Learning resource

Demonstrate and apply knowledge of AC motors

Level 4 | Credits 4

Te Pūkenga

Contents

AC Motors

Introduction

Electric motors are amazing! They tame the wild force of electricity and turn it into physical movement, and they do it really easily.

The world was transformed by the invention of the electric motor.

The humble electric motor has literally become the driving force behind so many domestic, industrial and commercial processes.

Electric motors are simple, clean, and easy. A lot of AC motors actually send power through the air to make them work, amazing!

In years past when electric motors were invented, they took the world by storm and the motor quickly became the most widely used source of driving power in industry. Without these motors industry as we know it today would not exist.

At first look, electric motors may be a little confusing, there are so many different types of motors and different designs.

You will however find they all work on the same basic principle of a magnet trying to get away from another magnet. Just how the magnetism is produced, what power supply is available and how the motor is designed differs.

Some motors are designed to be made easily and cheaply, some are made small and quiet for domestic use, some are made really grunty for industry.

There are a variety of motors available and you will need to understand a bit about them so that you can talk intelligently to your clients about them. You will need to be able to check them out when they stop working and test that they are okay before you install them.

In this resource, we will have a look together at rotating motors designed to run on AC power.

So, let’s get started on understanding the exciting world of electric motors!

Single phase AC motors

There are a range of motors designed for use on a single-phase supply. As the power supply to domestic housing is most often single phase, then single phase motors are very convenient for domestic use.

Obviously, they are not only used in domestic situations, they are used where ever a single-phase supply is the most suitable for the situation.

So that you can start understanding the different types of single-phase motors, here is an overview to help you get your head around them.

There are three main types of single-phase motors we will look at in this resource:

1. Universal Motors (a.k.a. Series Motor)
2. Shaded Pole Motors
3. Split Phase Induction Motors
    a. Standard - split phase motors.
    b. Capacitor start - split phase motors.
    c. Permanently split phase motors.
    d. Capacitor start capacitor run - split phase motors.

Parts of AC electric motors

Let’s have a look at the parts motors are made up from. Obviously, it depends on the type of motor as to which parts are used.

There are some parts that are in most motors and some that you will find in specific motors only.

Knowing about the different parts will help you identify what motor you have in front of you on the work bench.

There are parts that are stationary and then there are the parts that rotate.

Stator

The overall collection of stationary parts of an AC electric motor all put together is called the stator.

The stator has a few bits to it like:

1. Foot / flange / mounting plate.
2. Casing / frame.
3. End shields.
4. Fan cowl.
5. Bearings.
6. Yoke.
7. Field poles.
8. Field windings:
    a. Start winding or,
    b. auxiliary winding.
    c. Run winding or,
    d. main winding.
9. Brush holders and brushes.
10. Capacitor.
11. Centrifugal switch mechanism.
12. Integrated over-temperature protection.

AC Motor parts explained - Stator

1. Foot / mounting plate, flange.

Obviously, a motor needs a mount of some sort. Many motors have a lengthwise foot on the underside which is used to mount the motor for use.

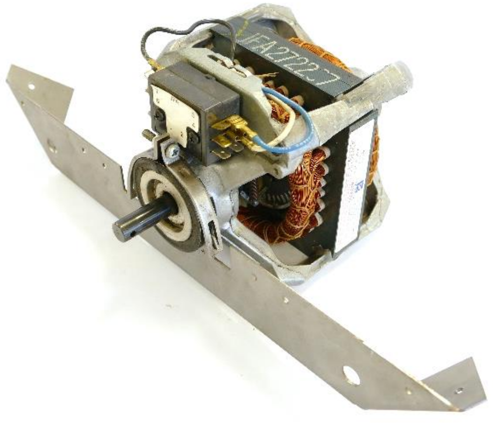
Flange mounts are common too. They are usually a circular plate at the end of the motor which allows the motor to be mounted directly to equipment like pumps for example.

2. Casing / frame.

The casing or frame of a motor is the body of the motor that all the other parts mount into / onto.

Depending on the motor type, the casing may have cooling holes in it or cooling fins instead of holes.

Motor casings are generally made out of cast iron, cast aluminium or pressed steel.



Some motors that are installed where they cannot be touched have a frame that is not enclosed.

They are designed to be economical to manufacture, lightweight and have good cooling airflow.

3. Cable termination box.

Mounted somewhere on the casing of a motor is the termination box where the tails of the winding are available to connect to the motor power supply cable.

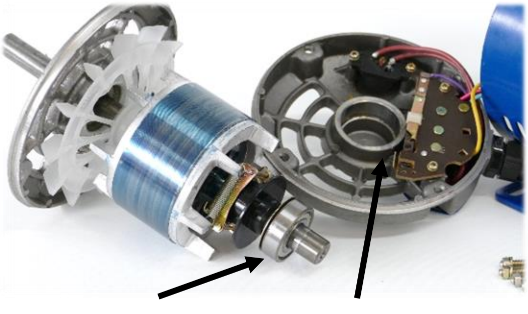
The box contains a cable termination block with screws or bolts to secure the cables. It may also have the motor capacitors in it.

4. End shields.

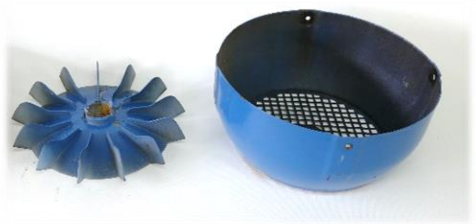
The end shields bolt onto the ends of the casing. They hold the bearings in place and complete the basic motor enclosure.

5. Bearings.

The bearings allow the armature to rotate. They are usually pressed into the end plates and depending on the motor design may be ball bearings or for cheaper motors, tubular bushes made of brass or other suitable material.



6. Fan cowling.



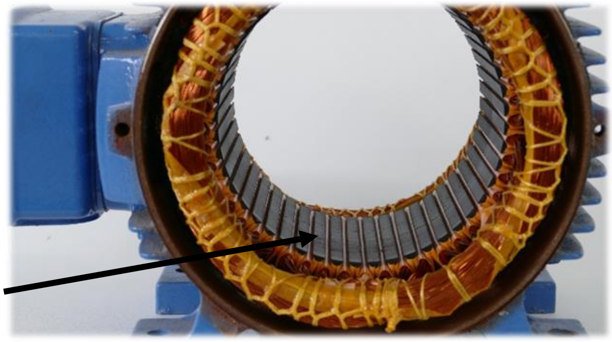
If there is an external cooling fan on the motor, then it will require a fan cowling to cover it to prevent the fan from being touched while rotating.

The cowl mounts over the fan and is secured to the motor casing.

7. Yoke

The yoke is a laminated steel "holder" for the motor windings. It is also where the stator magnetism forms and "circulates" and it is installed inside the casing or frame. The yoke is made by sandwiching many thin slices of steel together. These shaped laminations are usually punched out of silicon steel and are coated in varnish before being pressed together to form the yoke.

Eddy currents are currents that swirl around (like eddy currents in a river) inside a conductive material. They do not go anywhere in particular or do anything useful, they just waste energy.



The laminated construction of the yoke is to reduce eddy currents circulation in the yoke. Because the motor is being used for AC, the yoke will get current mutually induced into it.

The individual laminations prevent eddy currents being able to circulate freely throughout the entire yoke.

The resulting yoke is a great conductor of magnetism but as poor a conductor of current as possible.

The yoke has slots that the motor field windings are installed into.

8. Field windings (depending on the type of motor).

a. Start winding or,
b. Auxiliary winding.
c. Run winding or,
d. Main winding.

AC motors are basically two sets of powerful electromagnets, one set is fixed in position and the other is free to rotate.

The field windings are coils of copper conductors that are wound into the yoke to form the stationary electromagnets. Field windings are made in pairs with one on the opposite side of the yoke to the other.

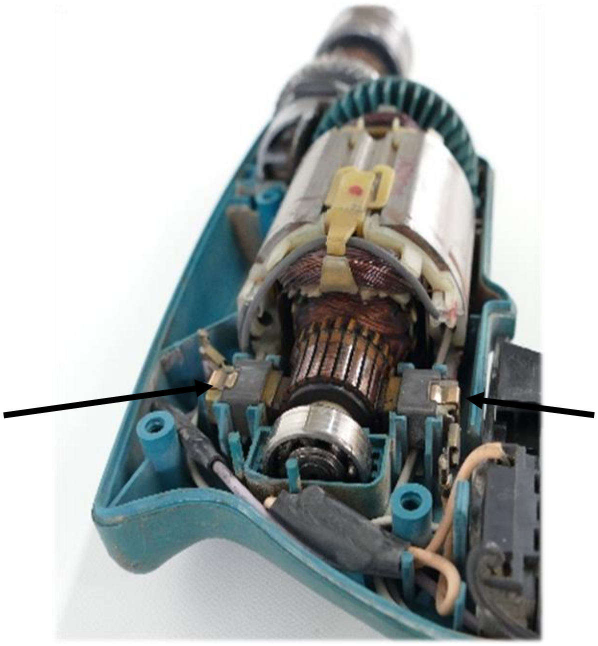
When energised they will form a north - south magnetism across the hole in the centre of the yoke.

9. Field poles

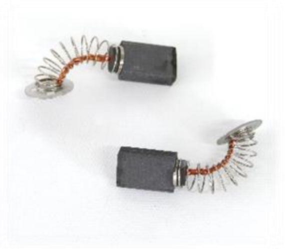
As each oval field coil is formed in the yoke, the coil circles part of the yoke metal. The face of that metal inside the coil becomes the place where the magnetic force developed by the coil is concentrated. This is called the field pole or field pole face.

10. Brush holders and brushes

Universal motors are one type of motor that requires an effective electrical connection to the rotating commutator on the armature.



Carbon brushes are made of rectangular pieces of carbon with a connecting wire. The brushes also have springs to press the brush firmly onto the commutator.



The brushes are conductive and make an effective electrical connection to the commutator segments. This allows the armature to maintain current flow into the rotor windings while it is spinning.

11. Capacitor

As you will learn, some split phase motors have capacitors that increase the motor torque (turning power). The capacitors generally mount on the outside of the motor and have a robust cover to protect them and hold them in place.

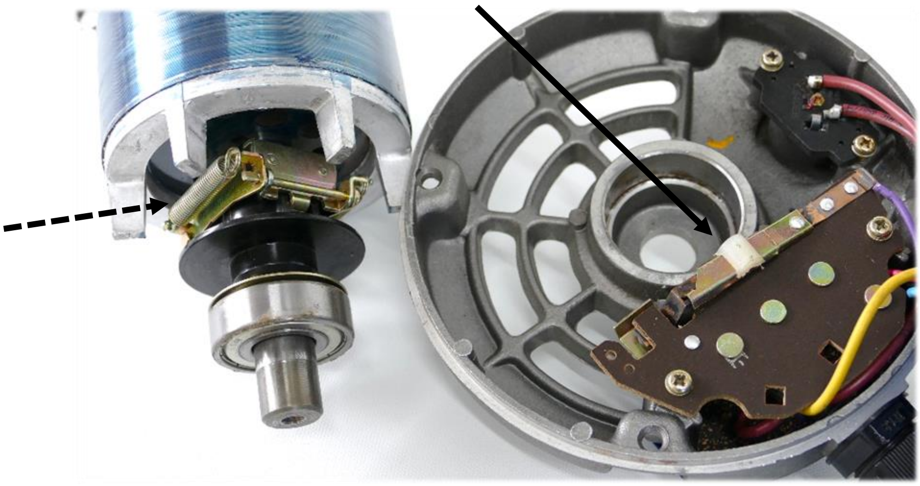
12. Centrifugal switch contact mechanism

Some split phase motors need to have a switch contact that opens when the motor reaches approximately 75% of its full operating speed. This disconnects the start winding and leaves the run winding to provide the normal running power of the motor.

Note: The centrifugal switch is one of the parts that involves both the stator and the rotor.

A centrifugal switch mechanism has hinged weights held in place by springs.

The mechanism is mounted on the rotor shaft and when the motor starts to spin the weights want to fly outwards but are held in place by the springs.



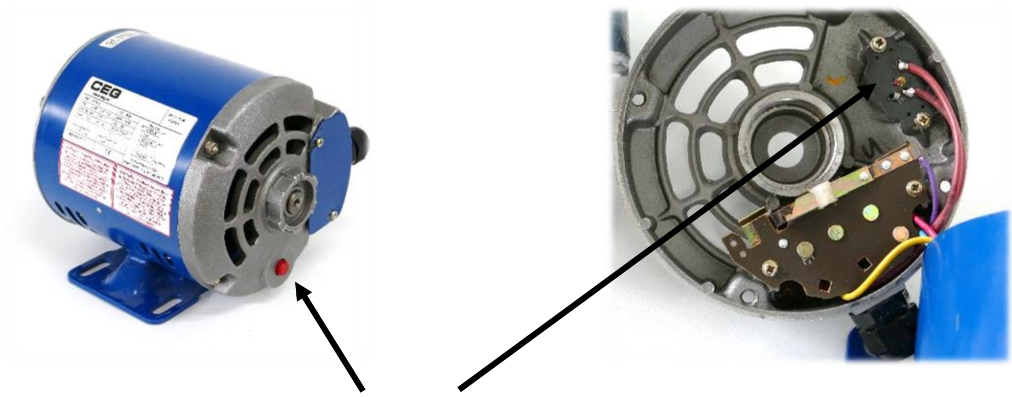
The weights and springs are carefully designed so that when the shaft speed rises to 75% of the full speed of the motor, the springs can't hold the weights back any more and the weights get flung out to their stops.

This action releases pressure on the stator mounted contact which springs open and disconnects the start winding of the motor.

When the motor is turned off and the rotor speed reduces below 75%, the springs are able to push the weights back in, the switch contacts are closed, and the motor is set ready for the next time is starts.

13. Integrated over-temperature protection

Some electric motors come with over-temperature sensors or mechanisms built-in, that is what integrated means, built-in or part of the motor.



The over-temperature protection device may be:

1. Directly wired into the motor supply to stop the motor or,
2. Indirectly wired into the motor control circuitry to cause a device in the motor control circuitry to stop the motor.

Some of these devices will stop the motor when it overheats and then as it cools automatically start the motor again.

Others are designed to stay disconnected until someone resets the protection device to start the motor again. This will give a chance for someone to find the reason for the temperature rise as a common cause is the motor being mechanically jammed.

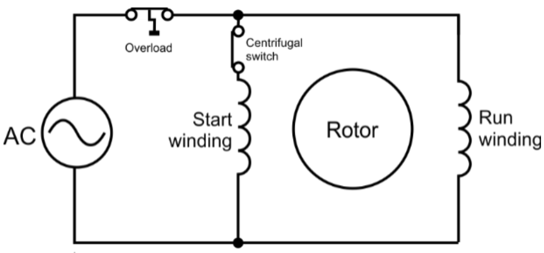
There are many different devices available to protect motors from overheating. It will depend on the manufacturer and market requirements as to which sort may be installed on a particular motor.

Some common integrated over-temperature protection devices are:

1. Semiconductor temperature sensors such as a Thermister.
2. Bimetal operated devices such as a Microtherm (brand name).
3. Directly connected bimetal operated devices like a Klixon (brand name).

Having an idea of what they are and what they do will help you when you come across one in the wild.

A typical motor circuit with directly connected integrated over-temperature protection device is shown below.



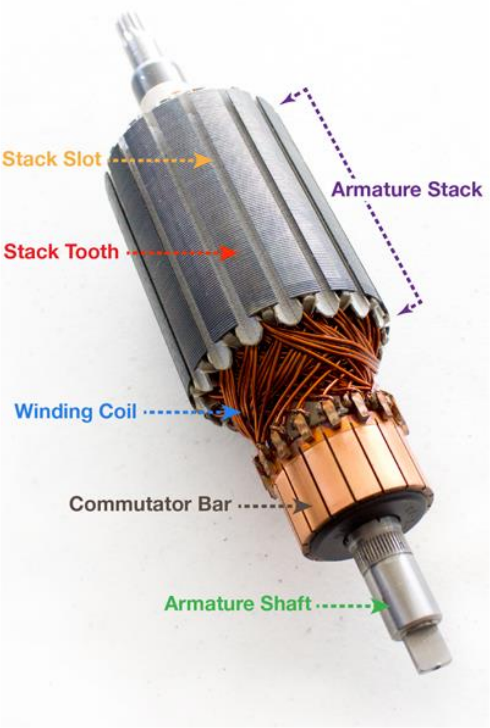
Rotor

The rotating part of an AC motor is called the rotor

There are two main ways of making a rotor:

1. Wound rotor.
2. Squirrel cage rotor.

We will look at the details of how they are made shortly.



The whole rotor will be made up of a few different parts depending on the type of motor. The rotor can have:

1. Laminated core / stack.
2. Winding.
3. Shaft.
4. Commutator.
5. Centrifugal switch actuator.
6. Cooling fan.

AC motor parts explained - Rotor

1. Wound rotor

In some AC motors the rotor has wires insulated with clear varnish wound onto a laminated steel core.

The wires form the armature of the motor and they connect to the commutator which connects the armature to a current supply, why? We will talk about that soon.

2. Squirrel cage rotor

In AC induction motors, the current in the rotor winding gets induced into it by transformer action, there is no electrical connection to the rotor, amazing!

Cut away squirrel cage rotor

An AC induction motor is actually a transformer with the secondary winding able to rotate!

We will also talk about that a bit more later in this book.

The rotor is called a squirrel cage rotor because if you could strip away the steel around the armature winding, you would find that it looks like one of those little round cages that a squirrel would run in.

The slots in the laminated core are often angled to improve starting and to reduce noise.

