Motor Fundamentals

E-learning course

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BACHELOR'S THESIS

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Abstract

The goal of this thesis was to create an internal online course for ABB which explains how an electrical motor works. The explanations should be as simple as possible, enabling a non-engineer to understand them. The personnel of the ABB Company will use the online course to learn more about how their products work.

There are many different electrical motors, but this thesis and the course that was made, focus mostly on the AC induction motor. The AC induction motor is the most used electrical motor in industrial applications worldwide. Other motors that are included are 1-phase induction motors, permanent synchronous motors and synchronous reluctance motors.

The theory used in the work was collected by studying literature on how electrical motors work, and by simplifying the explanations to suit the intended reader. The text that was researched and compiled contains explanations of the motor parts, theory about electromagnetism and how current is used to make an electrical motor rotate. Finally, a comparison between different motors is presented.

When all the text was gathered, it was combined with pictures and animations to help with the explanation. It was then combined into a comprehensive PowerPoint presentation as the final product.

Language: English Key words: Electrical Motor, Electromagnetism, Induction motor

EXAMENSARBETE

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Målet med detta examensarbete var att göra en intern online kurs för ABB som förklarar hur en elektrisk motor fungerar. Förklaringen skulle vara så enkel som möjligt så att en icke ingenjör skulle förstå den. ABB:s personal kommer att ta del av denna kurs för att förstå hur deras egna produkter fungerar.

Det finns många olika elektriska motorer, men detta examensarbete och kursen som skapades kommer för det mesta att fokusera sig på växelströmsinduktionsmotorn. växelströmsinduktionsmotorn är den mest använda elektriska motorn världen över när det kommer till industrin. Andra motorer som kommer att tas upp i slutexamensarbetet är 1-fas induktionsmotorer, permanent synkron motorer och synkron reluktans motorer.

Teorin som användes i kursen var samlad genom litteraturstudier om hur elmotorer fungerar, sedan förenkla förklaringar så att den passar användaren. Texten som undersöktes och sammanställdes innehåller förklaringar om motordelar, teori om elektromagnetism och hur ström används för att få en elektrisk motor att rotera, och till sist en jämförelse mellan olika motorer.

När hela texten var samlad, kombinerades den med bilder och animationer som hjälpte undervisningen. Allt detta användes för att skapa en PowerPoint-presentation som slutprodukten.

Språk: engelska Nyckelord: elektrisk motor, elektromagnetism, Induktionsmotor

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1 Introduction

This thesis was commissioned by ABB Motors and Generators. My supervisor at the company was Patrik Norrgård, Training Manager. Ronnie Sundsten supervised my thesis work at Novia.

1.1 Employer

ABB Motors and Generators is a leading company in technology that offers many motor and generator solutions. Their main office is located in Vaasa Finland.

1.2 Goal and disposition

The goal of this final thesis was to create an online course about electrical motors for the marketing team at ABB motors and generators. This is so the marketing team will have a greater understanding about the products they are selling or supporting to their customers. As the end user of the course are not engineers, the course material has to be as simple as possible so even an elementary school student would be able to understand it.

This final thesis contains lots of theory and not much practical work description. First I am going to write about motor theory and then later I will explain how all this information was used to make an online course.

1.3 Information collection

All the information collected for this final thesis are from internet sources, books and interviews of ABB personal. Since electrical motors are such a broad topic, it was easy to find information and sources for this final thesis. Some pictures and graphs were taken from the company’s intranet which is not accessible unless you are a company employee.

2 Different kinds of motors

There are many kinds of electrical motors which can be divided into two main categories: DC motors, where DC stands for direct current and AC motors where AC stands for alternating current. The AC motors can be divided in two sub categories, synchronous motors and asynchronous motors. That a motor is synchronous means that the motor shaft is rotating with the same speed as the rotating magnetic field inside the motor whereas an asynchronous motor rotates slower compared to the rotating magnetic field.

Small DC motors are used in cordless tools, small toys and disk computer drives, however, bigger DC motors are still used in some industrial applications.

AC motors are mainly used for industrial applications such as centrifugal pumps, fans, compressors etc. but can also be found in some household appliances such as washing machines.

By far the most commonly used AC motor is the induction motor. There are two types of induction motors, one with wound type rotor, also called slip-ring motor and another one with squirrel-cage rotor.

This final thesis will mostly be dedicated to induction motors but also to synchronous permanent magnet and reluctance motors.

3 Motor parts

As the Motor is made up of several parts, this chapter will serve the purpose to show what the parts look like and what they are called. There will also be a brief explanation to what is the purpose of the part that is described.

3.1 Outer parts

The stator house holds the stator package and protects the active inner parts from the environment. Another task of the stator house is to help with the heat transfer from inside the motor to the outside, this is the reason why motors often have cooling ribs to increase the surface for better heat dispersion.

The mounting feet and lifting lugs can be found on the stator house. In both ends of the stator house there is the end shields that fixates the bearings holding the shaft and protecting the inside of the motor from the environment.

On top of the motor lies the terminal box that houses the connectors which is used for connecting the motor to the electrical network. It also serves to protect the connectors from water and dust and to protect against live electrical parts.

Coming out of the end shield on one side is the shaft end that transmit torque from the motor to the driven application. The opposite side is referred to as non-drive end or ND end. In the non-drive end we have the fan cover to protect the fan that is mounted on the shaft and also direct the air flow created by the fan over the motor house. At the same time it protects humans, animals and objects from getting in contact with the rotating fan. (McPherson & Laramore, 1990, s. 240)

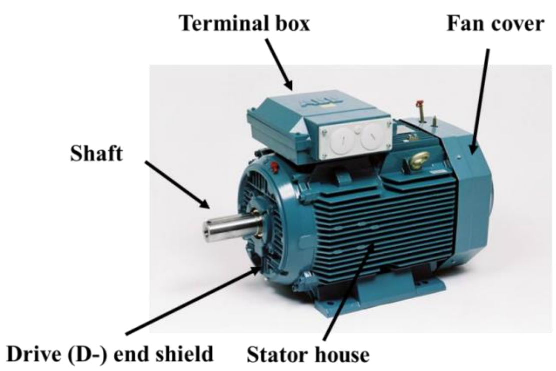


Figure 1. Outer parts of a motor

3.2 Inner parts

The stator core is fixated inside the motor house and is made of laminated electrical steel sheets. The stator core has slots that are filled with copper windings. Its purpose is creating a rotating magnetic field.

The rotor body is the rotating part of the motor and is made of a steel core with aluminium windings. With the use of the rotating magnetic field from the stator, the rotor is able to produce torque.

The rotor body is attached to the shaft in order to transmit the created torque from inside the motor to the driven application.

The rotor and stator together forms the so called active parts of the motor. (McPherson & Laramore, 1990, s. 240-241)

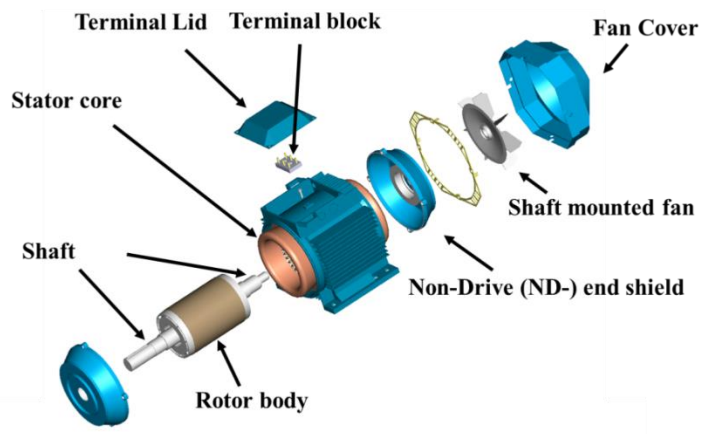


Figure 2. Inner parts of a motor

3.3 Stator

The stator core consists of several electrically laminated steel sheets which are fixed together to form the stator core. These laminated steel sheets are designed so that when fixated they create slots inside the stator core.

