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KTH Electrical Engineering

# HYBRID VEHICLE DRIVES

## System components
## –
## Electrical machines and drives

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# Contents

# 1 Drive systems

In any vehicle – whether it is a conventional, hybrid or an electric vehicle – several electrical drive systems can be found. They can for example be used for the actual propulsion of the vehicle, to drive a fan or to position the seats. In this part of the course, we will study the basics of these drive systems and also the components involved.
In general, an electric drive system consists of a motor and a motor controller. The controller consists of a power module containing mainly the power electronic switches and a control module with micro-processors and necessary software, see Figure 1.

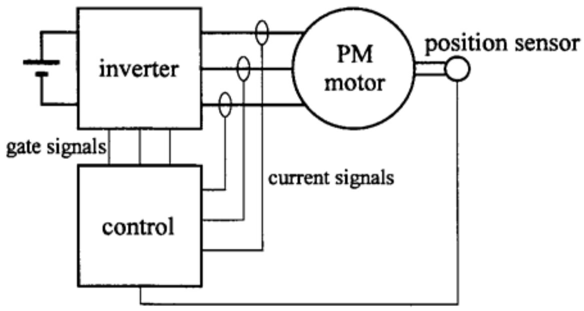


*Figure 1 Main components of an electrical drive system.*

## 1.1 Requirements on the drive system

Current efforts to develop electric and hybrid vehicles attempt to cover a wide range of different applications. There are small city cars, family sized commuter cars, various sizes of city buses, distribution vans and trucks and special vehicles such as garbage trucks, airport buses etc. The drive trains required for all these vehicles will of course be different, but there is a common basic structure as illustrated in Figure 2. The three main parts of a drive train is power supply, electric drive system and mechanical transmission. This functional structure remains even if the concept is extended to drive trains with two or four motors, parallel hybrids or other solutions.

It is important to chose the optimum drive train for each type of vehicle. Essential parameters are usually torque characteristic, efficiency, size and weight, reliability and cost. Influence on and sensitivity due to the environment are also very important. Factors as voltage level, type of transmission and installation requirements have also great influence on the electric drive system design. Therefore, development of an optimum drive train requires a correct specification and a close, interactive co-operation between vehicle development and the drive train development.

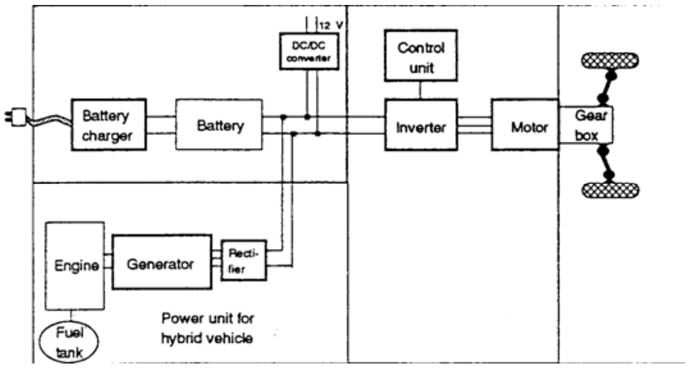


*Figure 2 Typical drive train.*

## 1.2 Possible types of electric motors

Electric motors can be DC type or AC type. The DC series motors were used in a number of prototype EVs in the 1980s and prior to that due to their developed status and ease of control, see Figure 3. However, the size and maintenance requirements of DC motors are making their use obsolete, not just in the automotive industry, but in all motor drive applications. The more recent EVs and HEVs employ AC and brushless motors, which include induction motors, permanent magnet motors, and switched reluctance motors.

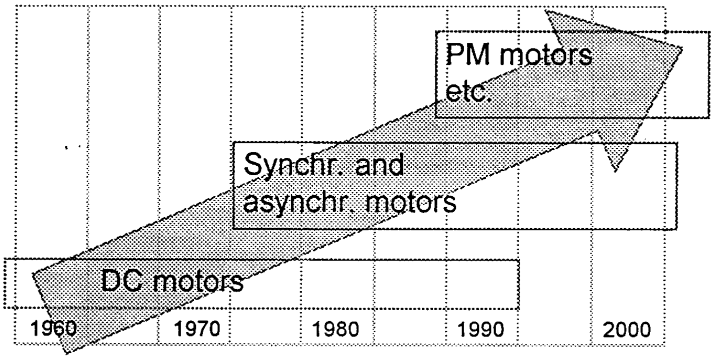


*Figure 3 Variable speed drives development.*

The performance of an electric drive system depends basically on the type of motor used provided the motor controller is properly adapted. An evaluation of various type of drive systems is therefore mainly a question of comparing different motors.
The diagram in the Figure 4 gives a brief structure of electric motor types which could be used in vehicle drive systems. Theoretically, all AC motors could have the same stators with three-phase windings while the rotors have to be different. They could also be fed from the same type of inverter but with different control software. Each of these motors has its advantages and disadvantages.
The major advantages with the DC motors are that they are easy to control and the motor controllers become fairly in-expensive. The disadvantages are that the motors, due to commutation restrictions, are large and heavy and also expensive. The efficiency is also relatively low.