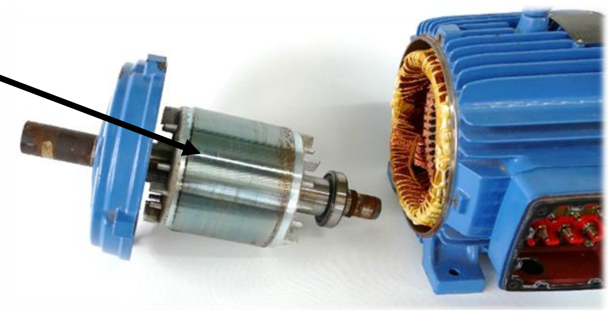
3. Armature

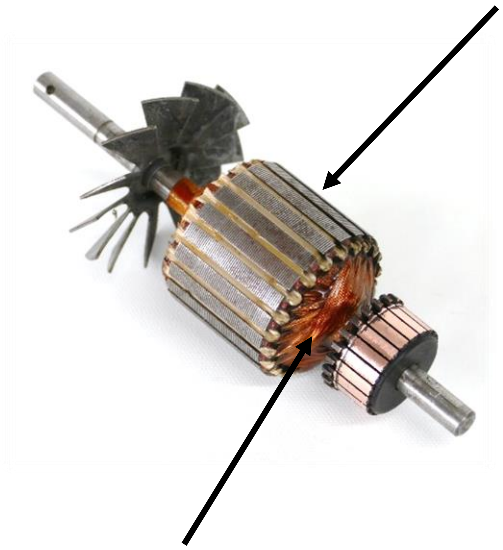
The armature of an electrical machine is the part that does the work, or in other words receives the ‘results” of the machine.

The armature can either be the rotating part, or the stationary part of the machine, it depends on the design.

For example, large AC generators usually have the stator as the armature – as the generated current is produced in the stator.

In the case of an AC motor, the rotor is the armature because the rotor is induced by the stator and does the work of turning the load.





4. Laminated core / stack

The rotor of an AC motor is an electromagnet. To make an electromagnet more effective, it needs a core that enhances its magnetism.

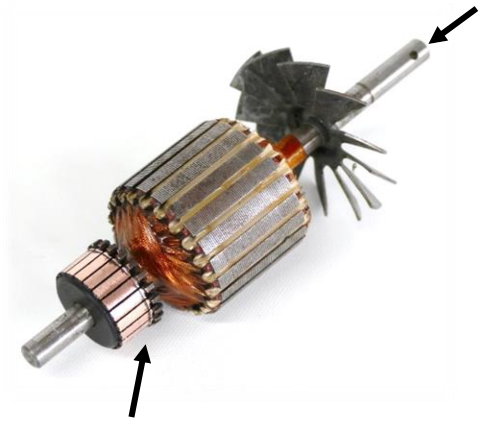
A wound rotor also needs something to wind the wire around to form it into the right shape.

The problem with steel in an AC motor is that it conducts electricity and will get current induced into it. That would waste energy and we don't want that.

Just like the yoke construction above, the core of the rotor is usually made of laminated silicon steel to limit eddy currents circulating in it while enhancing the magnetism.

5. Winding

As we mentioned, a wound motor rotor has wire wound around a core to form the armature. In electrical circles (scuse the pun) wherever a wire is formed into a coil we call it a winding.



6. Shaft

The rotor… well, rotates. So, the rotor is constructed complete with a shaft that is able to rotate in the motor bearings.

The shaft usually sticks out one end of the motor to connect to the load it is turning. The other end may also stick out if it needs a fan or other equipment on the other end. Some motors have a load on each end, like a bench grinder for example.

7. Commutator

An AC motor that requires current to be supplied to the rotor from the stator needs some sort of reliable rotating connection to the rotor.

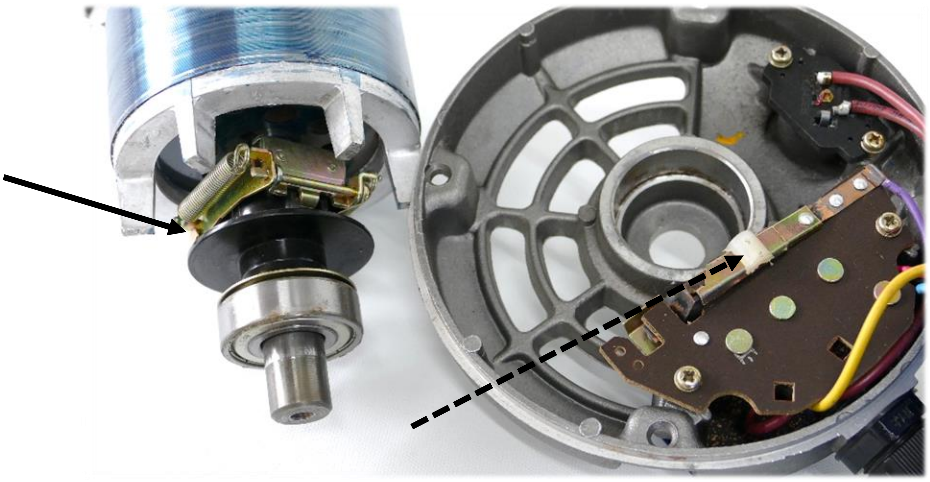
The commutator has a series of conductive bars or segments that are formed into a cylinder and insulated from each other.

The segments connect to the armature winding ends and provides a place for the carbon brushes (explained above) to press onto.

The commutator is a clever rotating connection set up that allows the brushes to power up the correct armature windings to make the motor work as the rotor rotates.

8. Centrifugal switch actuator

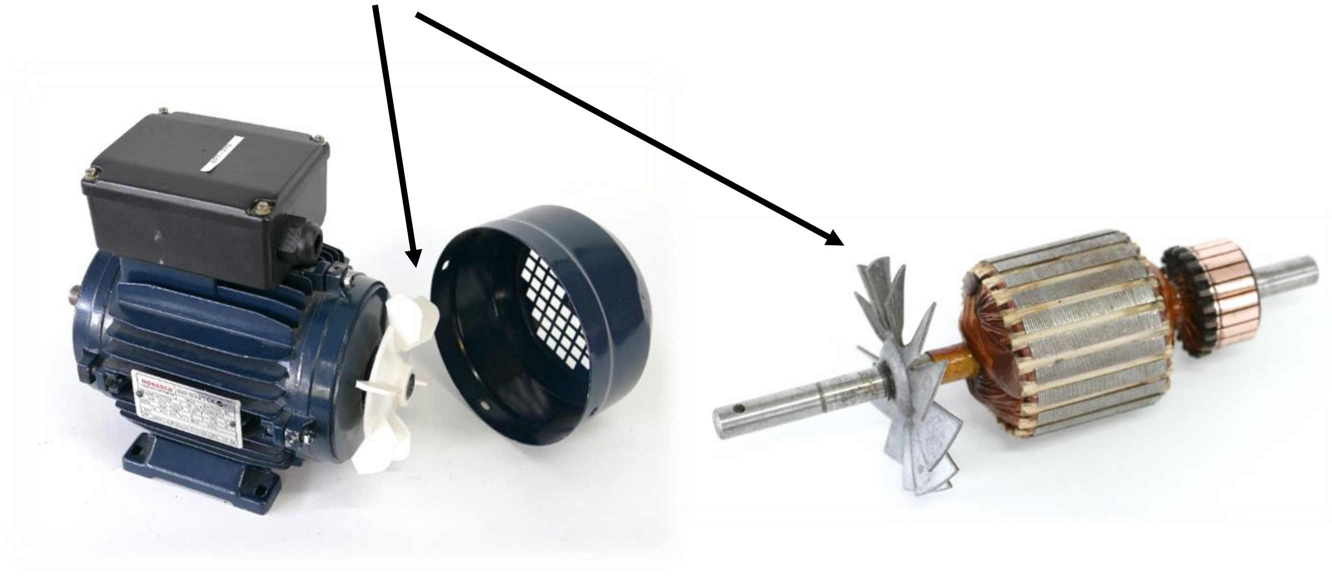
The rotating part of the centrifugal switch mechanism is the switch actuator with the sprung weights that we explained earlier in this resource.



9. Cooling fan

Electric motors can run hot, especially when they are under load. To help cool the motor, most electric motors have a fan built into them.

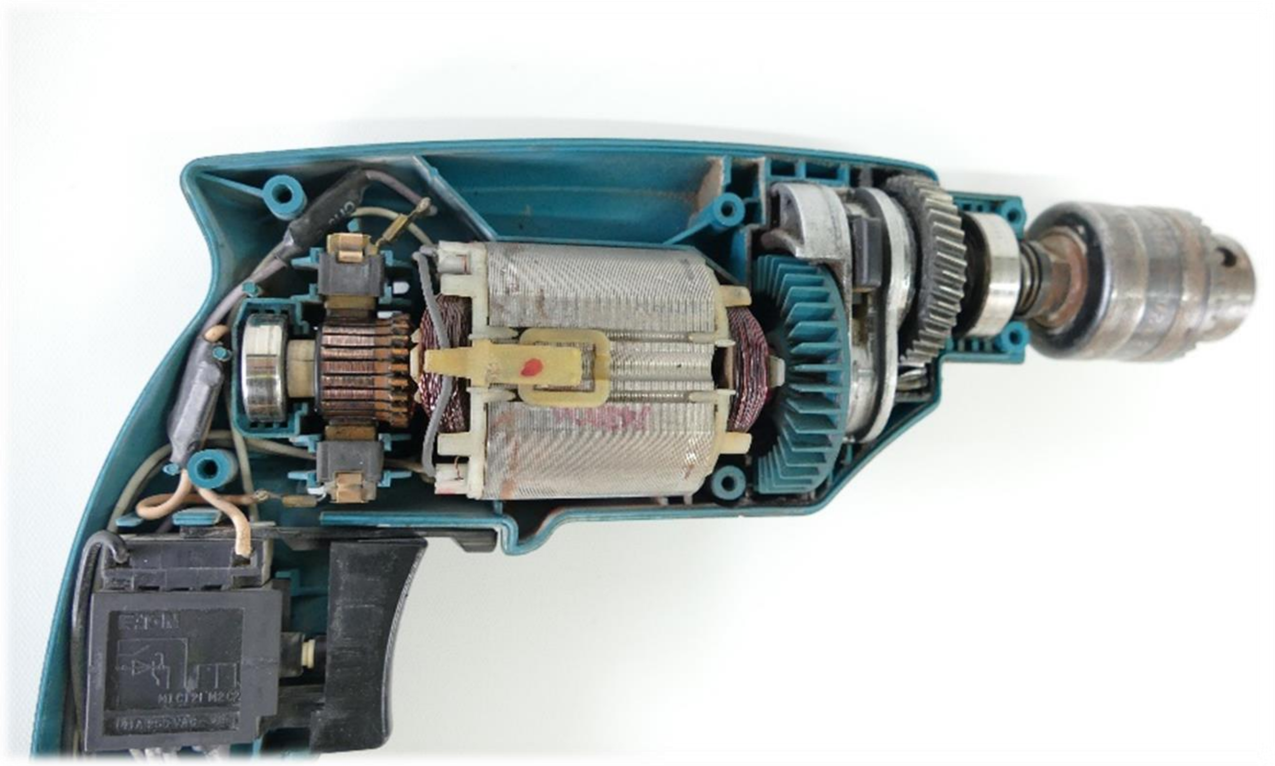
The fan is usually mounted on the rotor shaft and can either be inside the motor casing or outside the casing at the end. If the fan is outside, it will require a cowl over it to stop anything being able to touch or get caught in it.



Universal Motors

The universal motor is a great little motor that is used all over the place. If you did some electrical work today and you plugged in your power drill, then you probably used a universal motor.

Here is a trusty old well used drill with the cover pulled off and most of the dust blown out. You can see the universal motor inside.



Universal motors are called universal as they are one of the few electric motors able to be used on either AC or DC.

They have another name too, they are also called series motors, or series-wound motors because that’s how the three main components are connected together inside - in series.

Universal motors are used because they are:

1. Compact.
2. Powerful for their size.
3. Economical to make.
4. Easy to reverse.
5. Cheap and easy to vary their speed in a small space.

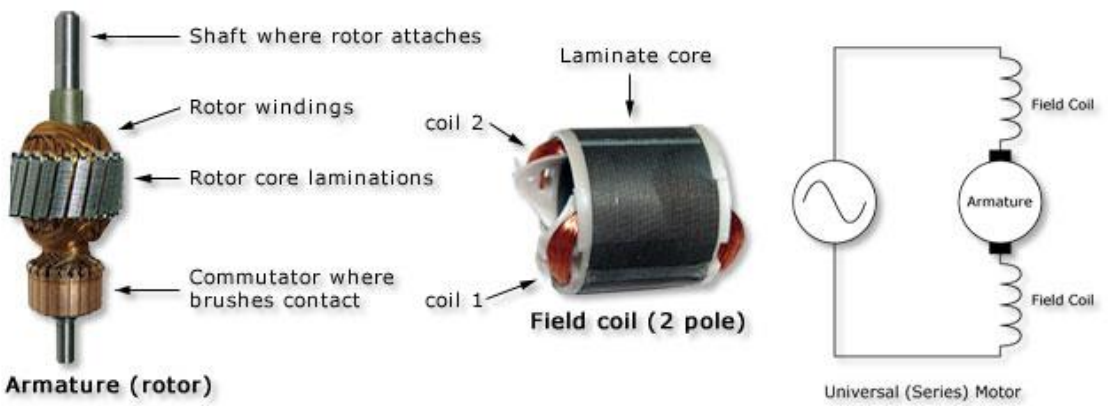
Typical applications for single speed and multi-speed universal motors.

As universal motors have a high power to weight ratio, it makes them ideal for most portable power tool applications. They are great for applications where they rotate at 3000rpm and above.

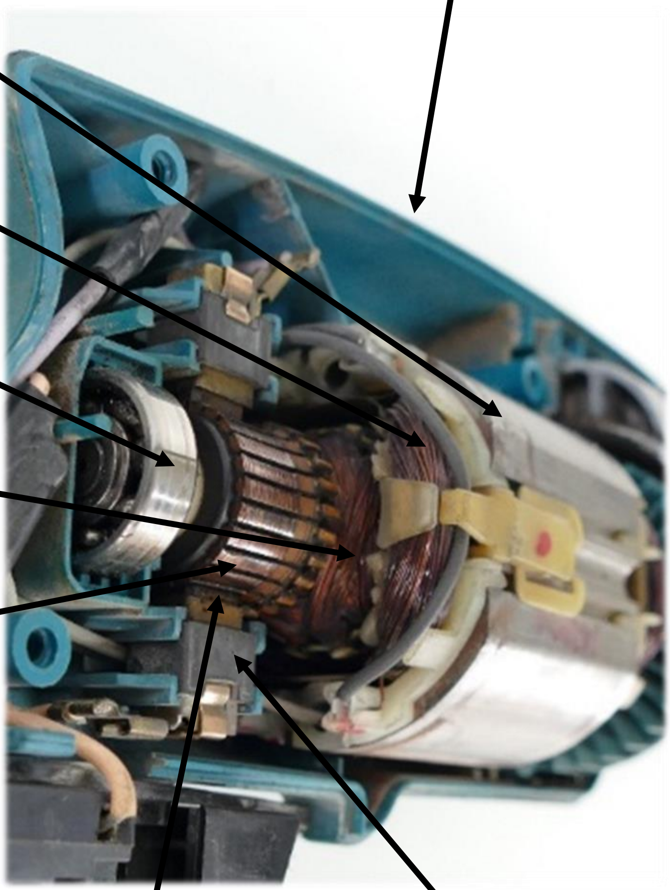
Typical use	Reason for suitability
Drills	Easy to change direction and control speed
Skill saws	Geared for constant no load speed and good torque
Electric weed whackers (line trimmers)	Small, lightweight and powerful
Angle grinders	High speed and suitable to fit into the small hand-held body of a grinder
Food mixers	Easily speed controlled, high starting torque
Vacuum cleaners	High speed and powerful
Printers and photocopy machines	Small, compact, low cost and reliable

You can easily spot a universal motor in the wild as they are usually the ones that have a wound rotor with carbon brushes and a commutator.

Construction of a universal motor



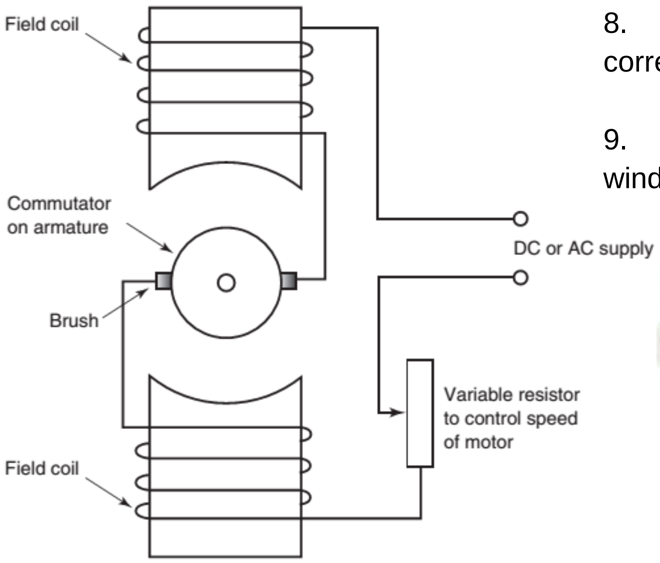
1. Universal motors are also commonly used for power tools and appliances. Often, as shown here, the body of the appliance is the **casing** of the motor.
2. The **laminated yoke** is secured inside the casing.
3. The **stator field windings** are wound into the slots in the yoke.
4. The **rotor** is held inside the stator by **bearings** at each end which allow the rotor to rotate.
5. The **rotor winding** is wound onto the laminated core on the rotor shaft. The slots in the rotor laminations may be slanted slightly to reduce AC buzzing and to help to give the motor uniform starting characteristics.
6. There is a **commutator** to provide a rotating connection to the rotor windings. Each of the insulated copper windings are wound through the laminated core and then the ends are terminated on to two commutated segments 180º apart.



7. **Brushes** are mounted in **brush holders** in a way that the brush springs push the brushes onto the commutator.