Figure 3. Stator steel sheets

The winding coil is then inserted into the slots of the stator core. Some might wonder why use laminated sheets instead of just one big iron core. The reason is to reduce the induced current in the stator which leads to overheating of the motor and energy losses that could be used for creating the magnetic field instead. This unwanted induced current is also called eddy current.

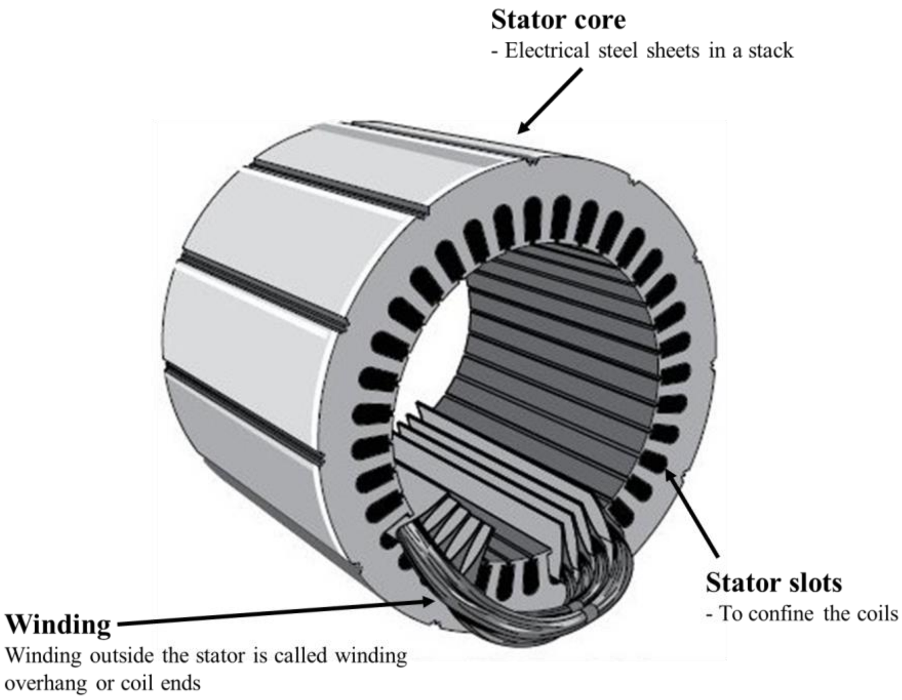


Figure 4. Stator

3.4 Rotor

The rotor is the rotating part of the motor and can be found inside the stator. As with the stator, also the rotor core consists of electrically laminated steel sheets. Inside the rotor slots there are aluminium windings that are casted together with short-circuit rings.

This is done by making holes in the lamination so that when they are stacked, channels will be formed through the rotor core. During the casting these channels will fill up with aluminium and form the windings that together with the short-circuit rings are shaped like a squirrel cage. Hence the name squirrel cage induction motor.

The windings inside the rotor do not go straight but are skewered for the purpose of reducing electrical noise and vibration. The rotor core helps conducting the magnetic field from the stator to the rotor windings.

There is an air gap between the stator and the rotor and since it is known that air conducts magnetic fields poorly the gap can't to be too big. The airgap cannot either be too small since metallic objects expand when heated and as the rotor gets warm there will not be enough space for it to rotate inside the stator. The rotor windings can also be called for rotor bars.

Next up is explaining how the rotor is able to spin inside the stator but first electromagnetic induction has to be explained.

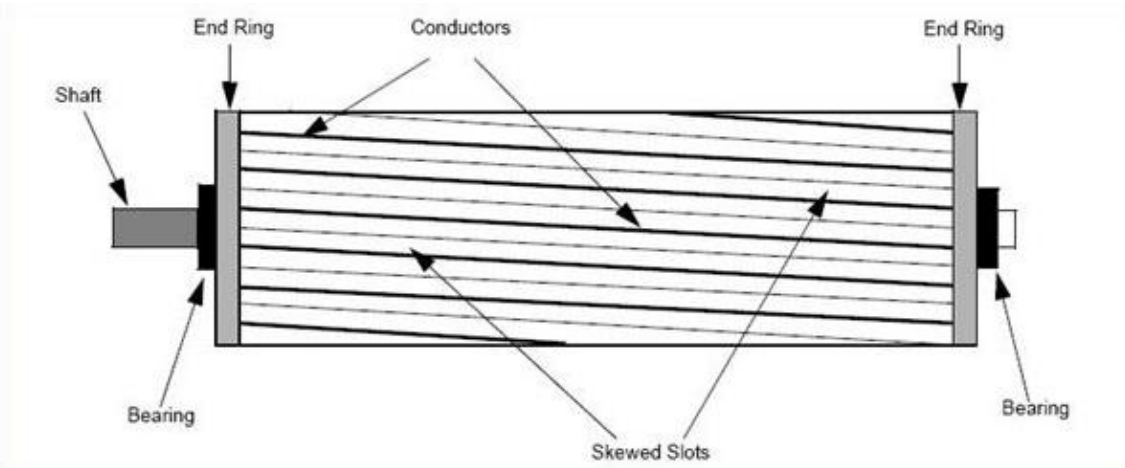


Figure 5. Squirrel cage rotor

4 Theory about electromagnetism

This chapter will explain how electromagnetism works and how it is used to make an electrical motor to rotate.

4.1 Magnets and magnetic fields

A magnet is an object or material that creates a magnetic field. Magnetic fields are an invisible force that attracts ferromagnetic metals such as iron, steel, nickel and cobalt. Magnets have two poles, a north pole and a south pole. The magnetic field travels from the North Pole to the South Pole.

The magnet also attracts or repels other magnets depending on which way the poles are facing. If the poles are of the opposite polarity, they will attract each other. If the poles are of the same polarity, they will repel each other.

This information is relevant for understanding the induction motor but even more useful in understanding how reluctance and permanent magnet motors work, which will be talked about after the induction motor.

There are two kinds of magnets, permanent magnets and electromagnets. Permanent magnets can be of two types.

They can be made from rare-earth magnet materials like neodymium-iron-boron or be of ferromagnetic type where a ferromagnetic object like iron have been magnetized to have a persisting magnetic field.

Electromagnets are temporary magnets created with the use of a current and a ferromagnetic core such as iron.

The biggest advantage of these electromagnet is that they can be controlled by a current. (HyperPhysics)

4.2 Electromagnets

A wire that conducts a current creates a magnetic field that will wrap itself around the wire, this idea is used in creating electromagnets.

Use your right hand fingers to determine which way the magnetic field will rotate if you place your thumb in same direction as the current in the wire.

This rule can also be used to determine which is the South and North Pole in an electromagnet. This rule is called the right-hand rule. If the current switches direction in the wire, the magnetic field will also switch direction.

Electromagnets are created by wrapping a conducting wire around an iron core and send a current trough the wire. Now the iron core will act as a magnet.

