.[5] It is made of a steel frame with slots that hold three separate sets of windings, one for each phase of the three-phase AC supply.[6] These windings are arranged so that they are physically spaced 120 degrees apart from each other.[7]
- **Rotor:** This is the rotating inner part of the motor, almost always a **squirrel cage rotor**.[8] It consists of a laminated steel core with thick copper or aluminum bars embedded in slots.[9] These bars are permanently short-circuited at both ends by end rings.[10] It gets its name because the bars and end rings look like a hamster wheel.[11]

The rotor is not electrically connected to the power supply; its current is induced from the stator's magnetic field.[12]

## Working Principle 🔄

The working principle of a three-phase induction motor is based on **Faraday's Law of Electromagnetic Induction**.[13] Here’s a simple breakdown:

1. **Creating a Rotating Magnetic Field:** When a three-phase AC supply is connected to the stator windings, it creates three separate magnetic fields.[14] Because the windings are physically spaced 120 degrees apart

and the currents are also 120 degrees out of phase, these three fields combine to produce a single, smooth **rotating magnetic field** in the air gap between the stator and the rotor.[15] This rotating field is the key to the motor's operation and why it's self-starting.[16]

2. **Inducing Current in the Rotor:** This rotating magnetic field "cuts" across the stationary bars of the squirrel cage rotor.[17] According to Faraday's Law, this induces a voltage and a current in the rotor bars.[18]
3. **Producing a Rotating Force (Torque):** The induced current in the rotor creates its own magnetic field. This new magnetic field interacts with the stator's rotating magnetic field. This interaction produces a strong force (torque) that causes the rotor to spin in the same direction as the stator's rotating magnetic field.[19] The rotor always spins slightly slower than the rotating magnetic field, which is a key characteristic of induction motors.[20]

## Real-Life Example 🏭

Think about the powerful motors you see in industrial settings, like those running large pumps, conveyor belts, or factory machinery. They are almost always three-phase induction motors. They are reliable and don't need any special starting mechanisms, making them perfect for continuous, heavy-duty operation.[21]

## Memory Tips 🧠

- **Three-Phase = Three-Times the Power:**[22] The three-phase supply creates a rotating magnetic field naturally and smoothly, so the motor starts on its own. No "helper" capacitor is needed.
- **Rotor = The Follower:** The rotor's only job is to follow the rotating magnetic field of the stator.[23] The faster the stator's field spins, the faster the rotor tries to follow it.
- **Induction = No Connection:** The motor works by **inducing** a current in the rotor.[24] The rotor is not directly connected to the power supply.[25]

Since single-phase motors can't start on their own, they need a special trick to get going. The three motor types you asked about are all different ways of doing this "starting trick" to create an initial rotating force (torque).

## 1. Split-Phase Motor

This is the simplest and cheapest type of single-phase motor. It has two windings in the stator: a **main winding** and a **starting winding**.[1]

### Construction and Working Principle

The two windings are designed with different electrical properties.[2] The **main winding** has low resistance and high inductance, while the **starting winding** has high resistance and low inductance.[3] This difference in properties causes the current in the two windings to be "split" or slightly out of phase with each other.[4] This creates a weak rotating magnetic field that is just enough to get the rotor spinning.[5]

A **centrifugal switch** is connected in series with the starting winding.[6] Once the motor reaches about 75% of its full speed, the switch opens automatically, disconnecting the starting winding.[7] The motor then runs on the main winding alone.[8]

**Real-Life Example:** These are used in simple, low-starting-torque applications like small fans, blowers, and washing machines.[9]

**Memory Tip:** The name says it all: the current is **"split"** to start the motor.[10] 🌀

## 2. Capacitor-Start Motor

This motor is an improvement on the split-phase motor.[11] It also has a main and starting winding, but it adds a **capacitor** in series with the starting winding.[12]

### Construction and Working Principle

The capacitor creates a much larger phase difference between the currents in the two windings (closer to the ideal 90 degrees). This larger phase difference results in a much stronger rotating magnetic field and a **higher starting torque** compared to a split-phase motor.[13]

Just like the split-phase motor, a **centrifugal switch** disconnects the starting winding and the capacitor once the motor reaches about 75% of its full speed.[14] The motor then continues to run on the main winding.[15]

**Real-Life Example:** Because of their high starting torque, these motors are used in applications that require a big push to get going, such as refrigerators, air conditioner compressors, and large pumps.[16]

**Memory Tip:** The **capacitor** is only there to **start** the motor.[17] Think of it as a shot of energy just for the initial push. ⚡

### 3. Capacitor-Run Motor

This type is also called a Permanent-Split Capacitor (PSC) motor.[18] Its main difference is that the capacitor and auxiliary winding are **never disconnected** from the circuit.

#### Construction and Working Principle

This motor has a capacitor permanently connected in series with the auxiliary winding.[19] It does **not** have a centrifugal switch.[20] The capacitor's value is chosen to provide a phase shift that not only starts the motor but also improves its performance and efficiency while it's running.[21] It helps keep the magnetic field rotating smoothly, which results in quieter operation and less vibration.

**Real-Life Example:** These motors are ideal for continuous-running applications with a low starting torque. The most common examples are ceiling fans, furnace blowers, and air-conditioning units.[22]

**Memory Tip:** The **capacitor runs** with the motor all the time.[23] It's a permanent part of the circuit.[24] 🏃

## 1. Electrical Circuit Elements - Resistance, Inductance, Capacitance |BEE|