8. The brush holders hold the brushes onto the correct place on the commutator.

9. The two stator field windings and the rotor winding are wired in series.

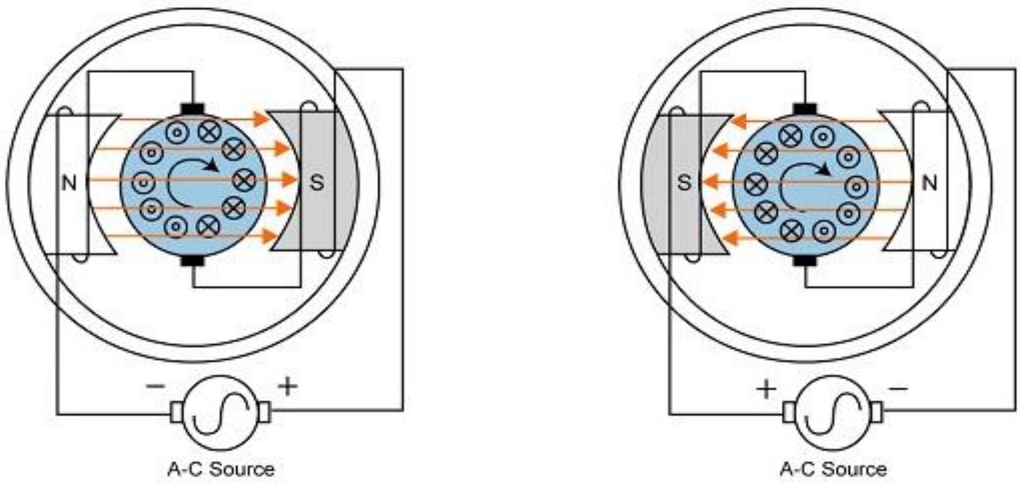


Principles of operation of a universal motor

1. When a universal motor is connected to a power supply, the current flowing in the motor's two stator field windings produces a north to south magnetic field across the centre of the motor from one side to the other.

2. As the rotor is wired in series with the stator field windings, the same current also flows in the rotor winding and a magnetic field forms around the rotor winding as well.

3. The current flowing in the motor results in two magnetic fields in the same place which cause both magnetic repulsion and attraction between the stator and the rotor. As the stator is fixed in place and the rotor free to turn, this magnetic interaction causes the rotor to rotate strongly on its bearings. Torque (turning force) is produced and the rotor can be connected to a load via the shaft.



First Half Period Second Half Period

4. As the rotor moves around to where it might otherwise stop and stay, the brushes swap connections on the commutator to another circuit in the rotor winding. This puts the motor back in the same magnetic position as it was before the rotor rotated and the whole process starts again.

5. As the rotor rotates, its connection via the commutator keeps swapping causing the rotor to keep turning as long as the supply current flows.

6. Because the stator windings and the rotor winding are all supplied by the same current, when the direction of current swaps each half cycle of the AC supply, the current in all three windings swaps. This causes the polarity of *both* magnetic fields to swap. As a result, the direction the rotor is forced to go stays the same. This allows a universal motor to be used successfully on AC and will also work on DC too. That is why it is called a universal motor.

   Note: A Universal motor will run faster on DC than AC of the same voltage. This is because with DC there is no reactance in the windings (X_L) to help limit the current as there is when run on AC.

While the principles of motor operation are the same, a universal motor designed to run on DC (like a car starter motor) will not work well on AC. There are different design needs, such as laminated cores for AC.

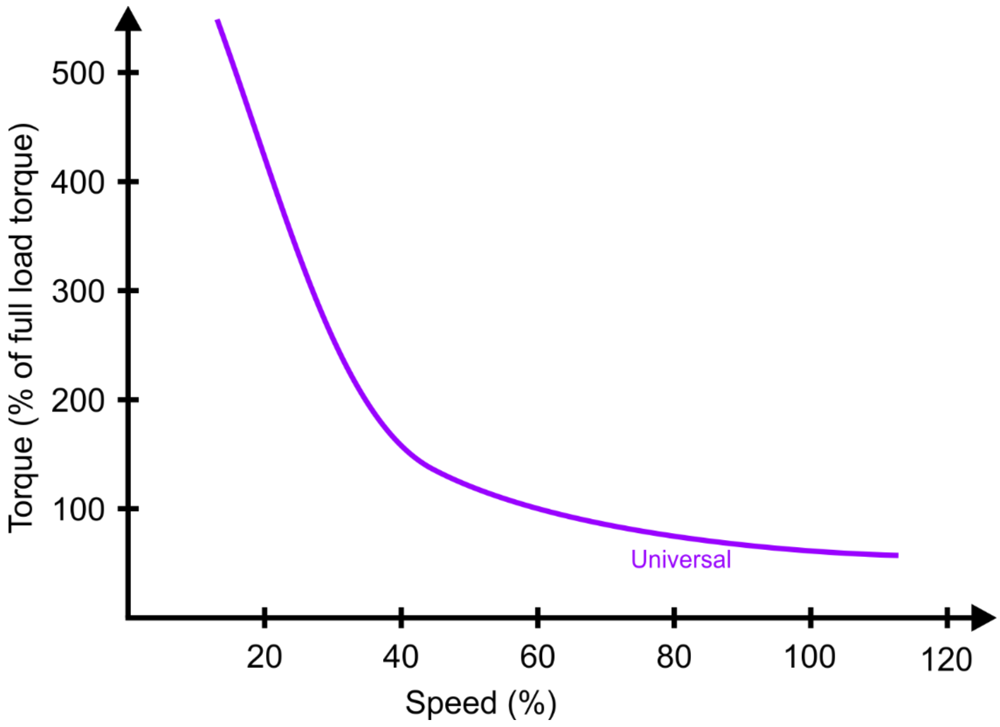
Summary of the operating principles of a universal motor:

1. Current flowing in the stator field windings produces the stator magnetic field.
2. The current also flows in the series rotor winding forming the rotor magnetic field.
3. The two magnetic fields interact causing the rotor to turn.
4. The commutator keeps the current in the rotor correct to keep the rotor turning.
5. When the AC power supply swaps polarity, the magnetism in both the stator and rotor swaps and the direction of rotation continues in the same direction.

Torque/speed characteristic curve for a universal motor

Some points about universal motors that can be seen from this graph are:

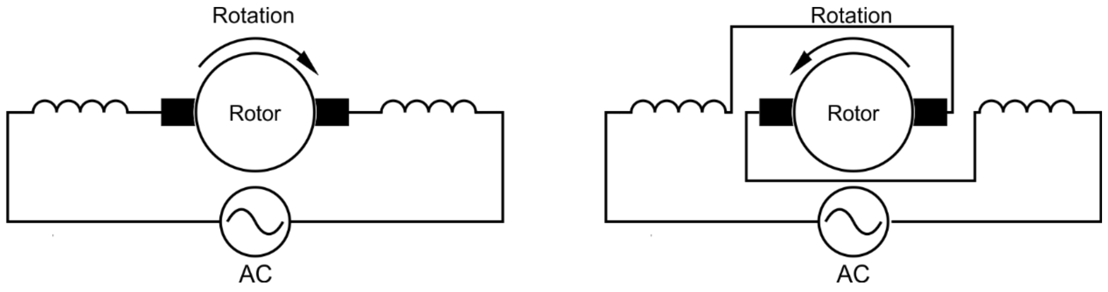
- The torque developed by the motor at low speed is very high.
- The speed can reach a very high value when the motor is operated without a load.
- The motor speed depends on the amount of load on the motor.



Reversing a universal motor

To reverse the direction of rotation of a universal motor you will need to reverse the polarity of one of the two magnetic fields, either the main stator magnetic field or the rotor magnetic field. This will cause rotation in the other direction.

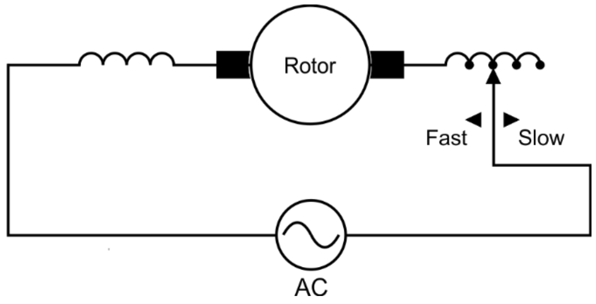
Reverse the connections to either the rotor circuit or the field circuit but not both.



Tapped-field universal motor

Winding connections

Tapped field universal motors are manufactured to have multiple connections (taps) to the field windings as shown in the diagram below.



Starting

Tapped field universal motors start rotating by magnetic interaction between the field windings and the rotor (just the same as a standard universal motor).

Speed change method

The speed of the motor is changed by swapping the connection between taps, this is usually achieved by using a multi select switch.

Principles of operation

Stepped speed control is achieved by changing the number of field turns connected to the power supply and therefore the number of turns creating the magnetic field.

The more turns connected, the slower the speed of the motor, and the less turns, the faster the motor will go. This is because less turns produces less back EMF induced into the winding and less back EMF equates to more motor speed.

Typical applications

Some typical applications for tapped field universal motors are:

Typical applications	Reason for suitability
Cake mixers	High starting torque and easily multi-speed controlled using multiple taps and a switch.
Blenders	High speed, powerful and able to conveniently provide a range of switched speeds.
Power drills	Small, low cost and easily made to have high/low speeds with small switch.

Speed control for universal motors

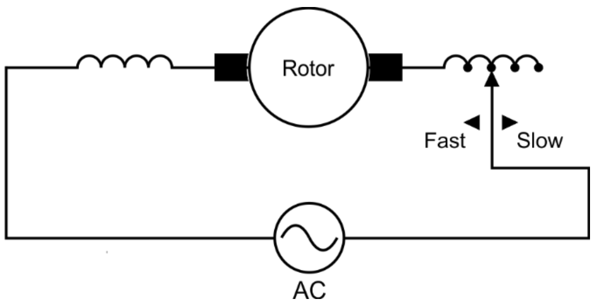
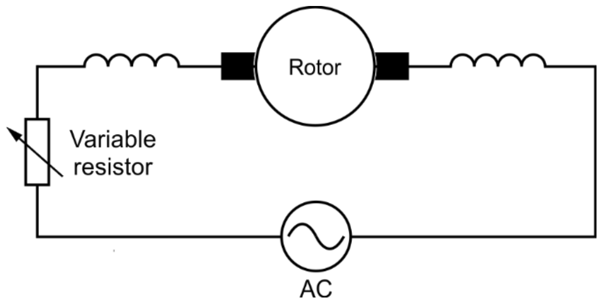
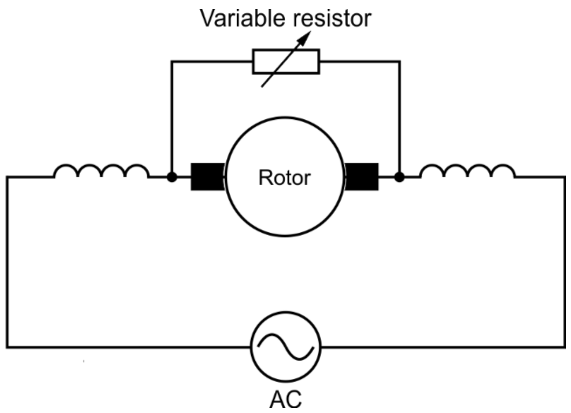
One of the main advantages of the universal motor is that its speed can be easily and simply controlled by a number of different methods.

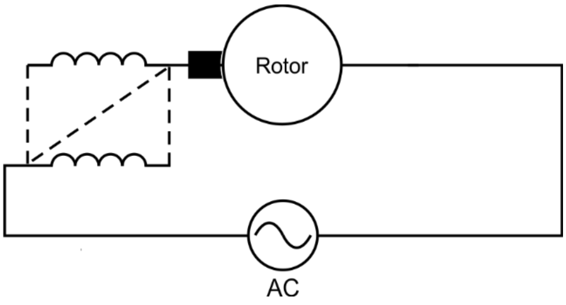
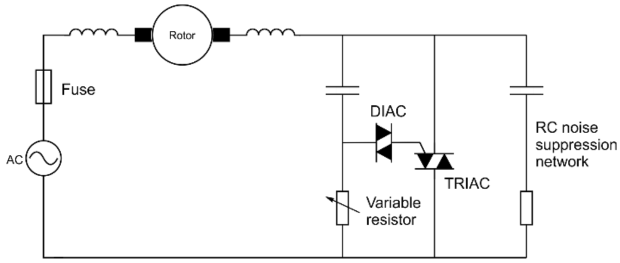
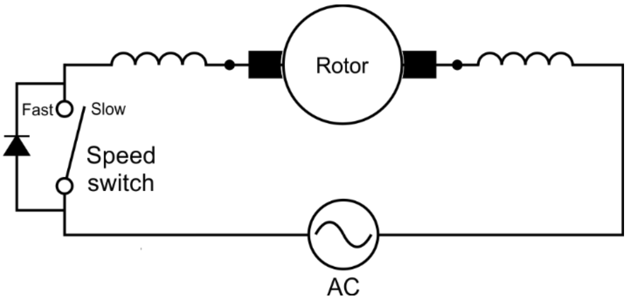
The normal speed range for universal motors is from 3000 to 20000 rpm, and even faster for some applications like routers for example, which may go faster even up to 35000 rpm.

To achieve the best general output characteristics of a universal motor, ideally it should run at at least 6000 rpm.

The speed of a universal motor is inversely proportional to the field strength, so by varying the field strength you can vary the speed of the motor.

Speed Control Methods

1 Tapped field winding		Used in food mixers and two-speed drills. In two-speed drills, only one field tap is necessary.
2. Variable series resistance		Continuously rated variable series resistance. Mainly used for pedal controls on sewing machines.
3. Armature diverter		Continuously rated variable resistance in parallel with the armature. Better starting control and smoother torque than the series resistance method.

4.	Series/parallel winding		Switching the field coils in series or in parallel with the aid of an external switch. Some brands of food mixer employ this method of speed control.
5.	Electronic method		Variable AC supply - controlled by a Triac. Often used in variable speed drills etc.
6.	Rectifier method		Connecting a diode in series with the motor so that it operates from a half wave rectified DC supply. A switch may be connected across the diode, which, when closed, by-passes the diode providing full AC mains voltage to the motor terminals. Often use in variable speed hair dryers.

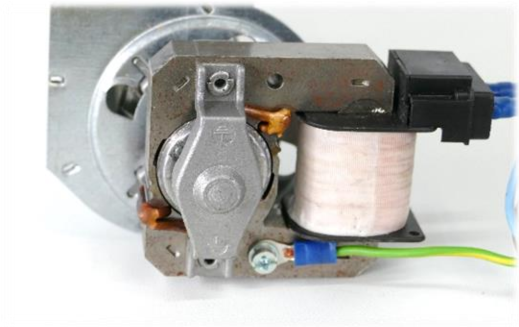
The Shaded Pole Motor

The shaded pole motor is a very simple and inexpensive little motor. More than likely, you have at least one of these at home or at the work office.

They are very simple to construct and therefore the least expensive single-phase motors available.

Shaded pole motors have a very clever design that is so simple but so effective it is one of those things you think - wow who came up with that idea?

A shaded-pole motor is a small induction motor with a squirrel-cage rotor.



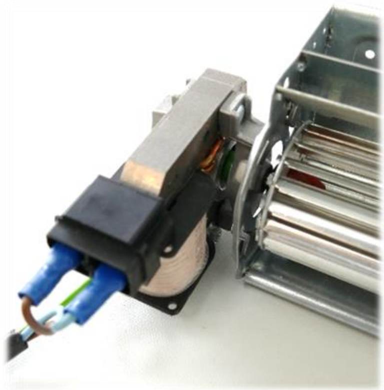
To prevent having to connect an electrical supply to the rotor, an induction motor uses transformer type action to induce current into the rotor.

This is a very clever idea to energise the rotor with current to make it an electromagnet without having any physical connection to it, wow that’s cool!

To induce current into the rotor, an induction motor needs to have a magnetic field that “moves”.

When moving magnetic lines of force cut across the bars of the squirrel cage rotor, current is induced into them and the resulting circulating current in the rotor causes a magnetic field around the rotor.

In a motor, obviously the goal is to get the rotor to spin. So, the magnetic field produced by the stator needs to move in a circular or rotating fashion. This achieves both the magnetism moving across the rotor to induce current into it and provides a force to cause the rotor to rotate.



How that rotating magnetic field is produced in a shaded pole motor is astonishing! All it takes is one or two rings of heavy wire! Shortly, we will explain how it works.

Shaded pole motors are used because they are:

1. Compact.
2. Quiet.
3. Cheap to make.
4. Require little to no maintenance.
5. Very reliable.
6. Speed controlled easily by altering the motor voltage.
7. Don't draw excessive current when stalled.

Typical applications for shaded pole motors

Typical use	Reason for suitability
Blowers for heaters and dehumidifiers	Cheap and reliable
Extractor fans and exhaust fans	Small and lightweight
Hair dryers	No maintenance and cheap to manufacture
Washing machine and dishwasher water pump motors	Cheap and reliable, low stall current
Electric timer motors	Compact and cool running
Record players	Gentle starting, constant speed
Refrigeration circulation fans	Compact, low cost and reliable
Servo motors and damper controllers	No maintenance, long life

Some disadvantages:

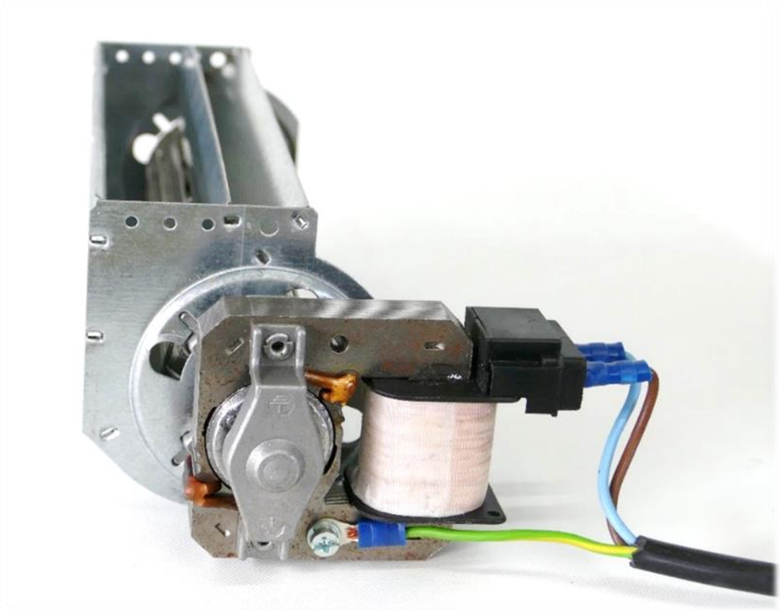
- Shaded pole motors have low starting torque.
- The speed varies as the motor load increases.
- The direction of rotation cannot be reversed easily (electrically).
- The efficiency of the motor is very low.