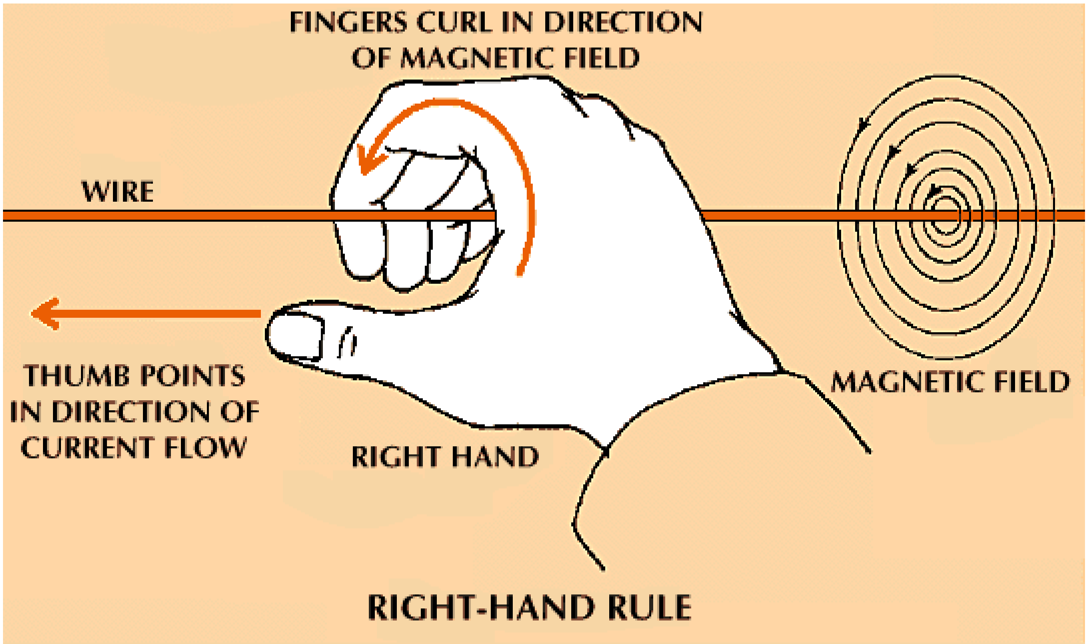


Figure 6. Right-Hand rule

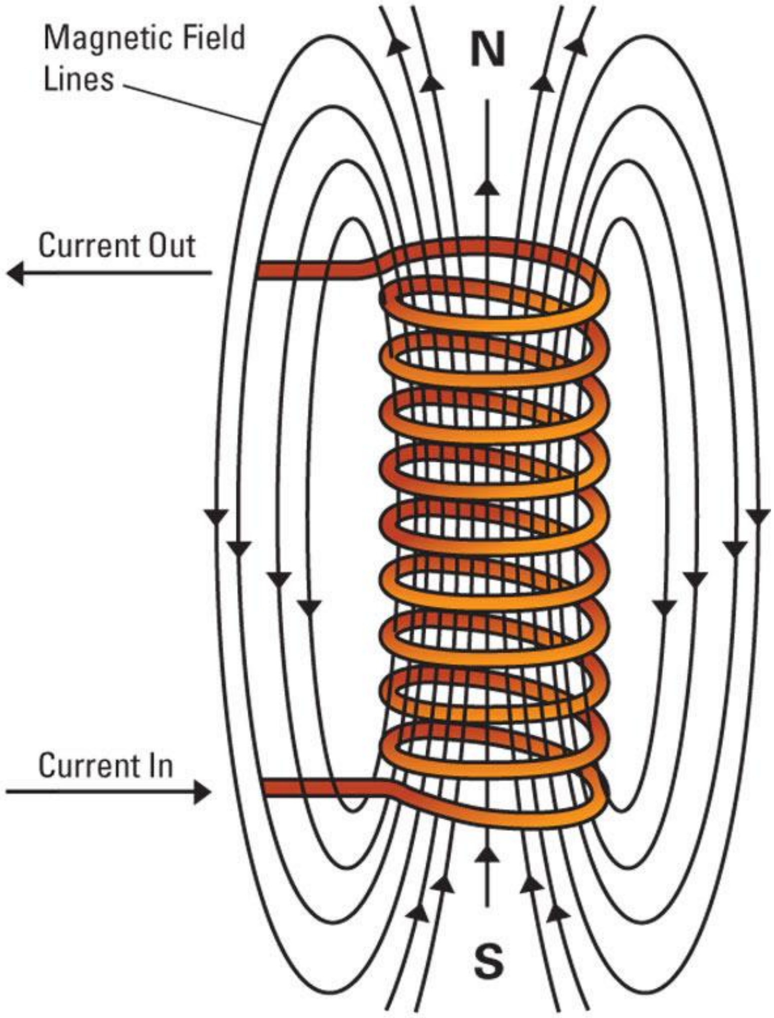


Figure 7. Electromagnet

If we use DC in the wire, the magnet has a stationary north and South Pole. If we use AC, the direction of the current will change with the sinusoidal wave so 50 times a second if connected to a 50Hz supply. This means that the direction of the magnetic field created also will change as often, and the pole polarity will shift 50 times a second as well. Electromagnets can be turned on and off by controlling the current.

An electromagnet does not need an iron core but it helps conducting the magnetic field and “boosts” the power of the electromagnet as a magnetic field flows very poorly in air.

The windings and the core in the stator acts as electromagnets which in turn creates magnetic fields. (HyperPhysics)

4.3 Electromagnetic induction and Lorentz force

Electromagnetic induction is the idea that a current will be induced in a closed electrical circuit when exposed to a changing external magnetic field.

It also works so that a closed electrical circuit that is conducting a current and is exposed to an external magnetic field will be affected by a force and start to move in the direction the fingers point in Figure 8. That force is called the Lorentz force and is a base principle on how an electrical motor works. (HyperPhysics)

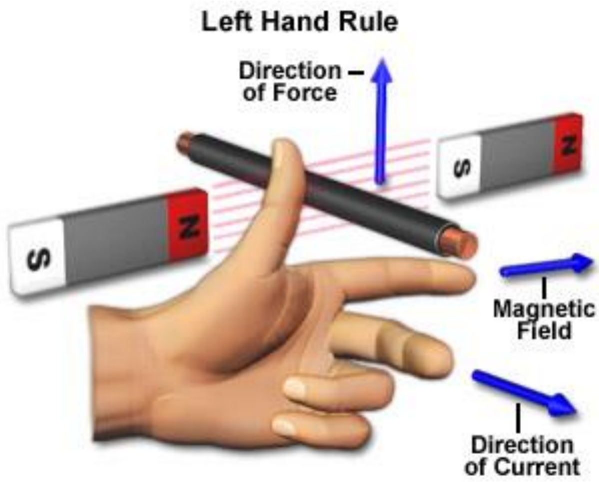


Figure 8. Left Hand Rule

5 How the motor spins

Next, it will be explained what makes the motor rotate for a three phase AC induction motor. In Figure 9 the stator slots are illustrated by the small circles and the black lines illustrates the coils in one phase of the stator winding.

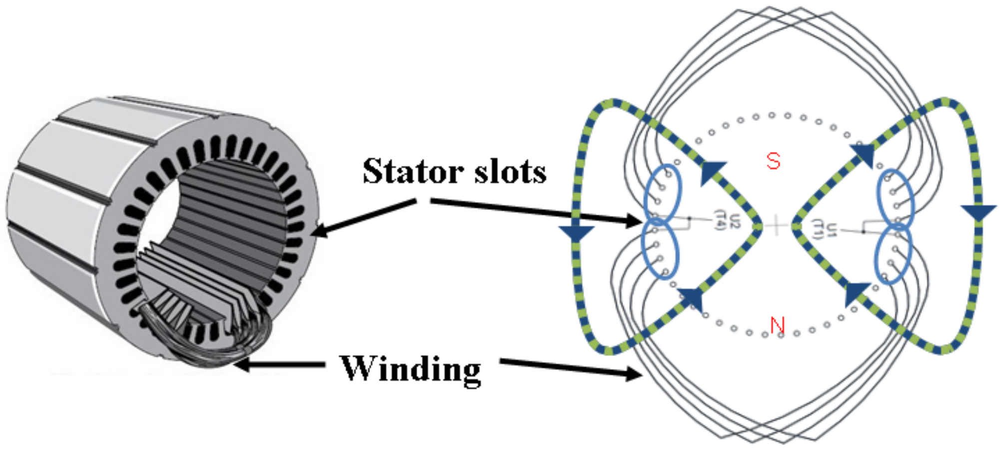


Figure 9. Stator windings and magnetic fields

The first phase winding is divided into two coils using eight slots each so a total of sixteen. For each coil four are used for going in, marked U1 and four for coming out marked U2. Notice that the number of slots in the stator will always be a multiple of 6 because the 3-phase coils will always use one slot going in and one coming out.

Now when voltage is connected a current starts running through the coils and this will create a magnetic field around the coil in the slot. The magnetic field is shown as green and blue striped lines in the picture above.

Applying the right hand rule that was told about earlier will show that the direction of the magnetic field around the slots where the phase goes in will be clockwise and around the slots where it comes out it will be counter clockwise. This is how an electromagnet with a north and South Pole in the induction motor is created. As this motor only create one north and one South Pole it's concluded that this is a two pole motor.

The stator core and especially the part between the slots usually referred to as the stator teeth will act as the core of the electromagnet and help transferring the magnetic field onto the rotor. The stator core is used for two reasons. The first reason is to keep the winding coils in place. The second reason is to help conduct the magnetic field. Now, one phase only is not going to make a motor so the other two phases has to be added. Add the same amount of coils for phase 2 and phase 3 which are indicated with the colours green and red.

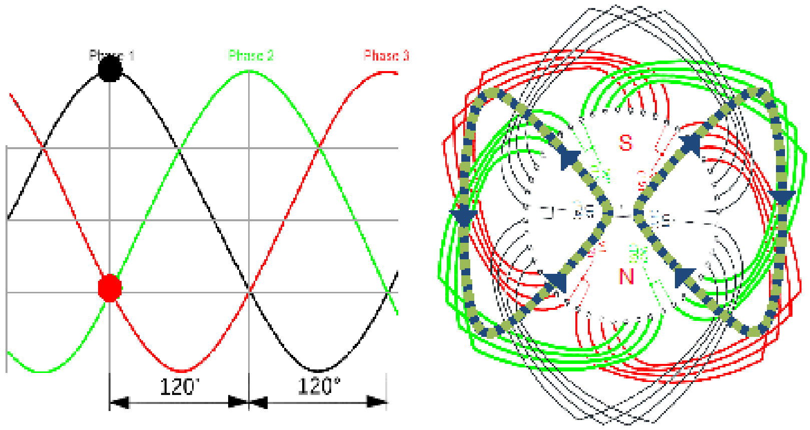


Figure 10. Phase coils and magnetic fields

These two phase coils have their coil ends marked V1-V2 and W1-W2. The coloured dots indicates the current in each phase. As the phases are fed with AC the currents direction varies all the time in a sinusoidal curve pattern.

Now as the current changes direction all the time its power to create the magnetic field will vary according to the sinusoidal curve pattern.

That means if phase 1 had the highest current value it will soon change direction and drop. Next in line will be phase 3 that reaches its peak current and the magnetic field will move onto phase 3 coils and then later to the phase 2 coils. This means that the magnetic field will start to rotate counter clock-vice in the stator.

Switching the phases that are coming from the electrical network so that phase 2 becomes high after phase 1, the magnetic field will rotate the other way. Each phase will have its own coils and depending on the size of the motor the amount of slots used for one phase will vary. As the diameter of the stator core increases the number of stator slots also increases. The phase coils will then be repeated to fill all slots to meet the desired pole number.

So with the use of AC we can get a rotating magnetic field in the stator. As we now have a rotating magnetic field projected onto the rotor from the stator. The rotor bars are currently standing still but because of the moving magnetic field, a current will be induced in the rotor bars. Now that we have a current in the rotor bars and the magnetic field from the stator, the rotor bars will be affected by Lorentz force that was explained in chapter 4.3 and start to spin in the same direction as the rotating magnetic field.

The motor is called an asynchronous motor because the rotor doesn't spin with the same speed as the rotating magnetic field. How much slower the rotor rotates compared to the rotating field is called the slip. With no load on the motor the slip is close to zero. However as we increase the load on the motor, the slip also increases and If the slip gets too big the motor stalls.

It is quite complicate to explain this in text, but it was a lot easier to explain in PowerPoint since it was possible to use animated pictures and videos to demonstrate the rotating magnetic field and the spinning rotor. (LearnEngineering)

6 Magnetic poles and rotating speed of the motor

This chapter will explain how the number of magnetic poles in the motor and the frequency of the current will affect the rotating speed of the motor

6.1 Magnetic poles

This chapter describes how to create other pole numbers. To the left is the picture of the two pole motor that we have been using so far.

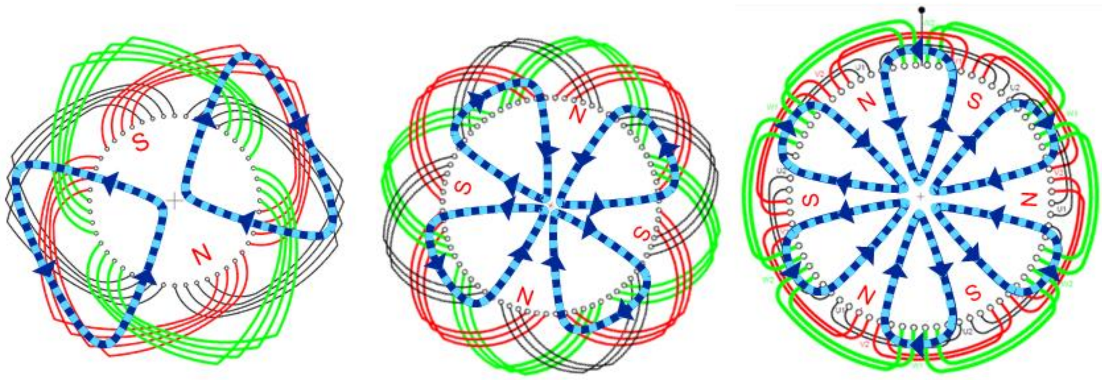


Figure 11. Motors with different amount of poles

In this motor each phase have two coils, and this resulted in one North Pole and one South Pole. So one pole pair or two poles

In the picture in the middle each phase has four coils. Double the amount of coils compared to the two pole motor. That means it has two north poles and two south poles which results in two pole pairs or four poles.

Now continue to increase the amount of poles by adding more and more coils for each phase like in the right picture. To create a six pole motor use six coils per phase that creates three north poles and three south poles and so on.

The number of stator slots is always a multiple of six. When it comes to the pole number it's always a multiple of two cause the north and the South Pole always come in pairs. It's not possible create a north pole without creating a south pole and vice versa. When talking about motors remember not to mix up the number of poles with the number of pole pairs. A combination of the frequency of the current and number of poles in the motor is what decides the rotating speed of the motor. (Electrical4u)

6.2 Rotating speed of the motor

As was said earlier the AC shift direction 50 times per second if it is a 50Hz network. Looking at the diagram, all the three phases will reach their peak on both the positive and negative side fifty times per second. This means that the magnetic field will rotate fifty times per second in a two pole motor as it has only one pole pair.

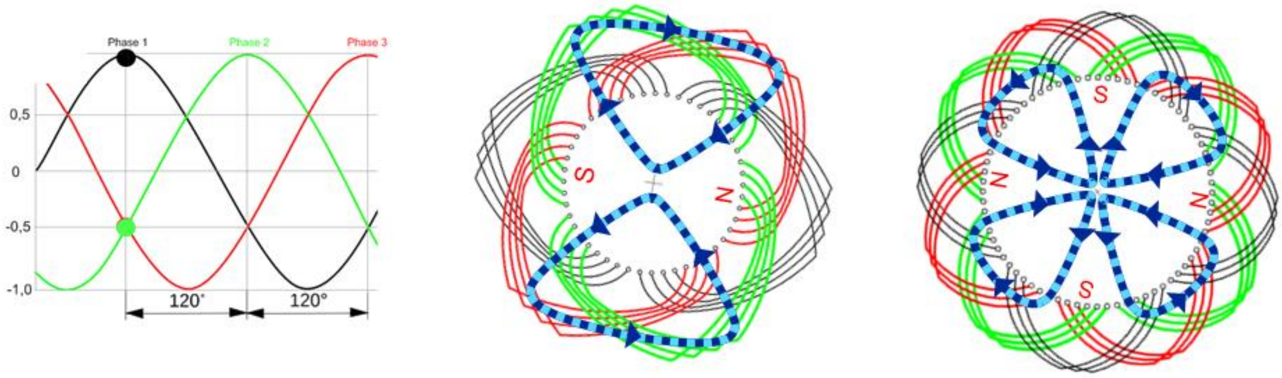


Figure 12. Rotating magnetic field in a stator

As the rotating speed of a motor is given in revolutions per minute. This means that if the magnetic field rotates 50 times in one second it will rotate 3000 times in one minute. The real rotation speed of the asynchronous motor will always be a bit slower because of the slip.

Now with a four pole motor which means two pole pairs. It will take double the time for the magnetic field to travel around the stator as it has double the amount of winding coils for each phase. So with a frequency of 50Hz the magnetic field rotates with a speed of 25 revolutions per second which means it will rotate 1500 times in one minute.