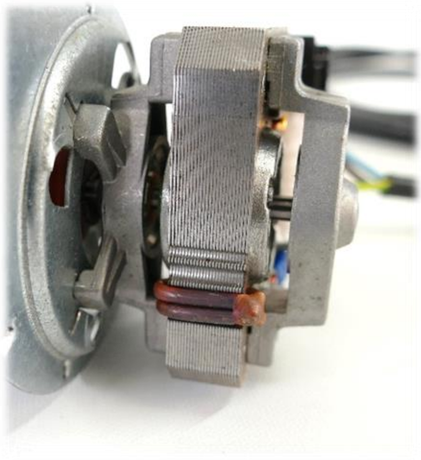
Construction of a shaded pole motor

1. Shaded pole motors have a laminated silicon steel yoke that forms the body of the motor. The stator field coil, motor shaft bearings and shading rings are mounted onto the yoke.

2. The stator field coil wraps around one leg of the yoke - off to the side of the hole for the rotor.

3. Shading rings made of heavy gauge copper are installed into slots surrounding a portion of the magnetic pole faces of the yoke.





4. The squirrel cage rotor is installed into the yoke and held in place by bearings.

Principles of Operation of a shaded pole motor

1. When AC current flows through the field winding, a rising and collapsing magnetic field is produced.

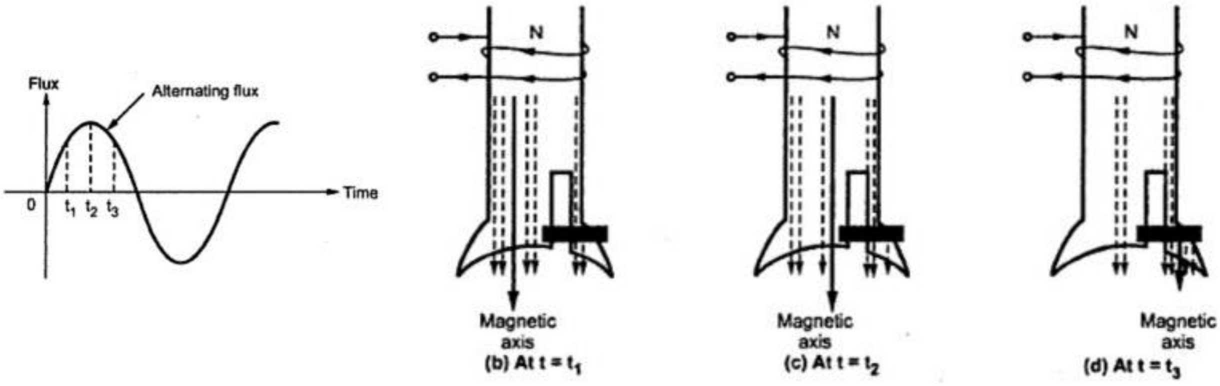
2. This magnetic field is concentrated by, and circulates in, the laminated steel yoke and forms an alternating north-south magnetic field across the hole in the yoke where the rotor is mounted.

3. The changing magnetic field cuts across the shading rings and induces current into them.

4. Because of the shading rings, the magnetism across the pole face has two parts to it. The main magnetism in the main pole face and the magnetism in the shaded pole portion with its magnetism altered by the shading rings.

5. The current induced into the shading rings causes a magnetic field around the shading rings themselves. This has the effect of changing the strength of the magnetism in the shaded part of the pole face.

6. As the main magnetism is increasing with the AC supply, the shading ring retards the rise of the magnetism in the shaded part of the pole face, resulting in a strong magnetism in the main pole face and a weaker magnetism in the shaded portion.



7. As the AC supply peaks, magnetism across the pole face stops changing briefly. As a result, the shading ring is not induced with current and has no effect on the pole magnetism, resulting in a uniform magnetism across the pole face.

8. As the magnetism of the main pole face drops away again (after the peak), the shading ring has the effect of boosting the magnetism in its part of the pole face, resulting in a stronger magnetism in the shaded pole and weaker magnetism in the main pole face.

9. The timing of the two magnetic fields effectively causes a rotating magnetism that moves across the magnetic pole face as the supply current cycles.

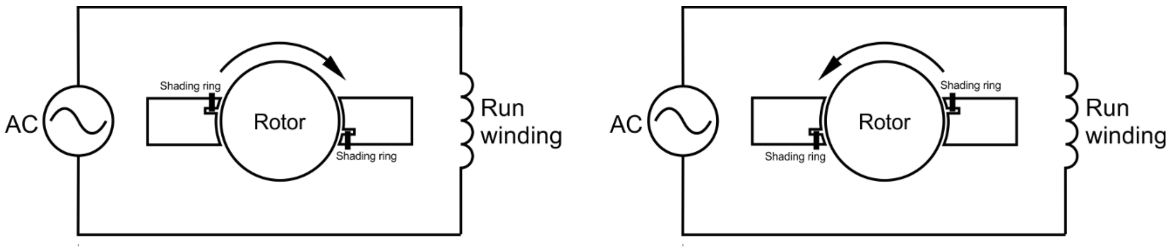
10. The cycling (rotating) magnetic field cuts across the rotor causing current to be induced into the rotor, which then becomes an electromagnet.

11. As long as the motor is supplied AC current the magnetism of the rotor and the rotating magnetic field interact to cause the rotor to turn and produce torque to drive a load.

Reversing a shaded pole motor

The direction of rotation of a shaded pole motor has to be reversed by altering the direction of the rotating magnetic field across the pole face.

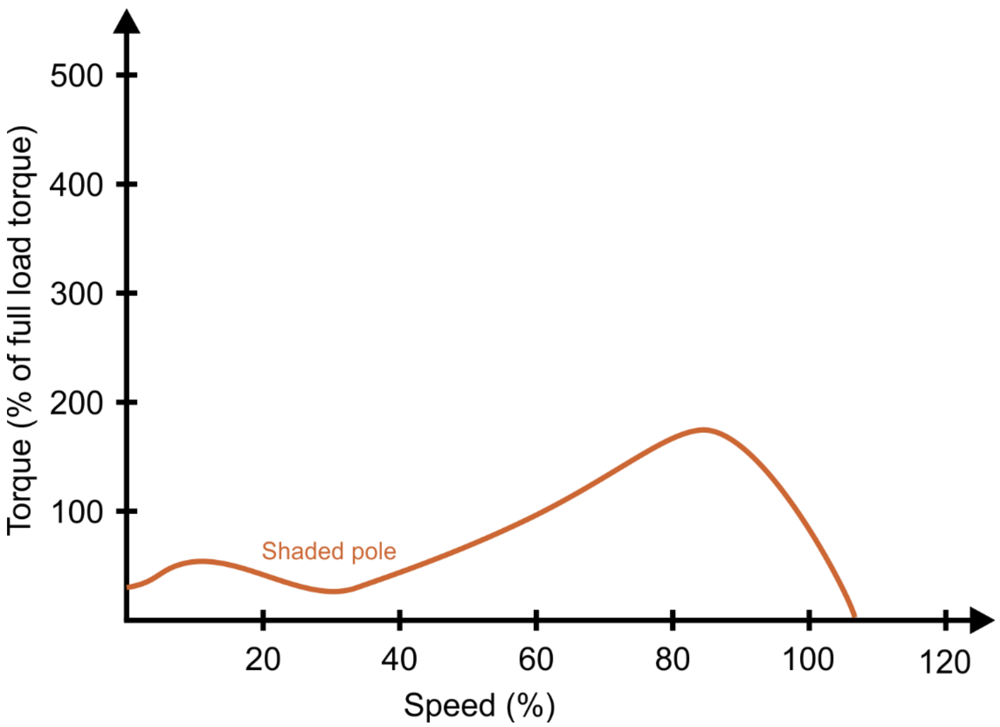
This is done by shifting the shading ring to the other side of the pole face where poles are fitted with slots on both sides for this purpose.



With other motors the only method is to physically swap the stator and rotor with reference to each other. This may not be possible in some shaded pole motors.

Another option is that some shaded pole motors come with two sets of shading rings, swappable by the use of a switch.

Torque/Speed characteristic curve for a shaded pole motor



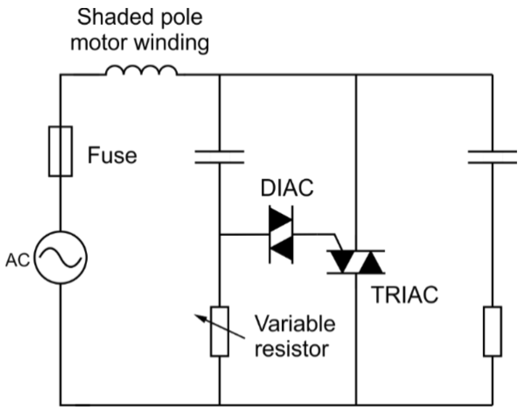
Speed control of a shaded pole motor

Resistances

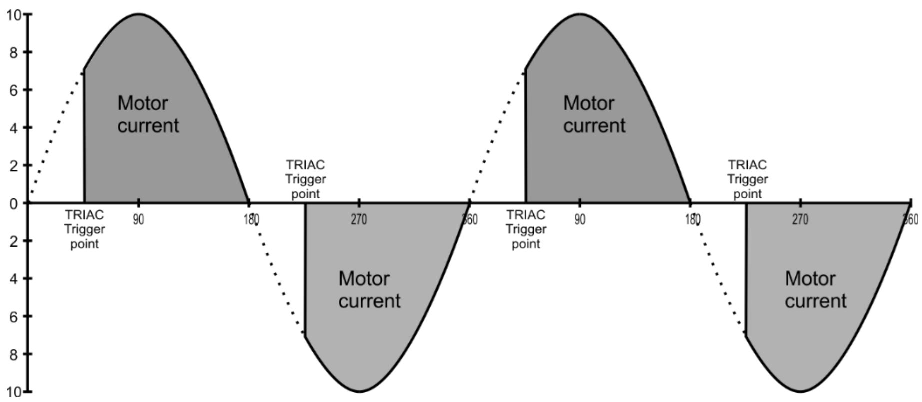
Resistances are used to reduce the motor supply voltage / current. The main disadvantage is the loss of energy in the resistance (as heat) which reduces the overall efficiency of the motor.

TRIAC speed control.

A Triac is a three terminal semiconductor device that is great for simple motor speed control, the speed of a motor can be controlled by controlling the Triac gate voltage.



A triac motor control circuit "chops" off the fronts of the AC sine wave. By adjusting the variable resistor, the amount of the sine wave chopped off is varied. The circuit controls the speed of the motor by varying the total amount of current allowed to flow to the motor.



Gears

Gears are also a method of motor output speed control. A gear assembly is coupled to the output of the motor. Shaded pole motors complete with gear boxes are available for various applications.

Split Phase Motors

Single phase - split phase motors are mass-produced and are found in many domestic, commercial, and industrial machines requiring a single-phase drive.

Split phase motors sound a bit scary at first but really, they are not.

Split phase motors "split" the single-phase supply into two sets of windings to create a rotating magnetic field. They cleverly produce two currents/magnetic fields with different (phase) timing.

Shaded pole motors are good examples of small split phase motors. Shaded pole motors use shading rings to "split the phase".

There are four other common split phase motors we will look at in this resource.

The split phase induction motor family:

1. Standard.

2. Capacitor start.

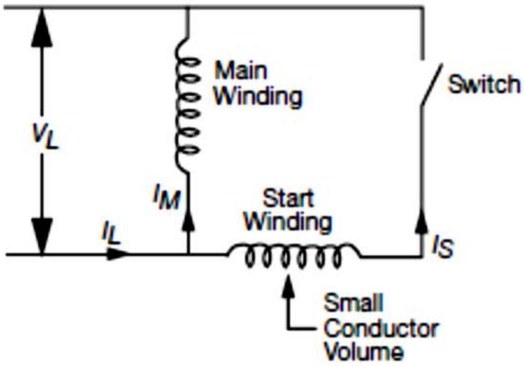
3. Permanently split capacitor.

4. Capacitor start / capacitor run.

The basic entry level motor is the standard - split phase motor. Once you understand this first motor then the rest are just variations, each one with design changes/enhancements to get more power out of them.

The Standard Split Phase Motor

To produce a rotating magnetic field from a single-phase AC supply a standard split phase motor has two sets of stator field windings. The primary run windings and a secondary set of windings called the start windings.



Typical applications for standard - split phase motors

Standard - split phase motors are at the bottom level of power.

As the starting torque is low the motor is limited to applications where the motor is started unloaded or lightly loaded such as:

- Washing machines.
- Dryers.
- Bench grinders.
- Fans and blowers.
- Light duty woodworking machinery.
- Rotary pumps.

Standard split phase motors are popular for low starting torque applications because they are cheaper than the other split phase motors.

Construction

1. The motor casing has the laminated silicon steel yoke installed inside it.

2. The Start and run windings are installed into the laminated yoke at 45°-90° apart.

3. The two sets of windings are made to have different values of resistance and inductance.

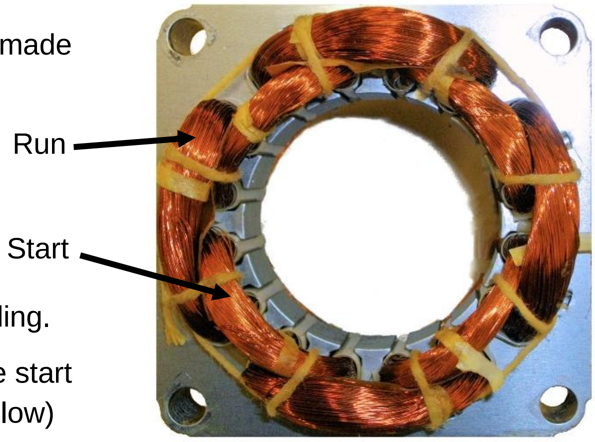
4. A squirrel cage rotor is held inside the stator by the bearings and the bearings are held in place by the end shields of the motor.

5. There is a centrifugal switch on the rotor shaft that disconnects the start winding at 75% full load speed.

6. A fan may be installed on the shaft to cool the motor.

7. The shaft of the rotor sticks out the end so that it can be connected to a load.

Principles of operation of a standard - split phase motor

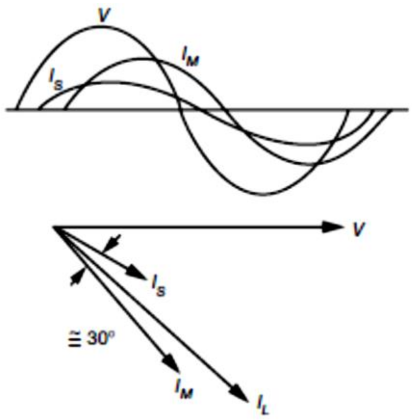


The start winding of a standard split phase motor is made from smaller gauge wire with fewer turns than the run winding.

The run windings are installed deeper into the yoke than the start windings.

This causes the start winding to have a higher resistance and a lower inductance than the run winding.

Due to its lower inductance the current flowing in the start winding peaks 30° earlier (electrically - as shown below) than the run winding.



Phasor diagram for the standard split-phase motor

As the magnetism of a winding is directly proportional to the current flow, the fact that the start winding current peaks 30° before the run winding current means that the magnetism in the start winding peaks before (0.0017 seconds) the run winding.

And there you have it, split phases! Just by making the two windings physically different.

As the magnetism peaks in the start winding and then peaks shortly after in the run winding, the main magnetic attraction moves from the start to run winding.

This repeats each AC supply cycle and causes a continuous (repeating) rotating magnetic field.

The moving magnetic field mutually induces current into the rotor and that induced current causes the rotor to become magnetised.

The interaction of the stator magnetic flux and the induced rotor magnetic flux causes the rotor to turn in the direction in which the stator magnetic flux is rotating.

As the rotor accelerates, when it gets to about 75% of full speed, the start winding is disconnected by the centrifugal switch and the motor continues to rotate using the run winding only.

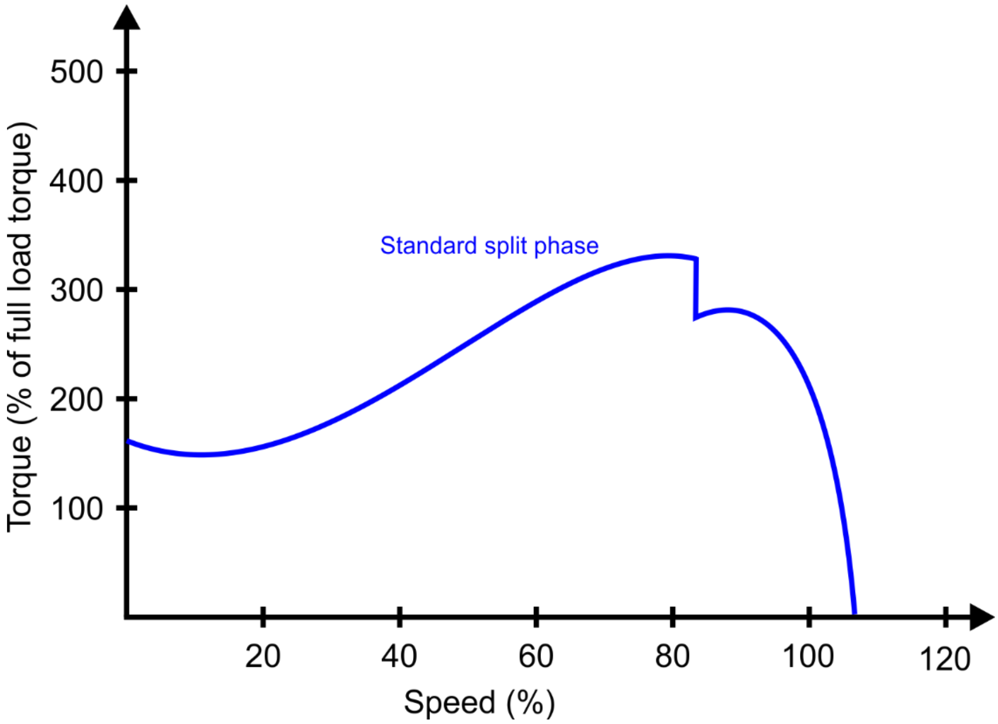
In summary:

1. Current peaking at different times in the start and run windings create a rotating magnetic field.
2. The rotating magnetism causes induced current in the rotor.
3. The rotor becomes magnetised.
4. The magnetism of the stator and rotor interact to cause the rotor to spin.
5. At 75% full speed, the centrifugal switch disconnects the Start winding.
6. The motor continues to run with the torque developed by the run winding only.

Torque/speed characteristic curve for a standard - split phase motor

Standard – split phase motors are the simplest split phase motor and so they are the cheapest to manufacture. The trade-off is, they are not as powerful as the others.

Standard - split phase motors have starting torque around 100% to 175% of rated load and the motors draw high starting currents of approximately 700 to 1,000% of their rated current.



Because of the high starting current, if a motor takes a bit long to start, the start winding will quickly burn out. If the load needs plenty of grunt to get it going, then you may need to choose one of the upgraded split phase motors like the capacitor start motor.

Standard split phase motors have a maximum running torque range of 250 to 350% of normal torque.

Torque/Speed Characteristic Curve

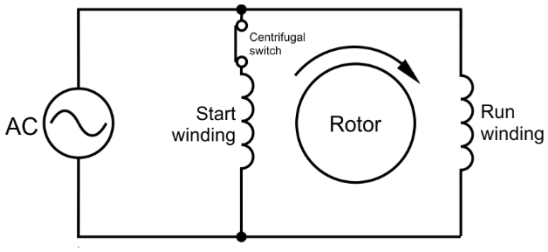
As shown on the graph:

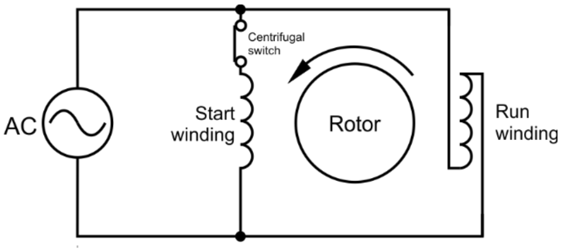
- The starting torque is relatively low.
- The speed is practically constant throughout torque range.
- Maximum torque is created at about 80% full speed.
- Zero torque is created if the rotor is at synchronous speed.

Reversing the rotation of a standard - split phase motor

To reverse the direction of a standard split phase motor, reverse the direction of current flow through one winding only. This can be done by exchanging the two end connections of either the start or the run winding, but not both.

Traditionally, if it becomes necessary to change the motor direction, the start winding is the one that tends to get reversed although either would work.





The Capacitor Start - Split Phase Motor

The first upgrade version of the split phase induction motor is the capacitor start split phase induction motor.

By simply adding a capacitor to the start winding, the starting torque is increased and here’s why.

As we said in the explanation about standard - split phase motors, the angle (time difference) between the peaks of magnetism in a standard split phase motor are about 30° on the sine wave graph.

Because the peaks in the two windings have only a small timing difference, while one of the windings is at its peak, the other winding still has quite a bit of magnetism.

This has the effect of attracting the rotor back while the field with the peak magnetism is trying to rotate it.

If we can somehow reduce the magnetism in the non-peaking winding when the peaking winding is providing the most magnetic power, we reduce the “hold back magnetism” of the rotor and the motor will have more power.

Adding a capacitor to the start winding does just that. It very simply increases the time between the peaks of the two windings to almost 90° electrically.

That means that, at start up, when the two windings are working together to get the motor started, a capacitor start - split phase motor with a capacitor on the start winding has more starting torque than a standard split phase motor.

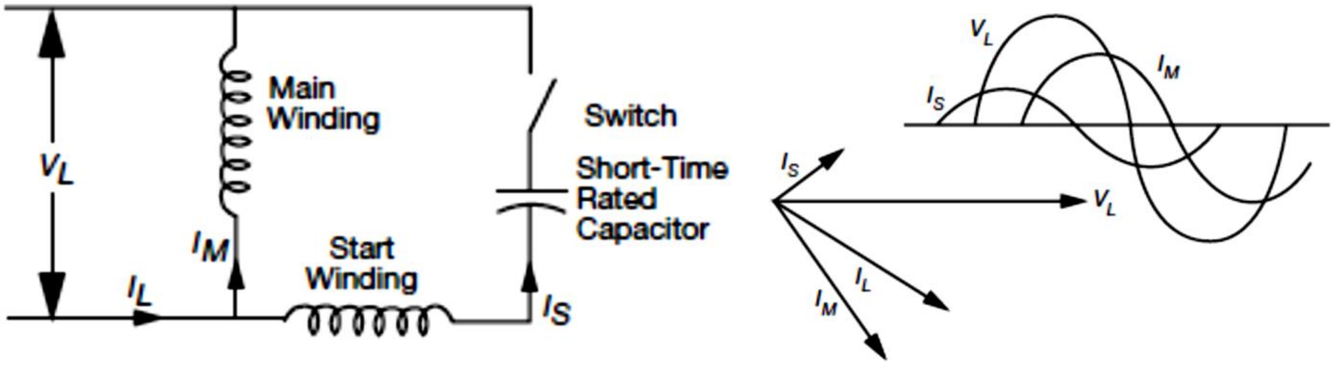
The other advantage is that now that the two current waveforms are separated by nearly 90°, the start and run windings are not using so much current at the same time.

This means that the combined starting current of the motor is lower. This results in a reduction in the start-up inrush current compared to the standard split-phase motor.

Once up to 75% full speed, the centrifugal switch disconnects the start winding and capacitor and the capacitor start - split phase motor has the same run torque as a standard split phase motor.

Can you see how simply adding a start capacitor increases the starting torque of a split phase motor? Simple aye!

Circuit Diagram



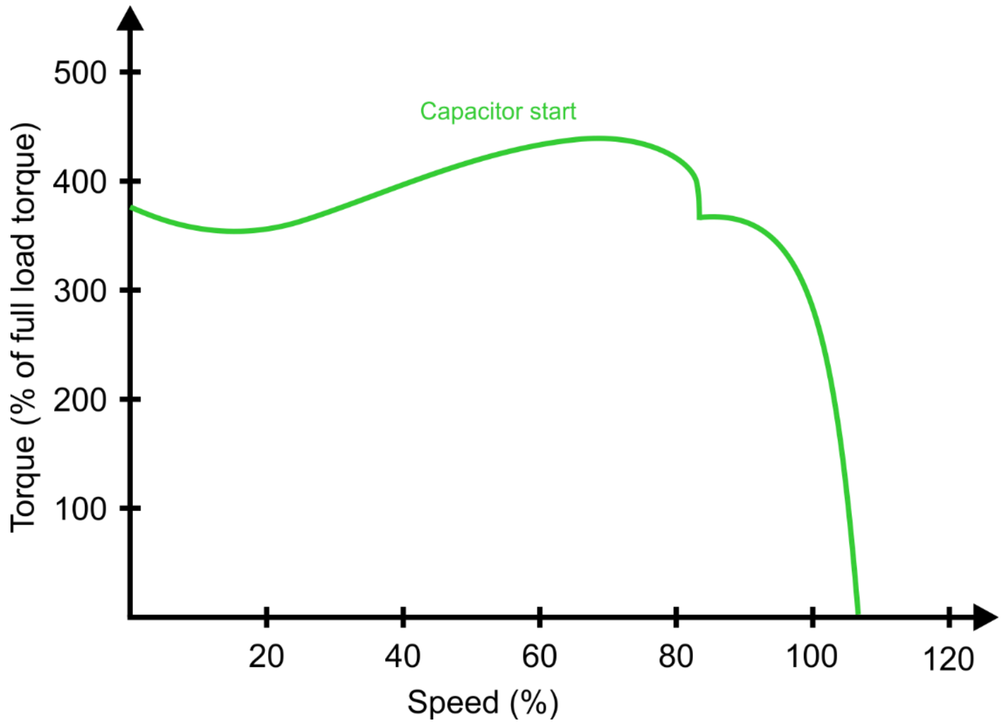
Typical applications for capacitor start - split phase motors

As the starting torque developed by the capacitor start - split-phase motor is higher than the standard - split phase motor, it can be used in applications where the motor is started under higher load conditions.

Some typical applications include:

- Large blowers.
- Small conveyors.
- Concrete mixers.
- Reciprocating pumps.
- Vacuum pumps.

Torque/Speed Characteristic Curve



Reversing Rotation

Reversing a capacitor start - split phase motor is just the same as the standard - split phase motor. Change the direction of current flow through either the start or run winding but not both. Usually you would do that by swapping the two end connections of any one winding.

Traditionally it is the start winding that is reversed but in this case, it may be simpler to change the run winding. It will depend on how the manufacturer has set up the wiring to the windings.

Permanently split capacitor motor

Has it occurred to you that it is strange to turn off the start winding at 75% full running speed?

Surely having both windings staying working while the motor is running would give more power? You would be right.

The next stage in the development of a split phase motor is the Permanently split capacitor motor.

The standard - split phase motor and the capacitor start - split phase motor both disconnect their start windings after starting.

The permanently split capacitor motor has two windings that both stay connected while the motor is running. This increases the motor run torque because two windings are now creating magnetism to turn the rotor. While there is an increase in torque, this plan does cause some design challenges.

Design challenges of the permanently split capacitor motor:

1. What to call the windings as they are no longer start and run windings.
    a. **Solution**: They are called main and auxiliary windings.

2. In a standard - split phase motor, to create the split phase it is easy and convenient to make the start winding with less turns of thin wire. It helps to create an inductance difference. Because the start winding is only powered for a very short time at start up, it doesn't have time to get too hot and burn out. If kept energised, like in a permanently split capacitor motor, it would heat up and burn out very quickly.

    a. **Solution**: The auxiliary winding is made in the same heavy wire and the same number of turns as the main winding so that it won't burn out when permanently connected.

3. Winding the auxiliary winding the same as the main winding means there is no inductance difference between the two and as a result no split phase.

    a. **Solution**: Add a (continuously rated) capacitor to the auxiliary winding to create a phase difference between the windings. This results in the split phase needed to create the required rotating magnetic field.

The trade-off of the permanently split capacitor motor is, the capacitor only manages a small phase angle displacement between the two windings and so the starting torque is low.

The advantage is that the run torque is high.

Typical applications for a permanently split capacitor motor

Permanently split capacitor motors are ideal for applications that don't need a lot of torque to get started but need more running torque than either the standard or capacitor start - split phase motors provide.

Some typical applications include:

- HVAC blowers and fans.
- Water pumps.
- Refrigeration pumps.
- Office equipment (because of quiet running).

Reversing the rotation of a permanently split capacitor motor

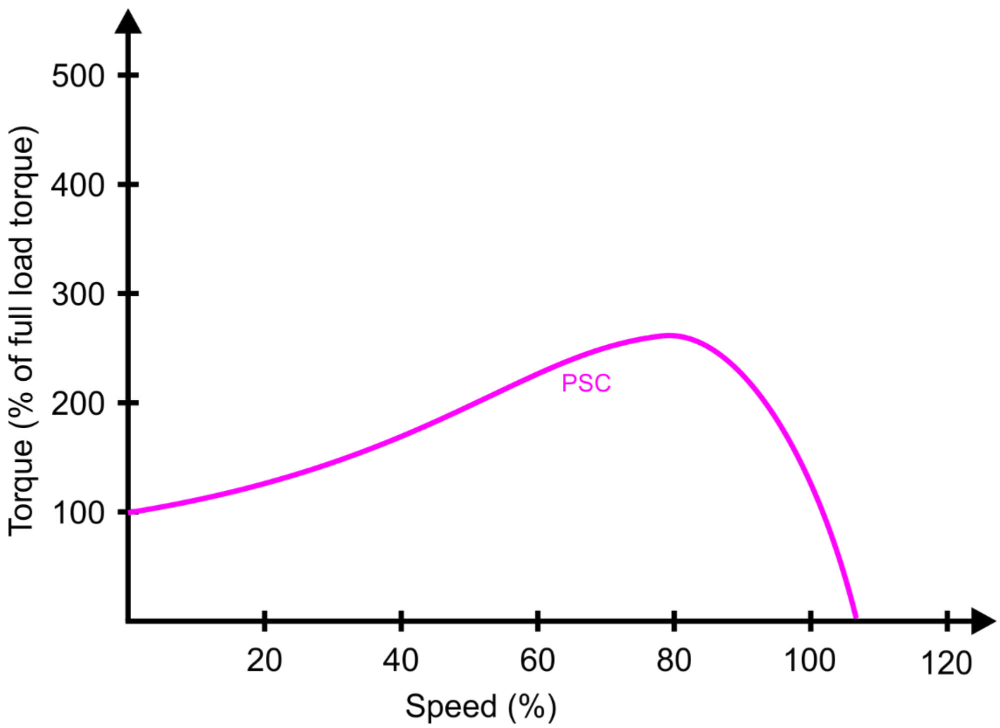
Reversing a permanently split capacitor motor is just the same as the standard - split phase motor, change the direction of current flow through either the main or auxiliary winding but not both.

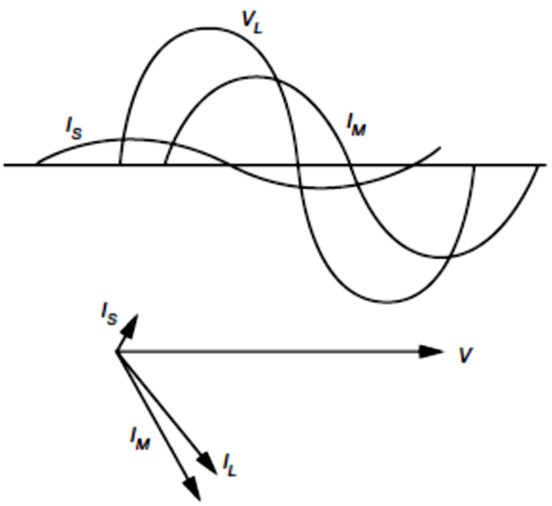
Usually you would do that by swapping the two end connections of any one winding.

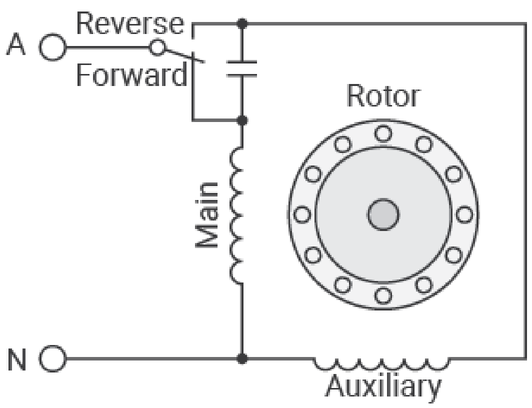
Traditionally it is the auxiliary winding that is reversed but it may be simpler to change the main winding as it does not have a capacitor.

It will depend on how the manufacturer has set up the wiring to the windings.

Torque/Speed characteristic curve for a permanently split capacitor motor







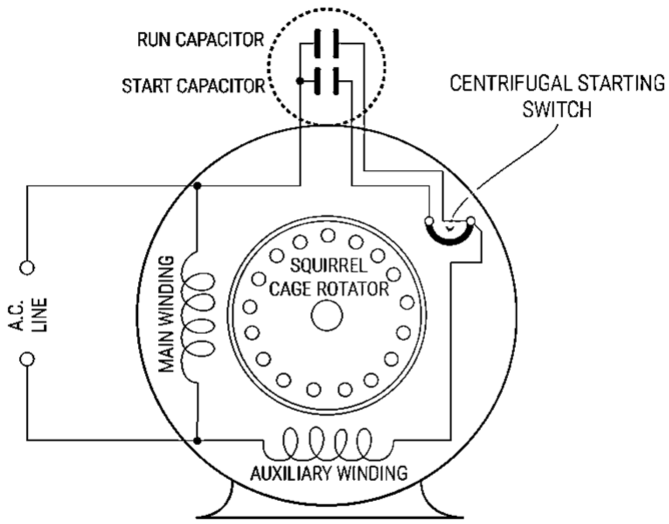
Capacitor Start / Capacitor Run - Split Phase Motor

So far, bit by bit we have been improving on the standard - split phase motor.

There is one more easy modification we can do to the split phase motor to make it even more awesome. We can combine all the previous versions of the split phase motor.

If we take the permanently split capacitor motor and add an extra start capacitor and centrifugal switch, we can have the higher running torque of the two permanently connected windings and the extra grunt a start capacitor gives on start up.

Adding the start capacitor gives the capacitor start / capacitor run motor the best of all the split phase motor worlds.



SPLIT PHASE CAPACITOR RUN ELECTRIC MOTOR

During starting, while the second capacitor is connected in series with the auxiliary winding, it increases the phase displacement between the winding currents for maximum starting torque.

When the rotor speed reaches about 75% of the rated speed, the centrifugal switch disconnects the extra starting capacitor from the circuit and the motor carries on running with the higher run torque of its main and auxiliary windings.

So, the capacitor start / capacitor run - split phase motor has the extra start power of the capacitor start - split phase motor and the extra run torque of the permanently split motor all built into one.