It’s possible to calculate the speed of a motor with any given amount of pole pair number with the following formula.

$$\frac{60\ seconds \times Frequency}{Number\ of\ pole\ pairs} = revolutions\ per\ minute$$

Take 60 seconds times the frequency of the AC network used divided by the number of pole pairs in the motor equals to the rotation speed of the motor given as revolutions per minute.

For example: $\frac{60seconds \times 50Hz}{1} = 3000rpm$

AC with a frequency of 50Hz gives these magnetic field rotation speeds depending on the amount of pole pairs in the motor.

- 1 pole pair = 3000rpm
- 2 pole pair = 1500rpm
- 3 pole pair = 1000rpm

50Hz and 60Hz are the standards used by various countries. The reason why there are different amount of poles is that the poles determine the rotation speed of the magnetic field which in turn decides the rotation speed of the motor.

The more poles, the slower the motor will spin. So now it is possible to choose between a higher rotating speed or greater torque production based on what applications the motor will be used for. (Electrical4u)

7 Star and Delta connection

When connecting a motor to the electrical network, it can be done in two ways. Either use star connection or Delta connection. The U1-U2, V1-V2 and W1-W2 that marks the coil ends of the three different phases that is present on the terminal block of the motor. The L1, L2 and L3 represent the three phases coming from the electrical network.

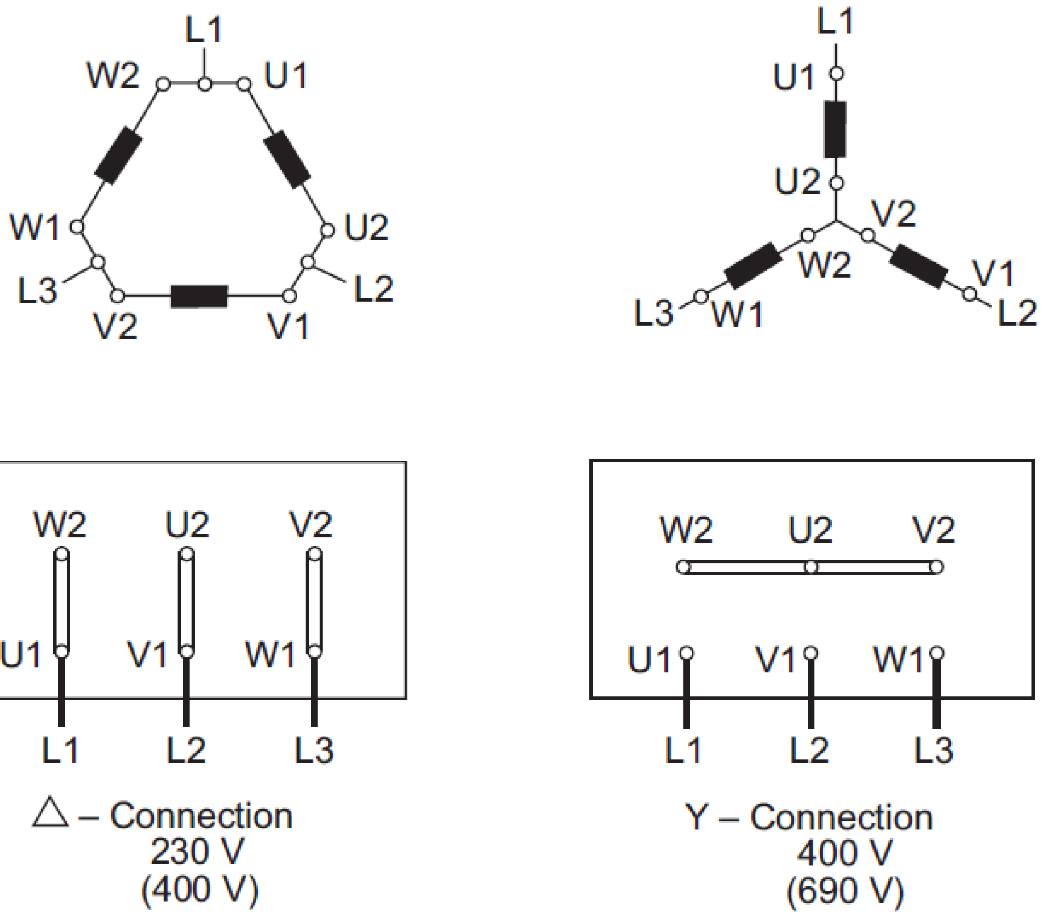


Figure 13. Delta and Star connection

A Delta connection is when the phase coils are connected across with connection bars and then later connected to L1, L2 and L3 according to Figure 13.

A Wye connection is when one side of all three phase coils are connected together with connection bars and the other side is connected to L1, L2 and L3 according to the picture above

The difference between star and delta connection is the difference in voltage over the phase windings. For example when a 400V network is connected to L1, L2 and L3 on the delta connected motor there is 400V over the different phases, meaning 400V between U1 and U2, 400V between V1 and V2 and also W1 and W2. But when the motor connected in star, it will still have 400V between L1 and L2 but only have 230V volts over each phase winding U1 to U2 and so on.

So in the star connected motor the network voltage divided by the square root of 3 over each phase winding while the delta connection have the same voltage as the network over the phase windings.

A lower voltage over the phase windings will also give a lower current in the windings.

As the ratio between star and delta connection is always the square root of 3, this means that a motor with a winding optimised for 400V delta could be connected in star to a 690 volt network and give the same performance, or a motor made for 400 volt star could also be used for 230 volt delta.

This is many times used in the industry where part of the factory might be running on 690 volt and other parts on 400 volt.

If one were to connect the motor so it won't get enough voltage, it will simply not start or it will not be able to handle the load. If one connect so the motor gets more voltage than it can handle, the circuit breakers will trip. (Electrical4u)

8 Starting methods

When starting a motor it's possible to do so in several ways

- Direct on line start
- Star delta connection start.
- Transformer start
- Soft starter
- Variable speed drive start.

8.1 Direct on line start

When starting a motor direct on line the electrical networks voltage is directly going to the motor

It is the simplest starting method, however the starting current can be as high as 8 times the nominal current as the motor requires additional current while the rotor needs to be magnetized while starting up.

In some scenarios one might want to have a lower starting current and that can be achieved with the use of the other starting methods.

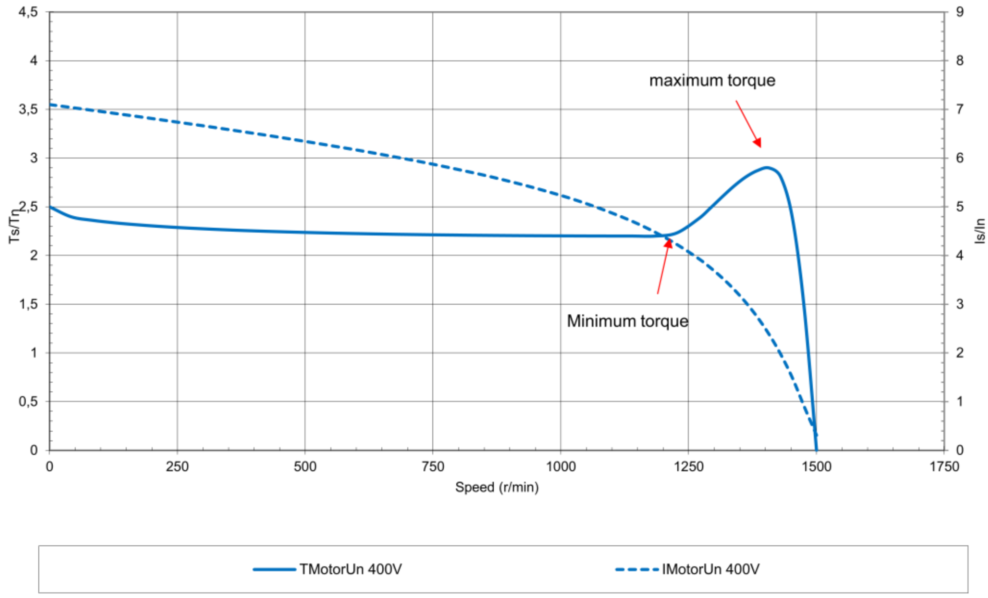


Figure 14. Direct on line start graph

In Figure 14, the dotted line shows the current and the filled line shows the torque. Seeing the starting current is seven times the nominal current for an example motor with direct on line starting method, but as the motor picks up speed the need of magnetizing current decreases down to the nominal current.

At the axes of the graph is T_s/T_n and I_s/I_n. T_s Stands for starting torque, the starting torque is the torque that the motor shaft is able to deliver at zero speed while T_n or nominal torque is the torque the shaft deliver at nominal speed in order to achieve the rated power of the motor.

During the ramp-up of speed, the value of the torque changes. Depending on the rotor slot design and materials used the form of this curve can also vary.

T_s Or starting torque as explained above. In addition to this, there is also minimum torque or pull up torque, meaning the point on the starting torque curve with the lowest value. This point is usually the factor determining if the motor will be able to start when the load from the application is applied.

Also we have the maximum torque or break down torque. This is the highest point on the starting torque curve. As the motor is in continual running you can overload it to the limit of the maximum torque before it stops. This would only be possible for a short time in practice as it will make the motor heat too much if overloaded during a longer time.

I_s stands for starting current and is the number of ampere drawn by the motor from the network at the time of the start before the shaft has started to turn. I_n or the nominal current is then the current drawn from the network at full speed when loaded at its rated power. The starting current curve falls as the speed of the motor is picking up, this is due to the rotor finding its place in the rotating magnetic field in other words the motor is decreasing its slip. During the start the motor needs a lot of current to magnetize the rotor but as the speed picks up the need of magnetizing current decreases.

8.2 Star delta connection start

In some scenarios one might want to have a lower starting current and that can be achieved with the use of a star delta start.

The star delta starter uses the star connection of the motor windings when starting and after a while it switches to delta connection, typically when the full speed has been achieved. This can reduce the starting current so it's only one third compared to the previous starting current.

Since it gives a lower starting current it also means it gives a lower starting torque which can be useful in some applications, but just as well could it make starting impossible in others so this needs to be checked prior to using such arrangements.

Figure 15 is a graph to compare starting current and starting torque for star delta start and Direct on line start.

The blue curves are for the Direct on line start and the red curves are for the start delta start. The dotted lines represent starting current and filled lines represents starting torque. As noticed there is a lower starting current and starting torque with star delta start compared to direct on line start

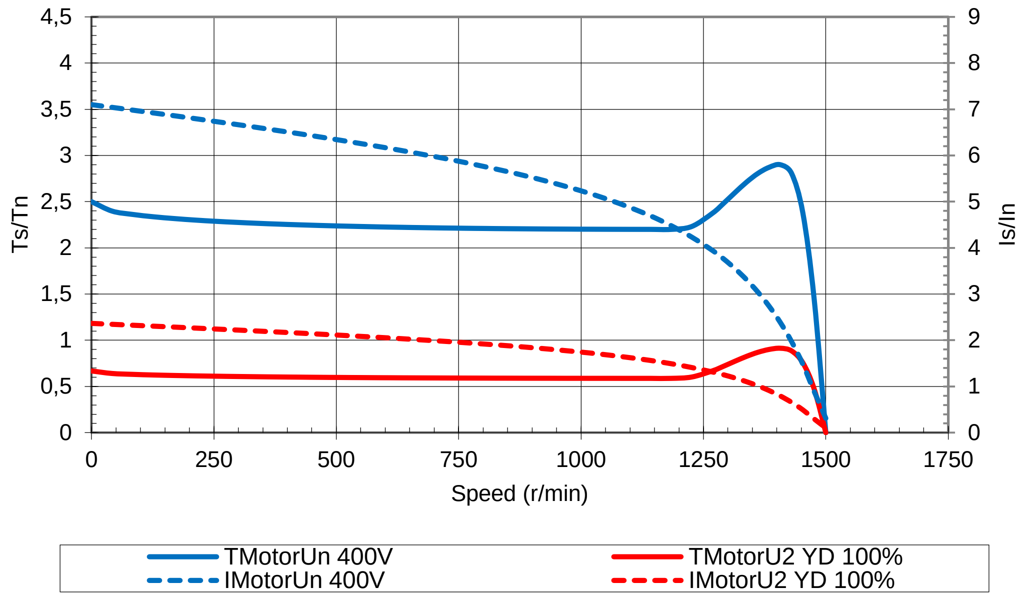


Figure 15. Star delta connection start graph

8.3 Transformer start

With a transformer start, a device called a transformer is used. With the use of the transformer the voltage to the motor can be reduced and thus reducing the starting current and starting torque. It is then possible to switch back to the nominal voltage whenever it's desired.

The difference between star delta start and transformer start is that the first method is locked to give one third of the Direct on line starting current, while when using transformer start the current depends on the output voltage of the transformer.

Figure 16 shows a graph to compare starting current and starting torque for a transformer start at 80% voltage and Direct on line start. The blue curve is for the Direct on line start and the red curves are for the transformer start. Dotted lines represent starting current and filled lines represents starting torque.

As noticed there is a lower starting current and starting torque with transformer start compared to direct on line start. This means that the transformer start can be more flexible compared to the star delta start.

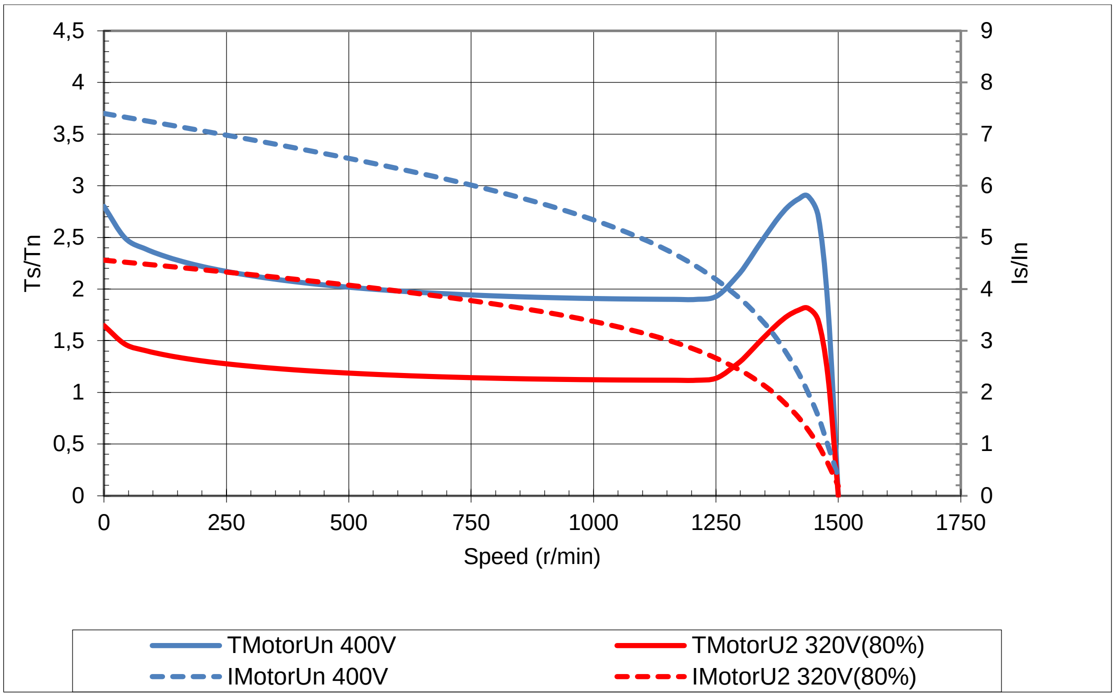


Figure 16. Transformer start graph

8.4 Soft start

A soft starter is a device that can adjust the voltage to the motor to achieve the wanted starting behavior. So if the motor have a low load, the soft starter can feed low voltage to the motor, if the motor have a higher load, the soft starter simply feed more voltage to the motor. With the soft starter, the motor can run with lower the voltage at the start and steadily increase the voltage over time.