Just a point of interest, the start capacitor can be rated for intermittent duty as it is only connected briefly while the motor starts, while the auxiliary winding run capacitor must be rated for continuous service as it is always connected.

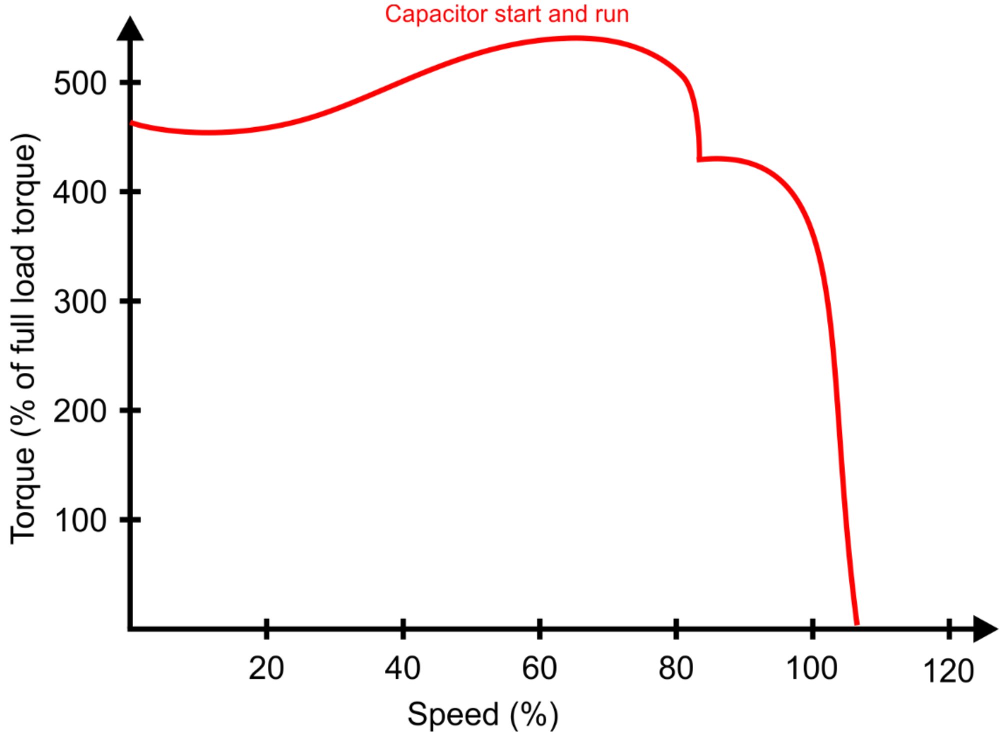
Applications for a capacitor start / capacitor run - split phase motor

The capacitor start / capacitor run - split phase motor will cope with heavy duty loads where a quite smooth-running motor is an advantage and it will also start loads that require high starting torque.

Some typical applications include:

- Air Compressors.
- Refrigeration compressors.
- Loaded conveyors.
- High pressure pumps.
- Floor polishers.

Torque/Speed Characteristic Curve



Reversing Rotation

Reversing a capacitor start / capacitor run - split phase motor is just the same as the standard motor, change the direction of current flow through either the auxiliary or main winding but not both.

Usually you would do that by swapping the two end connections of any one winding.

Methods of speed control for split phase motors

Traditionally, it is difficult to speed control single-phase split phase motors effectively. As variable frequency drive technology advances, some manufacturers are now producing VFD (variable frequency drive) speed controls for some types of single-phase split phase motors.

The speed the rotor spins is determined by the frequency of the supply to the motor.

Variable frequency drives (VFDs)

Variable frequency drives (VFDs) take the AC supply, convert it to DC and then use that DC to artificially produce an AC output of any frequency chosen to run the motor at the speed required.

The disadvantage of this type of control is a loss in motor torque and loss of motor cooling at lower speeds. Motors will need to be de-rated as a result and extra cooling may need to be provided.

Switching 4 - 2 poles

Switching poles comes with disadvantages. A 2 pole motor produces double the speed at the cost of a significantly reduced torque. The motor will also not run as smoothly on 2 poles compared with 4.

Multi speed split phase motor

Another speed control method for a split phase motor is to use a 4-pole motor set up to switch between running on 4 poles and 2 poles.

Different combinations of pole numbers are available such as, 4/2 pole, 8/4 pole, 8/2 pole and 6/4 pole.

Principles of operation

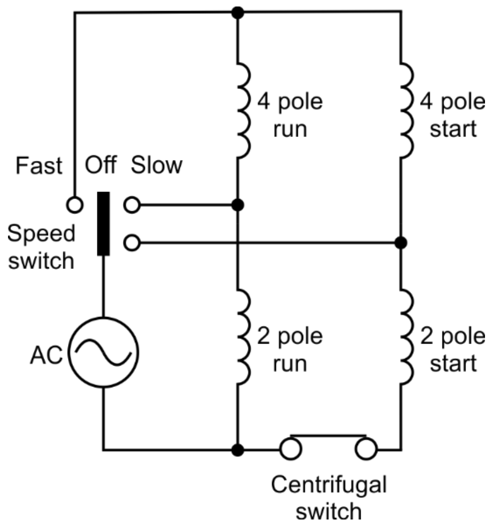
A motor with 2 poles (1 pair) rotates at double the speed of a 4 pole (2 pair) motor. The poles in a 2 pole motor cause a complete rotation of the rotor each AC sine wave, whereas, a 4 pole motor takes two sine waves to turn the rotor once.

The synchronous speed of a 4/2 pole motor is able to be changed by switching the motor between running on 4 poles (1500rpm) and 2 poles (3000rpm).

Switching poles comes with disadvantages. A motor running on 2 poles produces double the speed at the cost of a significantly reduced torque. Also, the motor will not run as smoothly on 2 poles compared with 4 poles.

Winding connections

A two speed 4/2 pole motor has the tails for both sets of pole windings available in its termination box. Those tails are connected to a pole change over switch.



Starting

A two-speed split phase motor starts rotating because of the interaction between the rotor magnetism and the stator pole magnetism. Care must be taken that a 4/2 pole motor isn’t overloaded when starting on two poles. The maximum load should be chosen to suit the starting torque produced on the 2 pole setting.

Speed change method

The speed of the motor is changed by either connecting 2 poles or 4 poles to the supply using a speed (pole) selector switch.

Typical applications

Some typical applications for multi speed split phase motors are:

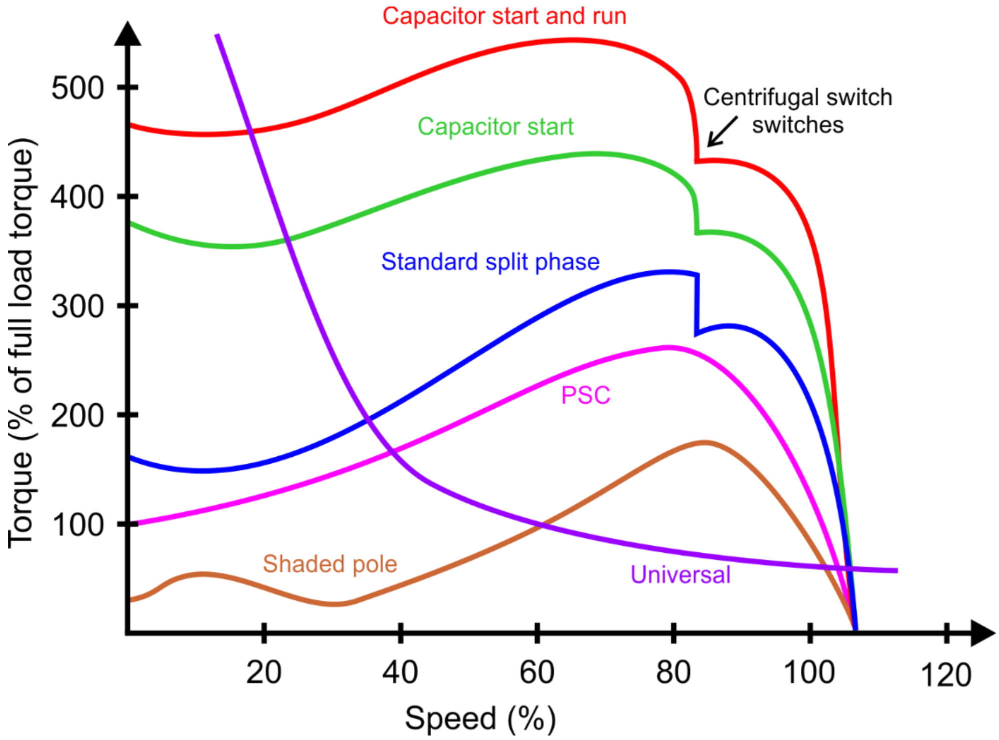
Typical application	Reason for suitability
Air conditioning fans	Simple, compact low-cost control switch for easy mounting for speed selection.
Pumps	No expensive speed drive to purchase or maintain.
Conveyor belts	One reliable motor with different fixed speeds.

Comparison of characteristics of single-phase motors

The following chart summarises the Performance and Features of Common Single-Phase Motors

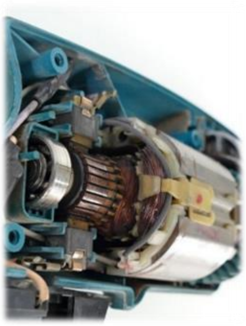
Motor Types - typical properties						
Properties	**Universal**	**Shaded pole**	**Standard - spit phase**	**Capacitor Start**	**Permanently split**	**Cap Start, Cap Run**
Supply	Single-Phase AC or DC	Single-Phase AC	Single-Phase AC	Single-Phase AC	Single-Phase AC	Single-Phase AC
Starting current times full-load	3 to 5	2	4 to 6	3 to 5	1.25 to 4	3 to 8
Power factor	-0.5 to 0.7	0.5 to 0.65	0.5 to 0.7	0.65 to 0.75	0.7 to 0.95	0.7 to 0.95
Efficiency	0.3 to 0.7	0.03 to 0.35	0.4 to 0.65	0.5 to 0.75	0.4 to 0.75	0.4 to 0.85
Speed range rev/min (sync)	3000 to 35000	1500 to 3000	1000 to 3000	1000 to 3000	750 to 3000	1000 to 3000
Method of staring	Magnetic interaction between wound armature and field poles	Magnetic movement across field pole faces	Phase angle between run and start windings (disconnected by centrifugal switch >70% FLS)	Phase angle between run and start windings with capacitor (disconnected by centrifugal switch >70% FLS)	Phase angle between main and aux windings with capacitor	Phase angle between main and aux windings with run capacitor and start capacitor (disconnected by centrifugal switch >70% FLS)
Reversing	Reverse field or armature connections	Normally non-reversible, swap side of shading rings	Reverse start or run windings connections	Reverse start or run windings connections	Transfer capacitor to other (identical winding)	Reverse start or run winding connections
Speed control	Tapped field. Series resistance. Armature diverter. Series/parallel winding. Electronic. Rectifier method. Gearing.	Resistance. Electronic. Gearing. VFD	2-4 Pole switching. Gearing.	2-4 Pole switching. Gearing.	2-4 Pole switching. VFD. Gearing.	2-4 Pole switching. Gearing.

Comparing Speed Torque Curves



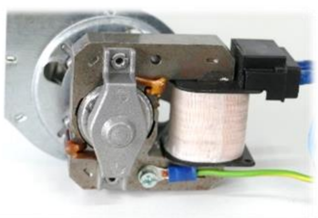
Torque-Speed Curves of Different Single-Phase Induction Motors

Summary of single-phase motors.



Universal motors: Have stator windings and a wound rotor wired in series. Magnetic interaction between the stator winding and the rotor winding creates starting torque.

Universal motors have a high power to weight ratio which makes them ideal for most portable tool applications, in particular ones that rotate at 3000rpm and above.



Shaded-pole motors: Have just one winding and a yoke with shading rings. This configuration causes a shift of the magnetic field across the yoke pole faces, creating starting torque.

Shaded pole motors have a low starting torque and are great for applications like blowers in heaters and ovens.

Split phase motors: Have two sets of windings positioned 45° - 90° to each other and split the magnetic field of the stator, inducing starting torque.

Standard - split phase motors are at the bottom level of start and run power out of the four main versions of the split phase motor. As the starting torque is low the motor is limited to applications where the motor is started unloaded or lightly loaded like washing machines and dryers.

Capacitor start - split-phase motors: The most common single-phase motor manufactured. They are a modified split-phase motor having a capacitor in series with the start winding to provide a starting torque boost.

As the starting torque developed by the capacitor start – split phase motor is higher than the standard - split phase induction motor, they can be used in applications where the motor is started under higher load conditions.

Permanently Split Capacitor (PSC) motors: Use identical main and auxiliary windings with a capacitor to provide starting and run torque. They are the most reliable single-phase motor because they don't have a centrifugal starting switch.

Permanently split capacitor motors are ideal for applications that don't need a lot of torque to get started but need more running torque than either the standard or capacitor start - split phase motors provide.

Capacitor-Start / Capacitor-Run (CSCR) motors: Use identical main and auxiliary windings with a capacitor to provide starting and run torque and a start capacitor to increase starting torque. They are the highest spec motors of the split phase range combining the best of all the split phase motors.

The capacitor-start / capacitor-run split phase motor will cope with heavy duty loads where a quite smooth-running motor is an advantage and can start loads that require high starting torque.

Three phase induction motors

Three-phase induction motors are one of the most commonly used electrical machines in industry because of their simple design and impressive load characteristics.

Combined with electronic motor- speed control it is now easy to change the starting torque and speed of three- phase motors. With their rugged construction and minimal moving parts, they have become the industry standard for a wide range of applications.

The reasons for their wide use is that they:

- Are reliable and easy to construct.
- Do not need physical electrical connections to the rotor
- Have good efficiency.
- Produce high power for their size.

Three-phase motors range in size from small motors of a few kilowatts to huge megawatt motors that need cranes to lift them into position.

General Construction

The figure below shows an exploded view of a typical three-phase induction motor. It consists of two main groups of parts:

1. The stator.
2. The rotor.

Most of the components are of a rugged metal construction. The rotor is suspended by ball-bearings between the end plates. The connection box on the side of the stator is for terminating the supply cables to the stator windings. A fan is mounted on the rotor shaft to blow cooling air over the motor while it is operating.

The motor is bolted into position through bolt holes provided in the mounting foot.

The parts of the stator are:

- Casing, (usually cast iron) complete with mounting foot or flange.
- Laminated iron yoke (core), which is slotted to hold the windings.
- Three sets of windings.
- End shields and bearings.
- Termination box.
- Fan cowling.

The parts of the rotor are:

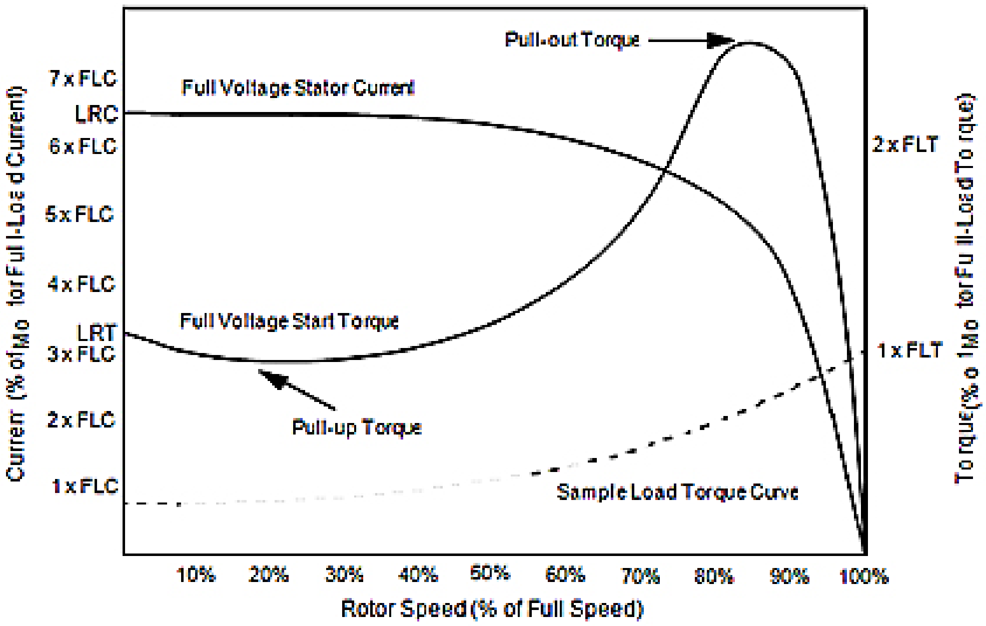
- Laminated iron core.
- Rotor winding (often cast aluminium) in the form of a squirrel cage.
- Steel shaft.
- Cooling fan.

Reversing the rotation of a three-phase motor

Three phase motors are simple to reverse, just swap any two phases of the three-phase supply to the motor! Nice.

Motor speed torque curves

A typical speed-torque curve is shown in the figure below.



There are three important points on the graph above which need to be considered when selecting and using an induction motor.

1. LRT: locked rotor torque (or starting torque).

   This is the torque produced at zero rpm, (when a stationary motor is energised). The locked rotor torque of a motor must be more than the torque required to start the load or the motor will not be able to turn when it is switched on.

2. Pull-up torque is the weakest point on a motor curve, it is the lowest amount of torque a motor produces during acceleration from standstill to operating speed.

3. Pull-out torque (breakdown torque) is the maximum torque able to be developed by the motor.

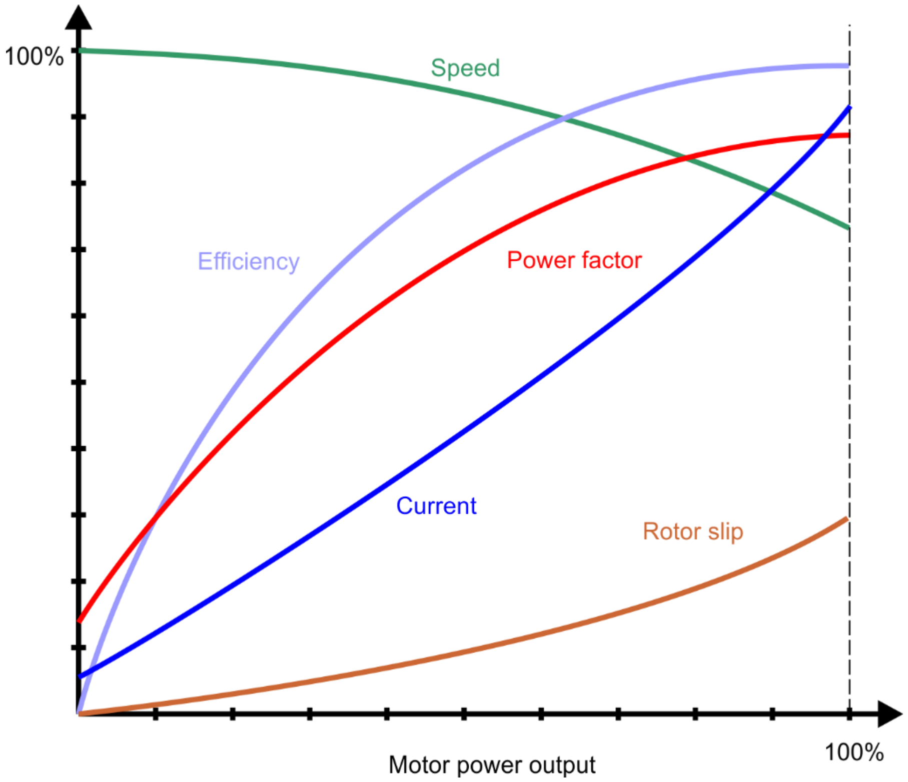
An important aspect of correctly matching a motor to a load is the acceleration time of the motor.

If a motor does not accelerate fast enough it will over-heat on start up. With a larger motor, it is important to know how long the motor will take to reach its full rated speed.

Manufacturers of electric motors usually specify a maximum starting time, during which acceleration can safely take place.

Factors affecting motor performance

There are some situations that will cause a motors performance and output to reduce.



Increased load

Increasing the load on a motor from no load to full load will increase the motors efficiency, power output and power factor. Motors are designed to run well at full load.

If a motor is overloaded above its capacity, the motor slip increases more (the rotor slows down), the motor torque reduces and eventually the motor will stall as the load exceeds the motors capacity to drive it.

As an overloaded motor slows down and the current increases there is a double heating effect on the motor.

The higher current causes more heat, and the slower fan cools less. Can you see where this is going? The motor is going to get very hot surprisingly fast and can burn out in minutes if badly overloaded.

Multiple starts

Multiple starts, especially in a short period of time, will cause the motor to heat up. Each start causes 6-9 times full load current to flow in the motor, causing a lot of heat to be produced.

If a motor is starting a lot, the fan is not able to cool the motor enough and the motor may overheat, burn the insulation off the windings and short out.

Decreased voltage

If the supply voltage to a motor is reduced, either by a slump in the supply system voltage or using a reduced voltage starter, the motor torque will be reduced to the square of the voltage.

I.e. if the voltage to a motor is reduced to 0.58 of its normal value then the torque will reduce to 0.33% (0.58 x 0.58).

As the torque reduces, the slip of the rotor will increase (the rotor slows down) until the motor produces enough torque to keep rotating the load. When this happens, the cooling fan will be less effective and the motor current increases causing the motor to produce much more heat.

If the voltage dips too low, or drops for long periods of time, the increase in motor current and heat may burn the motor out.

Voltage surges

Voltage surges in a motor will cause the motor speed to surge with increased motor current. This un-even speed may have an adverse effect on the load.

The increased current may trip overcurrent protection and can produce unwanted harmonics in the mains supply.

Overcurrent may cause damage to the motor depending on how close to fully loaded the motor is.

If you notice a motor pulsing badly, then the motor should be stopped immediately, and the condition rectified.

Lightning strikes

A lightning strike will send a sharp, steep faced square wave of high voltage (i.e. a HV spike) down the power line which will affect any connected equipment. A lightning pulse may be 1 million volts or more.

The winding insulation in a motor hit by lightning will most likely be burnt and the motor destroyed.

Motors and motor control equipment hit by lightning may fail later in time due to weaknesses caused by the lightning.

Harmonics

VFDs are one source of harmonics that can circulate in motor windings.

Harmonics, wherever they originate, add to the current flowing in a motor and they can be difficult to detect.

Harmonics can add to the heating of motor windings and increase the chances of a "stressed" motor burning out.

Loss of phase

As a general rule of thumb, if the motor is operating at loads in excess of 35% at the time of the loss of one phase, the motor speed will gradually drop to zero – it may take from 1 to 30 seconds but as the speed reduces the current in the other two phases increases to compensate.

a) **Star connected motor:**

If one phase of a three phase motor supply is lost, it will cause the motor to what is called 'two phase' or 'single phasing'.

- While running, the motor will sound and feel uneven and rough as if a bearing has failed.
- This situation causes the current to increase in the other two phases in an attempt to compensate and to provide full load torque.
- Whilst this increase in current does not endanger the motor in the short term, the increased supply line current may cause the motor overload to trip as it senses the extra current.

b) **Delta connected motor:**

For delta connected three phase motors, the loss of one phase is much more serious. With a delta connected motor, the voltage and current are higher.

- In this instance the current increases by around 50% in the other two windings in order to keep the same power.
- The motor power output is reduced, and the remaining windings will overheat quickly.
- If the motor stalls, it will not have enough power to restart and the motor is left in a locked rotor state. The motor will overheat almost instantly which will damage the motor and potentially any attached equipment.

To protect against loss of a phase a phase failure relay should be used.

As most motors now have thermistors fitted into the stator windings. These should be interfaced with the motor control equipment so that when the temperature of the stator exceeds a pre-set temperature, the thermistor sends a signal to shut down the motor.

Further overcurrent protection is needed and can be provided using thermal overloads, fuses, MCBs, and current limiting devices which should trip the supply to the motor.

Reversed winding

The effect of a reversed winding on one phase of a three-phase motor is quite different to a loss of a phase.

For example, if one winding is transposed in a three-phase motor, then the magnetic field of that winding is reversed compared to the other two.

The motor's rotating magnetic field becomes uneven and the motor speed will pulse as will the torque produced. This may also lead to voltage and current surges causing an increased level of harmonics on the power system.

Methods of rectifying a reversed winding

Use the motor labelling

If you discover a motor with a reversed winding - and you are lucky, the labelling on the windings may still be there. If the correct labelling is there you will be able to see the winding that is out of order and change it.
Star connected motor:

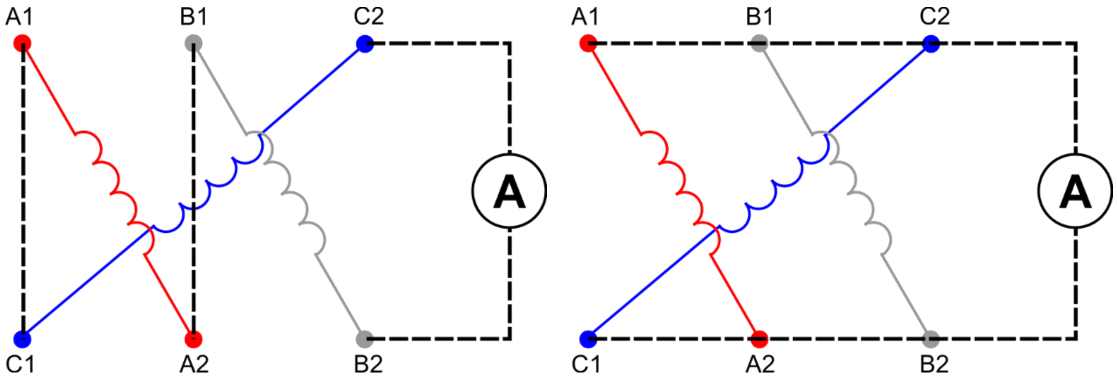
- Make sure either all of the 1's or all of the 2's are connected together at the star point.
- Delta connected motor:
- The 1 of each winding is connected to the 2 of the next.
- If you find they are not, then simply correct the connections.

Use the series or parallel method

If you are not in luck and the labels are not there, then while it will be more work, all is not lost.

By using a milli-ammeter there are a couple of methods used to correct a reversed winding - the series or parallel methods. The two methods are very similar, the difference is that they have the windings connected in either series or parallel during testing.

Using an ammeter on milliamps, connect it to the windings as shown below. The connections may seem confusing, they are laid out as in a typical three phase motor terminal box layout. You may notice winding C is reversed in the diagram.



- Use your hand to slowly turn the rotor.
- If very very little or no current is indicated, then the polarity of the windings is correct.
- If the meter indicates a significant current movement, a winding is reversed.
- Choose a winding, swap its ends over and check by rotating the rotor again.
- If there is now very little or no current indication on the meter, then you have fixed the reversed winding.
- If there is still a significant current reading on the meter, swap the ends of the next winding and check again.
- There should now be no deflection and the windings are correctly connected.

AC Motor calculations

There are some motor calculations you will need to be able to do. Let's have a look at some motor formulas now.

Horsepower

Some older electric motors and motors that come from the US are rated in the old imperial unit for power, called horsepower (HP).

$f(x)$

$$1HP = 746\ watts$$

Motor power

With a motor there is the input power, (what we put in to a motor), and output power, (the usable output power of a motor after the losses have taken their bit).

Input power

In practice, the power stated on a motor is generally the output power of the motor. To find the input power you will need to use the following formulas:

$f(x)$

Single phase:

$$P_{In} = V_L \times\ I_L\, x \times\ p.f$$

Three phase:

$$P_{In} = \sqrt{3}\ \times\ V_L \times\ I_L\ \times\ p.f$$

Where:

V_L = Line voltage

I_L = Line current

pf = power factor

Output power

If you have to work out the output power of a motor, you can use the following formula:

$$P_{out} = V_L \times I_L \times p.f \times efficiency$$

Three phase:

$$P_{In} = \sqrt{3} \times V_L \times I_L \times p.f \times efficiency$$

$f(x)$ Where:

V_L = Line voltage

I_L = Line current

pf = power factor

Motor efficiency

Induction motors are quite efficient, but they do have some losses.

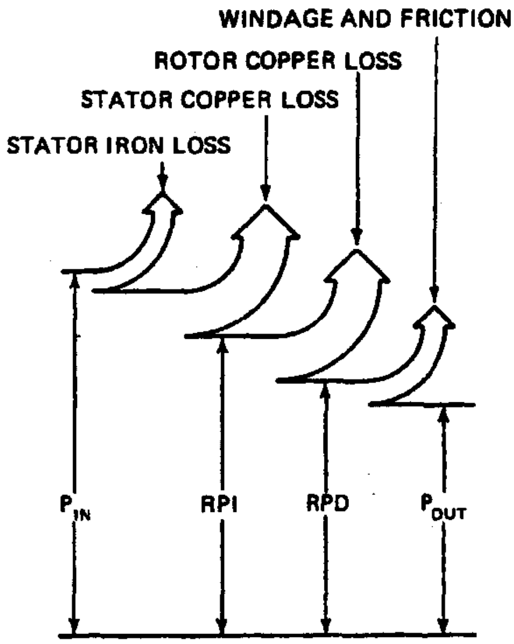
That means you will have to put a little more power into a motor than the useable power you are going to get out of it.

The constant losses in a motor are the iron or magnetic losses in the iron circuit.

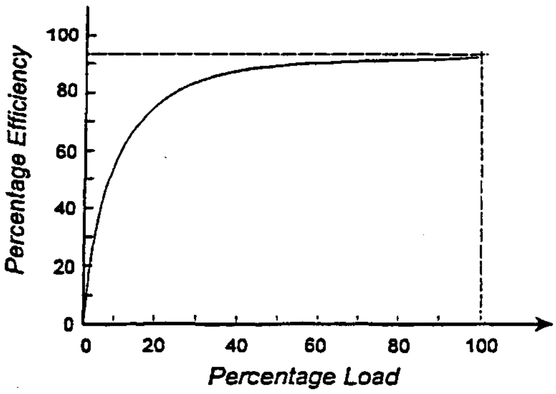
The variable losses are the copper losses in the stator and rotor conductors.

The maximum efficiency of a motor occurs when the constant losses equal the variable losses, this is usually designed to occur when the motor is running at full load.

It can also be seen that as the load increases on an induction motor, the efficiency increases, up until the point where the motor is fully loaded.



Power-flow diagram



$$\boldsymbol{Efficiency\ (\eta) = \frac{Output}{Input}}$$

$f(x)$

Where:

$\eta = Efficiency$

$Output = output\ power\ of\ motor$

$Input = input\ power\ of\ motor$

Motor percentage efficiency

Efficiency is often written as the percentage difference between the input power and the output power.

The percentage efficiency of a motor can be calculated by dividing the power output by the power input and multiplying the answer by 100 to obtain a percentage value.

$$\boldsymbol{Efficiency\ (\eta) = \frac{Output}{Input} \times 100}$$

$\boldsymbol{f(x)}$

Where:

$\eta = Efficiency\ in\ \%$

$Output = output\ power\ of\ motor$

$Input = input\ power\ of\ motor$

If the output power and the efficiency of a motor is known, the equation can be transposed to calculate the input power of a motor.

$\boldsymbol{f(x)}$

$$\boldsymbol{Input = \frac{Output\ \times 100}{\eta}}$$

Motor current

In practice, motor current is generally read off the nameplate of a motor. The formula to calculate run current for a single-phase motor is as follows (the power unit is watts):

$f(x)$

$$\textbf{Single phase motor run current} = \frac{\textbf{Rated power}}{\textbf{voltage} \times \textbf{PF} \times \textbf{efficiency}}$$

For starting current, as a rule of thumb, you can use 7 times the run current:

$$\textbf{Single phase motor start current} = 7 \times \frac{\textbf{Rated power}}{\textbf{voltage} \times \textbf{PF} \times \textbf{efficiency}}$$

The formula for the run current of a three-phase motor (where the rated power is in watts) is as follows:

$$\textbf{Three phase motor run current} = \frac{\textbf{Rated power}}{\sqrt{3} \times \textbf{voltage} \times \textbf{PF} \times \textbf{efficiency}}$$

For a three-phase induction motor, a rule of thumb you can use is 4 times the run current. So, the formula you can use to calculate the start current would be:

$$\textbf{Three phase motor starting current} = 4\ x\ \frac{\textbf{Rated power}}{\sqrt{3} \times \textbf{Voltage} \times \textbf{PF} \times \textbf{efficiency}}$$

Motor speed

The synchronous speed (the speed of a motors rotating magnetic field) is calculated using the formula:

$f(x)$

$$N_S = \frac{60 \times f}{p}$$

Where f = Frequency
p = Pairs of poles

In an induction motor, (one with a squirrel cage rotor for example) the rotor has to rotate at a slower speed than the magnetic field.

If the rotor did actually catch up to the same speed as the magnetic field, the rotor and the magnetic field would be moving together. The field magnetism would no longer cut (move) across the rotor bars.

If that happens, no current would be induced into the rotor, the rotor would lose its magnetism and would no longer produce torque.

The rotor has to “slip” behind in speed compared to the rotating magnetic field for the motor to work. The difference between the two speeds is called the slip speed and is usually expressed as a percentage of the synchronous speed.

$f(x)$

$$\textit{Slip speed} = N_S - N_R$$

Where N_S = Synchronous speed in rpm
N_r = Rotor speed in rpm

Slip as a percentage

$$\%_{SLIP} = \frac{(N_S - N_R)}{N_S} \times 100$$

$f(x)$

For three-phase motors the typical percentage slips are:

- 3% to 6% for small motors.
- 2% to 4% for larger motors, (for larger motors the slip can be quite small).

Example 1.1

Calculate the rotor shaft speed using the following motor details:

- 4 pole motor.
- 3 phase supply.
- 50 Hz.
- With a slip of 5%.

1. Calculate the motor synchronous speed.

$$N_S = \frac{60 \times f}{p}$$

$$N_S = \frac{60 \times 50}{2}$$

$$N_S = 1500\,rpm$$

2. Calculate the slip speed in rpm.

$$Slip = N_S \times \%_{SLIP}$$

$$Slip = 1500 \times 5\%_{SLIP}$$

$$Slip = 75\,rpm$$

3. Calculate the rotor speed in rpm.

$$N_R = N_S - Slip\ speed$$

$$N_R = 1500 - 75$$

$$N_R = 1425\,rpm$$

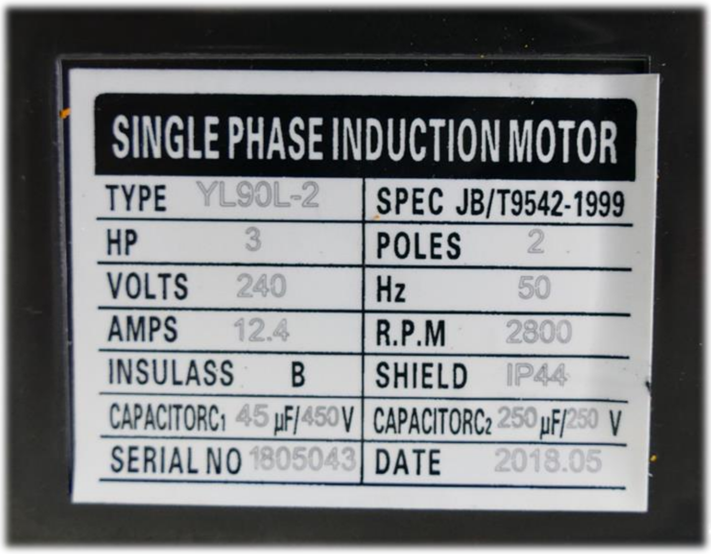
Taking motor measurements

You may find yourself in the situation of making motor calculations for expected results and then comparing them to actual measurements you take from the motor.