The difference between a transformer start and a soft starter is that the transformer switches the voltage between two values while the soft starter goes from zero to nominal voltage over a span time that can be adjusted.

8.5 Variable speed drive start

A Variable speed drive is a device that can change both frequency and voltage used by the motor. So like a soft starter but instead of adjusting the voltage only, it also has the possibility to adjust the frequency of the current at the start.

As the variable speed drive can adjust both voltage and frequency it means that it can keep the electromagnet flux inside the motor constant, so it does not lose any of the motor torque during the start. This means that it can use the nominal torque of the motor already from zero speed and at the same time it can limit the starting current of the motor to its nominal value.

This makes the variable speed drive the most versatile of all the starting methods. It also gives an additional feature to control the rotation speed of the motor. (Electrical4u)

9 1-phase induction motor

The 1-phase motor has the same design of the rotor as the 3-phase motor but the windings in the stator are a bit different. There are a number of different types of 1-phase motors but this chapter will focus on explaining on how the permanent split capacitor motor works.

Since the motor is now only fed 1-phase AC instead of the 3-phase AC, the motor can still create a magnetic field that switches direction in the motor windings, but since the motor have no phase shift it can't create the rotating magnetic field in the stator as it did on the 3-phase motor. This problem is solved by dividing the motor windings into two windings, a primary winding and a secondary winding.

On the secondary winding a capacitor is connected. By connecting the capacitor on the secondary winding, the current on the primary and secondary winding doesn't change direction at the same time. In other words it will create a phase shift close to 90 degrees between the two. This will now create a rotating magnetic field just like in the 3-phase motor but with two phases instead of three.

That means if the primary winding had the highest current value it will soon change direction and drop. Next in line will be the secondary winding that reaches its peak current and the magnetic field will move onto the secondary winding coils and then back to the primary winding coils. one can reverse the rotation of the motor by switching the capacitor to the primary windings according to Figure 17. So with only one phase the motor can still get two separate phase windings and a rotating magnetic field.

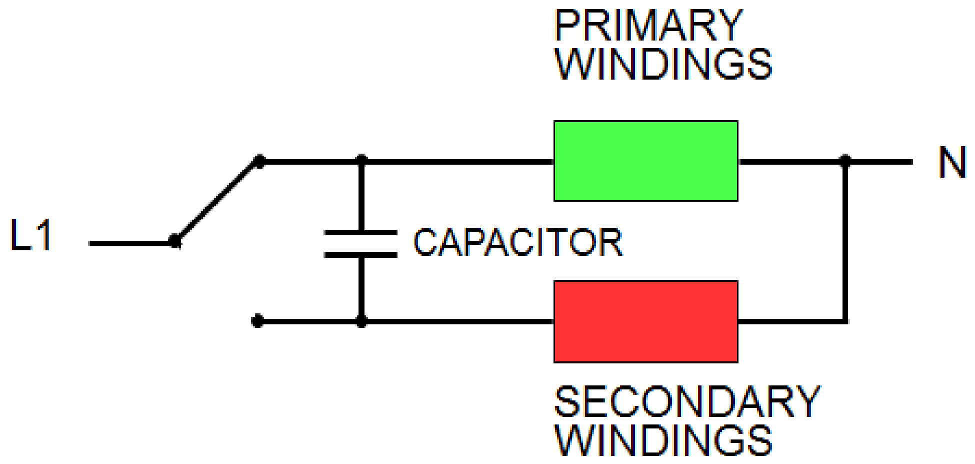


Figure 17. 1-phase induction motor winding schematic

However the rotating magnetic field will not be as strong as the one in the 3-phase motor and thus the motor will get a lower break down torque.

Other typical 1-phase motor types are, Capacitor start induction run which means the secondary windings are only used in the start. Capacitor start and run which means it will have an extra capacitor in the start compared to permanent split capacitor in order to further increase the starting torque.

As with a 3-phase motor we can also create a motor with different amount of pole pairs. It's possible to control the rotation speed of a 1-phase motor but it's seldom used nowadays.

If a 1-phase motor with speed control is wanted, the standard method is to connect the 1-phase to a variable speed drive and then connected the variable speed drive to a small 3-phase motor. (LearnEngineering)

10 Synchronous motors

All previous chapters have been about Asynchronous motors, now this chapter will explain about how Synchronous motors works.

The big difference between the two kinds of motor types is the difference in the working principle in the rotor as all motors have the same stator functioning principle. In the asynchronous motor the rotor rotated a bit slower than the rotating magnetic field from the stator which is why it's called an asynchronous motor. In the synchronous motors the rotor will rotate at the exact same speed as the rotating magnetic field from the stator.

10.1 Permanent magnet synchronous motor

A synchronous permanent magnet motor have practically same working principle of the stator as in the 3-phase asynchronous induction motor but a different rotor working principle. Instead of using a squirrel cage winding, it uses permanent magnets in the rotor.

As the stator just like in the induction motor creates a magnetic field, the magnets wants to align themselves with the magnetic field. When the magnetic field from the stator rotates, the magnets will follow and make the rotor to spin with the same speed as the rotating magnetic field.

Having the rotor spin at the same speed as the stators magnetic field is called synchronous. Therefore it is called a synchronous motor.

When starting the motor the magnetic field rotates too fast for the permanent magnets to lock themselves with the rotating magnetic field. So in order to start the motor it would need a variable speed drive. With a slower rotating magnetic field, the magnets can easily lock themselves with the stators rotating magnetic field.

To know how the variable speed drive should operate, the motor uses a resolver that tells the position of the rotor angle. Now the variable speed drive can calculate and steer the rotating magnetic field according to the rotors position.

There is also a possibility to start a permanent magnet synchronous motor direct on line but then in additions to the magnets, it would also need to integrate a squirrel cage in the rotor. These types of motors are usually referred to as hybrid permanent magnet motors.

Now the motor will just work like a 3-phase asynchronous motor until it picks up enough speed for the permanent magnets to lock themselves with the magnetic field and the motor will start to spin at the same speed as the rotating magnetic field.

There are many different types of permanent magnet motors with different rotor designs. As seen from the chart here the magnets position could either be on the rotor core surface or inside the rotor core. Each design has its pros and cons and one type could not really be compared to the other.

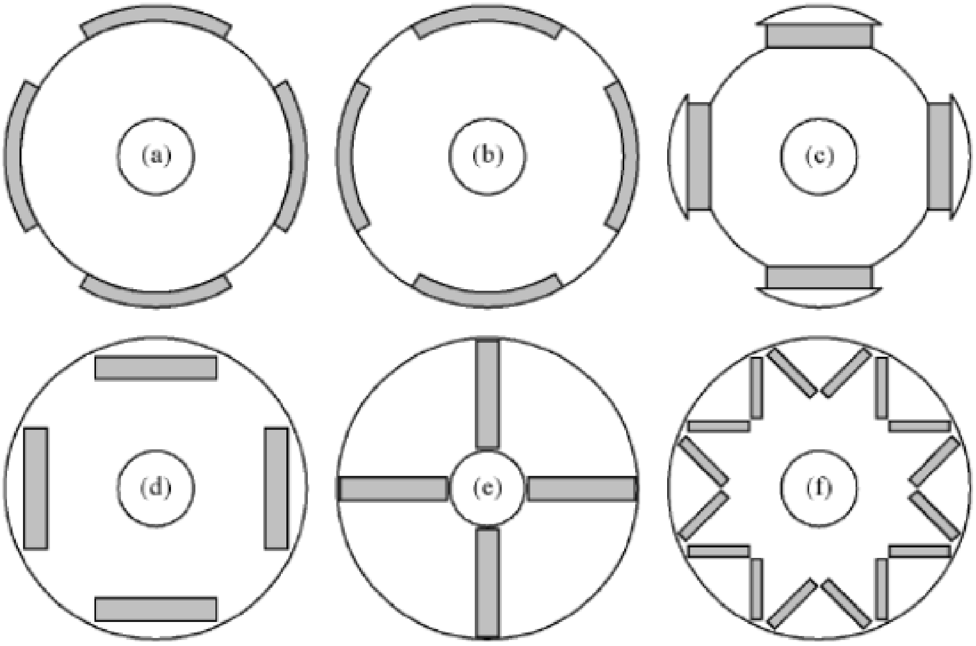


Figure 18. Different kinds of magnet positions in a rotor

One can also choose from several kinds of magnets to be used in the rotor when developing the motor. They can either be made from rare-earth magnet materials like Neodymium iron boron or Samarium cobalt or be of ferromagnetic type for example Alnico, an alloy of Aluminum, nickel and cobalt.