You may find that there is a difference in the values between your calculations and the measurements themselves. This can be a result of a few different things such as:

- Variations in the load on the motor.
- Variations in supply voltage.
- Meter tolerance – how accurate the instrument has been manufactured to be.
- Corrosion on terminals or poor connection to the motor circuit.
- Faulty or resistive meter leads.
- User error.
- Calculation error.

If you find that your calculations are quite different to the actual motor readings taken, then you need to work out what has gone wrong. You may start with taking the measurements again, or re-looking at your calculations for errors.



Common faults with electric motors

Single phase motors – troubleshooting

As you know, a split-phase motor has a start and a run winding. Depending on the type of motor, the start winding is disconnected by a centrifugal switch as the motor accelerates.

Some split-phase motors have a thermal switch that disconnects the motor if it overheats or draws too much current.

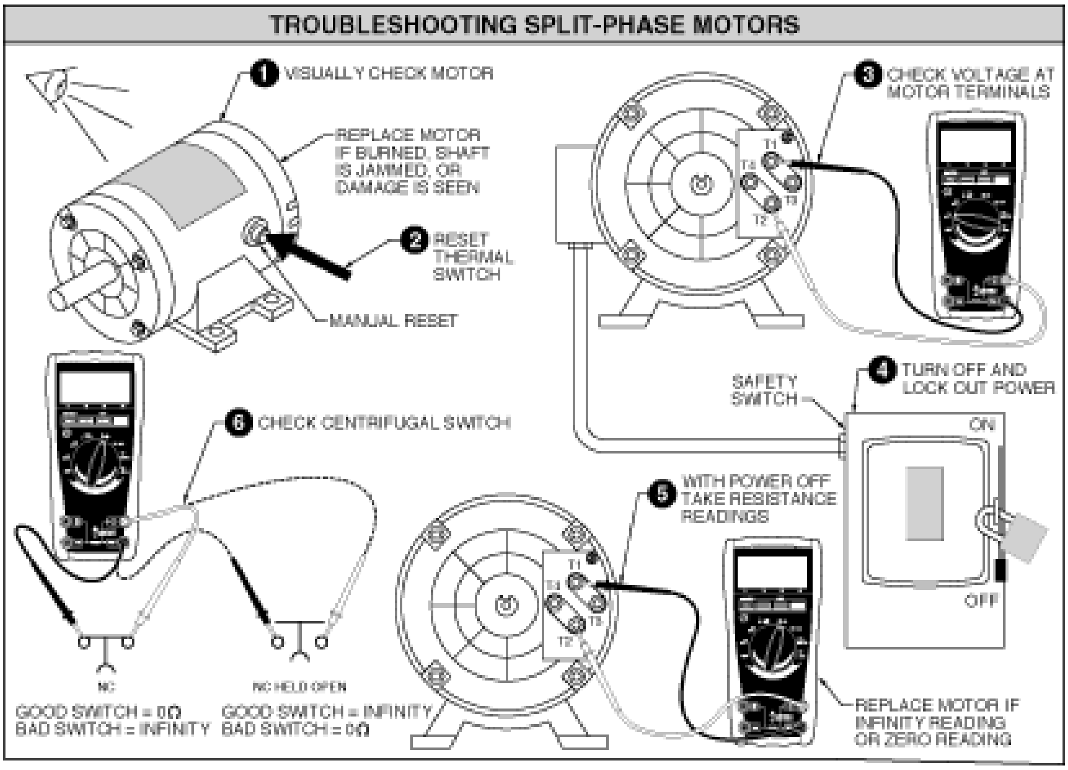
Caution:

1. Disconnect power to the motor before performing service or maintenance.
2. Discharge all capacitors before working on the motor.
3. Always keep hands, hair and clothing away from moving parts.
4. Be sure the required safety guards are in place before starting equipment.

Troubleshooting split - phase motors

Most problems with single-phase motors involve the centrifugal switch, the thermal switch, or the capacitor(s). If the problem is in one of these, the motor is usually repaired.

> Thermal switches can have a manual reset or else they automaticly reset. Caution should be taken with any motor that has an automatic reset, as the motor could restart at any time.



If the motor is more than 10 years old and less than 1 hp, (746 Watts), it is getting to the point where the motor is better off being replaced than repaired. If the motor is less than 200 Watts, it is almost always more cost effective to replace it.

Troubleshooting a split-phase motor:

1. Turn the power supply to the motor off. Visually inspect the motor. Replace the motor if it is burnt out, the shaft is jammed, or if there is any sign of irreparable damage.

2. Check to determine if the motor is controlled by a thermal switch. If the thermal switch is manual and needs resetting, reset it, check and run the motor.

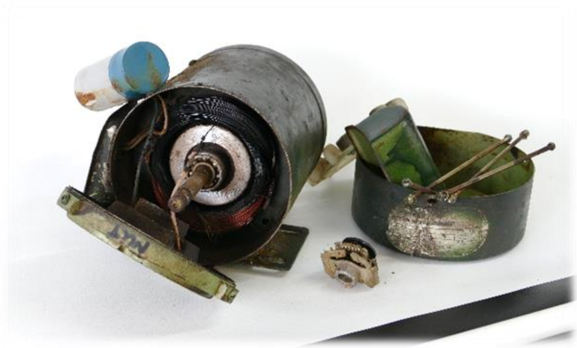
3. If the motor does not start, use a voltmeter to check for voltage at the motor terminals. If the voltage is not correct or missing, check the supply circuit to the motor.

4. Isolate the motor and confirm by testing. Lock out and tag the supply as per your company policy.

5. With the power isolated, connect an ohmmeter to the motor terminals. The ohmmeter will indicate the combined resistance of the start and run windings as they are in parallel. The combined resistance should be less than the resistance of either winding alone. If the meter reads zero, there is a short circuit. If the meter reads infinity, the windings are open circuit.

6. Manually operate the centrifugal switch and check it for signs of burning or broken springs. If any obvious signs of problems are present, service or replace the switch. If the motor is good, the resistance on the ohmmeter will increase when the switch is operated. If the resistance does not change, a winding is open circuit.

Troubleshooting capacitor motors



A capacitor motor is a split-phase motor with the addition of one or two capacitors. Capacitors give the motor more starting / running torque.

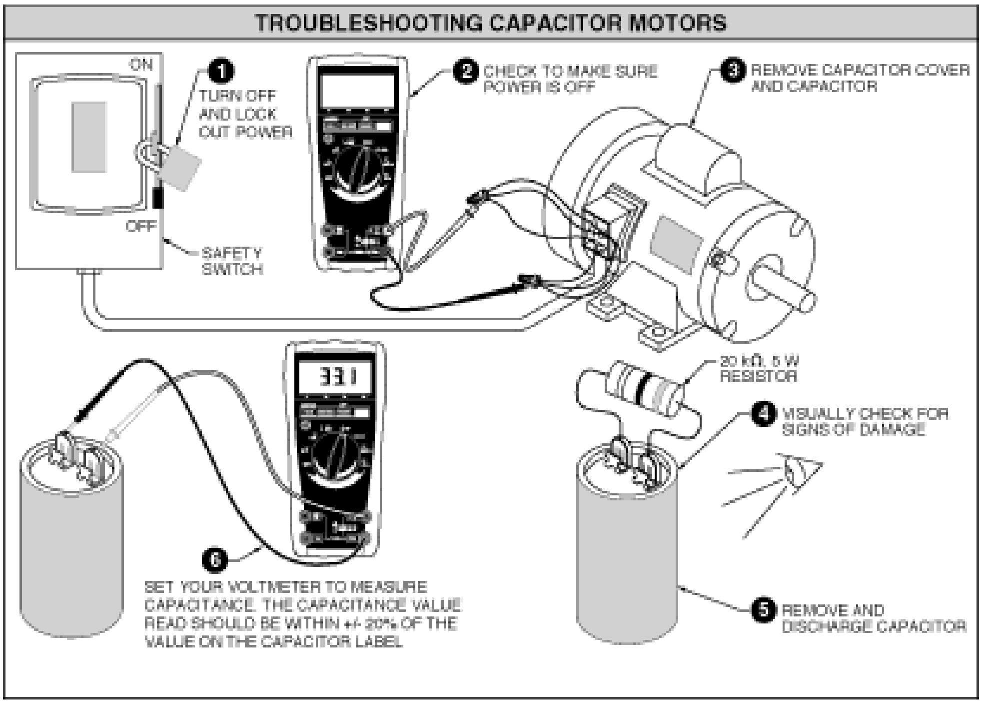
Troubleshooting capacitor motors is similar to troubleshooting split-phase motors. The only additional device to be considered is the capacitor/s.

Capacitors have a limited life and are often the problem in capacitor motors. Capacitors may have a short circuit, an open circuit, or may deteriorate to the point that they must be replaced.

Deterioration can change the value of a capacitor which can cause problems. When a capacitor short-circuits, the winding in the motor may burn out.

When a capacitor deteriorates or opens, the motor has poor starting torque. Poor starting torque may prevent the motor from starting, which can trip the overloads or burn the motor windings out.

AC capacitors are used with capacitor motors. Capacitors that are designed to be connected to AC have no polarity. See Figure below.



1. Isolate the motor and confirm by testing. Lock out and tag the supply as per your company policy.

2. Visually check the capacitor for leakage, cracks, or bulges.

> Caution: A good capacitor will hold a charge, even when power is removed. Discharge the capacitor.

3. Safely discharge any capacitors, place a 20,000 ohm, 2 W resistor across the terminals for five seconds.

4. After the capacitor is discharged, remove the capacitor from the circuit and connect the ohmmeter leads to the capacitor terminals. An ohmmeter will indicate the general condition of a capacitor. A capacitor is either good, shorted, or open.

5. Or, if you have a test meter with a capacitance setting, take a reading of the capacitance value, it should read within +/- 20% of the value on the capacitor label.

6. Replace the capacitor if necessary.

Some other typical faults with this type of motor are:

1. The starting switch contacts remain closed after the motor starts – the start winding is usually of a lighter gauge wire and is not designed for continuous duty.

2. After a period of 20 to 30 seconds the start winding will over heat and then burn-out and fail completely. This will result in an expensive motor repair or a complete motor replacement.

3. The starting switch remains open-circuited. The motor will fail to start, and high current will flow in the run winding. This excess current, if allowed to continue, will overheat and burn the winding insulation if there is not adequate circuit protection installed.

Three phase motors

Troubleshooting three phase motors.

1. Use a voltmeter to check for the correct voltage at the motor terminals and that all three phases are present. If the voltage is not correct or missing, check the supply circuit to the motor and starting equipment.

2. Isolate the motor and confirm by testing. Lock out and tag the supply as per your company policy.

3. If the motor is contactor controlled, inspect the contacts closely. Manually engage the starter and measure the resistance through its contacts. You should read 0.09 ohms or less.

4. Turn the motor shaft to determine if it rotates freely. Listen for unusual noises (such as scraping), smell for burned insulation, and feel for excess heat.

5. Check the motor starter for loose connections and hot spots indicated by discoloration.

6. Check the motor connections — many motor failures result from loose terminals, insufficiently insulated connections grounding inside the junction box or shorting together.

7. Check the resistance of the windings. You are looking for a few ohms resistance depending on the size of the motor. This requires the removal of the terminal box cover. The exact measurement value is less important than the balance between phases. While you can't expect identical readings, they should be very close (within a maximum of 5% variance of each other), If they are not even, this indicates a problem in the windings of the motor.

8. Use your insulation resistance tester to test the insulation resistance to earth and between the windings. Disconnect the windings from each other, having carefully marked which ones go where. A low reading between two phases could indicate a problem. If the motor fails this test, look for problems in the connections or failed conductor insulation. If you find a phase-to-phase short, the motor needs evaluation for a rewind or for replacement. If you find a phase-to-ground short, a motor shop may be able to do an in-place repair for a large motor. However, you might end up needing to rewind or replace it.

Note: A stator phase resistance test will identify a bad motor but isn't an absolute verification of a good motor.

Final load voltage and current tests verify a good motor. You never know when you'll find a motor that tests well but has a thumb-sized hole blown from the coils.

Final tests and procedures.

Once you've corrected all identified problems and the motor is installed and aligned, you're almost done. Energise the motor and test the controls and overall system operation.

While the motor is running, record the operating voltage and current, check the balance, and verify that your measurements are within the nameplate specifications.

Then apply the sense tests again:

- Listen for unusual noises.
- Smell for smoke or hot insulation.
- Feel the motor for excessive heat or vibration.
- Look for possible obstructions.

Now engage the load. Apply the four sense tests again. Once you're sure you've addressed all of the problems with this motor, it's time to go home.

Table of faults diagnoses for electric motors.

Problem	Like causes	What to do
Motor fails to start upon initial installation.	Motor is miswired. Motor damages and rotor is striking stator. Fan guard bent and contacting fan.	Verify motor is wired correctly. May be able to reassemble; otherwise, motor should be replaced. Replace fan guard.
Motor has been running, then fails to start.	Fuse or circuit breaker tripped. Stator is shorted or went to ground. Motor will make a humming noise and the circuit breaker or fuse will trip. Motor overloaded or load jammed. Capacitor (on single phase motor) may have failed. Starting switch has failed.	Replace fuse or reset the breaker. Disassemble motor and inspect windings and internal connections. A blown stator will show a burn mark. Motor must be replaced or the stator rewound. Inspect to see that the load is free. Verify amp draw of motor versus nameplate rating. First discharge capacitor. To check capacitor, set volt-ohm meter to RX100 scale and touch its probes to capacitor terminals. If capacitor is Ok, needle will jump to zero ohms, and drift back to high. Steady zero ohms indicates a short circuit; steady high ohms indicates an open circuit. Disassemble motor and inspect both the centrifugal and stationary switches. The weights of the centrifugal switch should move in and out freely. Make sure that the switch is not loose on the shaft. Inspect contacts and connections on the stationary switch. Replace switch if the contacts are burned or pitted.

Problem	Like causes	What to do
Motor runs but dies down	Voltage drop. Load increased.	If voltage is less than 10% of the motor' rating contact power company or check if some other equipment is taking power away from the motor. Verify the load has not changed. Verify equipment hasn't got tighter. If fan application verify the air flow hasn't changed.
Motor takes too long to accelerate	Defective capacitor. Faulty stationary switch. Bad bearings. Voltage too low.	Test capacitor per previous instructions. Inspect switch contacts and connections. Verify that switch reeds have some spring in them. Noisy or rough feeling bearings should be replaced. Make sure that the voltage is within 10% of the motor's name-place rating. If not, contact power company or check is some other equipment is taking power away from the motor.
Motor runs in the wrong direction.	Incorrect wiring.	Rewire motor according to wiring schematic provided.
Motor overload protector continually trips	Load too high. Ambient temperature too high. Protector may be defective. Winding shorted or grounded.	Verify that the load is not jammed. If motor is a replacement, verify that the rating is the same as the old motor. If previous motor was a special design, a stock motor may not be able to duplicate the performance. Remove the load from the motor and inspect the amp draw of the motor unloaded. It should be less than the full load rating stamped on the nameplate. Verify that the motor is getting enough air for proper cooling. Most motors are designed to run in an ambient temperature of less than 40^{0}C. (Note: a properly operating motor may be hot to the touch.) Replace the motor's protector with a new one of the same rating. Inspect stator for defects, or loose or cut wires that may cause it to go to ground.

Problem	Like causes	What to do
Motor vibrates	Motor misaligned to load. Load out of balance. (direct drive application) Motor bearings defective. Rotor out of balance. Motor may have too much endplay. Winding may be defective.	Realign load. Remove motor from load and inspect motor by itself. Verify that motor shaft is not bent. Rule of thumb is .001" runout per every inch of shaft length. Test motor by itself. If bearings are bad, you will hear noise or feel roughness. Replace bearings. Add oil if a sleeve of bearing. Add grease if bearings have grease fittings. Inspect motor by itself with no load attached. If it feels rough and vibrates but the bearings are good, it may be that the rotor was improperly balanced at the factory. Rotor must be replaced or rebalanced. With the motor disconnected from power turned shaft. It should move but with some resistance. If the shaft moves in and out too freely, this may indicate a preload problem and the bearings may need additional shimming. Test winding for shorted or open circuit. The amps may also be high. Replace motor or have stator rewound.
Bearings continuously fail.	Load to motor may be excessive or unbalanced. High ambient temperature.	Besides checking load, also inspect drive belt tension to ensure it's not too tight may be too high. An unbalanced load will also cause the bearings to fail. If the motor is used in a high ambient, a different type of bearing grease may be required. You may need to consult the factory or a bearing distributor.
The motor, at start up, makes a loud rubbing or grinding noise.	Rotor may be striking stator.	Ensure that motor was not damaged in shipment. Frame damage may not be repairable. If you cannot see physical damage, inspect the motor's rotor and stator for strike marks. If signs of rubbing are present, the motor should be replaced. Sometimes simply disassembling and reassembling motor eliminates rubbing. Endbells are also sometimes knocked out of alignment during transportation.

Problem	Like causes	What to do
Start capacitors continuously fail.	The motor is not coming up to speed quickly enough. The motor is being cycled too frequently. Voltage to motor is too low. Starting switch may be defective, preventing the motor from coming out of start winding.	Motor may not be sized properly. Verify how long the motor takes to come up to speed. Most single phase capacitor start motors should come up to speed within three seconds. Otherwise the capacitors may fail. Verify duty cycle. Capacitor manufacturers recommend no more than 20, three-second starts per hour. Install capacitor with higher voltage rating, or add bleed resistor to the capacitor. Verify that voltage to the motor is within 10% of the nameplate value. If the motor is rated 208-230V, the deviation must be calculated from 230V. Replace switch.
Run capacitor fail.	Ambient temperature too high. Possible power surge to motor, caused by lightning strike or other high transient voltage.	Verify that ambient does not exceed motor’s nameplate value. If a common problem, install surge protector.

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0800 327 648 (0800 EARN IT)