10.2 Synchronous reluctance motor

Same as with the permanent magnet motor, the reluctance motor have the same stator design as the induction motor but a different rotor design

The word reluctance means resistance for magnetic flux. An object that has high reluctance won't conduct a magnetic flux whereas an object that has low reluctance will conduct a magnetic flux.

Now this is used in Synchronous reluctance motors to create magnetic flux barriers and to create magnetic flux paths. As the rotor consists of air gaps with high reluctance and steel arcs with low reluctance. The magnetic flux created by the stator wants to follow the path of least reluctance so it goes through the steel barriers. Now as the magnetic field rotates, the steel barriers wants to keep the magnetic flux path intact and forces the rotor to rotate with the rotating magnetic field from the stator.

There are other kinds of reluctance motors called Switched reluctance motor, variable reluctance motor and variable reluctance stepping motor

But we will only cover the synchronous reluctance motor

When starting the motor the magnetic field rotates too fast for the rotor to lock them with the rotating magnetic field. So in order to start the motor it would need a variable speed drive. With a slower rotating magnetic field, the rotor can easily lock themselves with the stators rotating magnetic field.

There are many different designs of the rotor as can be seen in the picture below but the transverse laminated rotor shape is the most common used. There are also hybrid motors that make use of permanent magnets in the rotor to boost the effect of the motor. Those motors are called Permanent magnets assisted synchronously reluctance motors (PMaSynRM)

There is also a possibility to start a Synchronous reluctance motor direct on line but then it would need to integrate a squirrel cage with the rotor. Now the motor will just work like a 3-phase asynchronous motor until it picks up enough speed for the rotor paths to lock themselves with the magnetic field and the motor will start to spin at the same speed as the rotating magnetic field.

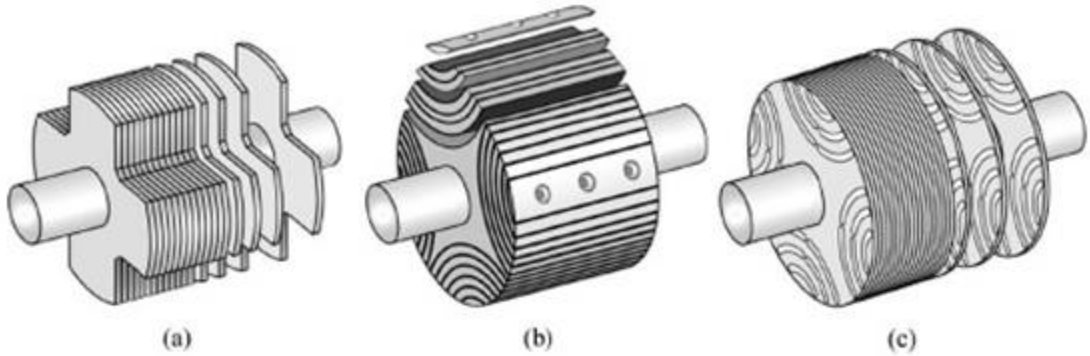


Figure 19. Different rotor designs for reluctance motors. (a) is for high speed design, (b) complicated to manufacture. (c) is electrically superior.

11 Summarize of different kinds of motors

This chapter will summarize the different motors. One of the reasons is that each motor type produces a different amount of torque compared to its size.

An example with every motor type that are all the same sizes. Now the synchronous Permanent magnet motor would be able to produce the most torque and the synchronous reluctance motor would produce 2^{nd} most torque and the induction motor would produce the least amount of torque

Motor efficiency also falls in the same order. So the permanent magnet and reluctance motor would be more efficient than the induction motor

Over all the synchronous reluctance motor is probably the most environmental friendly of them all as it can be made with very high efficiency and doesn't contain any magnets. The productions of magnets themselves are not so environmentally friendly.

The best thing about the induction motor is that it can be started direct on line without a variable speed drive that makes operation very easy. For a short overview of different motors, check Appendix 1.

12 Final product

After having gathered and gone through all the theoretical text, I simplified the text so a non-engineer would understand it and made a comprehensive PowerPoint with all the information. Pictures taken from the internet and books were added to help explain concepts that were hard to understand with just text. I also made some simple animations with the tools that were available in PowerPoint. The pictures I choose for the PowerPoint were merely suggestions of what would be in the final release of the PowerPoint that would be uploaded to the company's intranet, since the company has to use their own official pictures instead of those that I had taken from the internet and various books.

13 Discussion

This was an interesting final thesis project since it involved a lot of theory but not much practical work. I had the theory knowledge while my supervisor had the pedagogical experience so that was a nice teamwork combination when working on simplifying the text that was added to the PowerPoint. The most problematic problem was trying to explain a hard concept in an easy way such as how the rotor can rotate with the help of electricity, the argument was that I have to come up with a simpler explanation, my counterargument was that there was no way to make it anymore simpler.

14 Reference list

Figure 3. https://www.indiamart.com/proddetail/electrical-motor-lamination-12945311633.html

Figure 4. http://www.ticgalicia.com/2016/06/el-motor-de-jaula-de-ardilla-la-base-de.html

Figure 5.

http://www.brighthubengineering.com/diy-electronics-devices/43723-how-are-squirrel-cage-induction-motors-constructed/

Figure 6. https://socratic.org/questions/what-is-the-right-hand-rule

Figure 7. http://www.ece.neu.edu/fac-ece/nian/mom/electromagnets.html

Figure 8. https://www.electrical4u.com/fleming-left-hand-rule-and-fleming-right-hand-rule/

Figure 12. http://www.solidfonts.com/3-phase-motor-wiring-star-or-delta/

Figure 19. https://www.researchgate.net/publication/224110912_Synchronous_Reluctance_Motor_With_Form_Blocked_Rotor

HyperPhysics

http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html [Accessed 16.05.2017]

Electrical4u

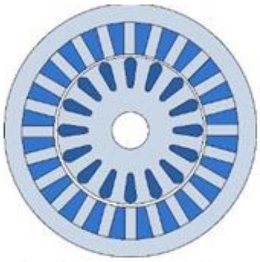
https://www.electrical4u.com [Accessed 16.05.2017]

LearnEngineering

http://www.learnengineering.org [Accessed 16.05.2017]

McPherson & Laramore, (1990). *An introduction to electrical machines and transformers, Second edition.*

Appendix 1



Induction motor

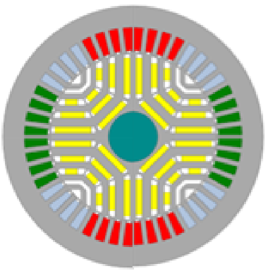
- Familiar and well-proven technology
- Robust
- Starts DOL
- Easy to use and maintain

- Lower efficiency at lower speeds
- Slip losses in rotor heats up bearings
- Torque only in asynchronous operation
- High speed accuracy difficult without sensors

SynRM

- High energy efficiency
- High power density
- Accurate speed control even without sensors
- Low bearing temperatures and longer bearing lifetime
- No REE – just air
- Easy to use and maintain

- Lower power factor and higher current demand (handled by VSD)
- Only for VSD operation



PMaSynRM motor

- Very high energy efficiency
- Excellent power density
- Accurate speed control even without sensors
- Low bearing/winding temperatures
- Easy to tailor design performance
- No REE
- High PF and great field weakening range

- Demagnetization risk
- Only for VSD operation

Typical PM motor

- Very high energy efficiency
- Compact
- Synchronous speed
- Low speed bearing temperatures and longer bearing lifetime

- High cost
- Only for VSD operation
- Rare-earth magnets
    - Uncertain cost variation
    - Demagnetization risk
    - More difficult service due to forces from magnets

Source: ABB intranet.