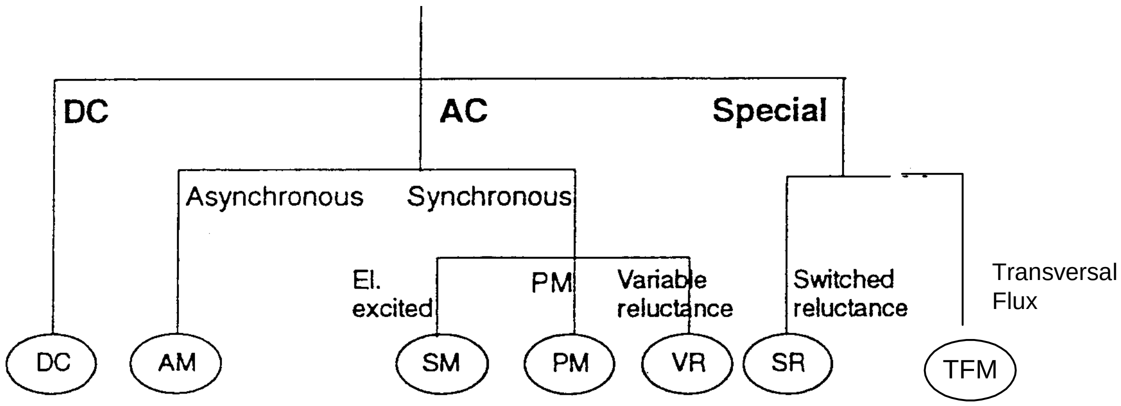


*Figure 4   Family tree of electrical machines.*

The squirrel cage asynchronous motor is a robust, low cost work horse. It can be operated at high rpm which consequently will reduce its size. It has no significant draw-backs except for that it requires higher currents due to lower power factor. The efficiency is higher than for DC motors but lower compared with synchronous motors.
The separately excited synchronous motor has an excitation winding in the rotor, which can be fed with the necessary DC current via sliprings or from a brushless exciter. It has very good torque characteristic and its is comparable with the asynchronous motor in size. The efficiency is fairly high but so is also the cost.
The permanent magnet synchronous motor is a high performance motor. It has high torque vs. weight ratio and high efficiency. Its major disadvantage has, so far, been high costs for the permanent magnets. The design and the properties of this type of motor will be further presented later.
The synchronous reluctance motor, also called variable reluctance motor, is similar to the PM motor in that sense that it has no rotor winding. The rotor salience concentrates the magnetic flux to the pole regions so that a torque can be transferred. Like the asynchronous motor, this motor is excited from the stator currents, and it has also similar properties. It has the advantage of better efficiency compared with the asynchronous motor but it becomes somewhat larger.
Special motors as e. g. switched reluctance motors, permanent magnet step motors and transversal flux motors can also be used for vehicle applications. Some of them can be suitable as low rpm wheel motors. However, they require special motor controllers and it is difficult to find any synergy with existing electric drive systems. They will not play any significant part during the next 10 years.
For each specific type of vehicle there are some alternative motors to chose. Several factors as those mentioned earlier must be considered. There is nothing like a universal motor concept for electric and hybrid vehicles, but a very promising high performance motor is the PM motor. Figure 5 shows a photograph that gives that gives the general outline of such a motor.

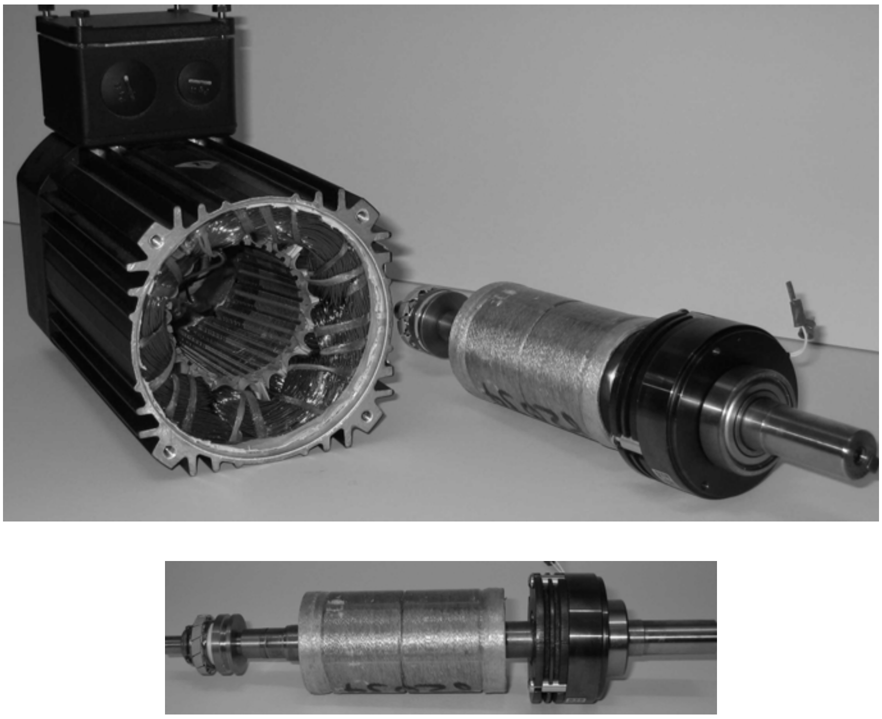

*Figure 5   Photograph of a PM motor.*

# 2 Basic principles of electromechanical energy conversion

The basic objective for any electrical machine is to produce a torque. The direction of the torque with respect to rotational direction will determine whether the machine is operating as a motor or a generator, see Figure 6. All electrical machines can operate both as motors and generators, it is merely a question of power direction.
In this chapter the basic principles of electromechanical energy conversion will be described by using the DC machine as an example. The machine type is very old and do have disadvantages due to its mechanical design, but it is easy to use for a basic understanding of the energy conversion. Furthermore, if you study the electrical motors used in a modern car, the majority is still DC motors due to their low price and simplicity to speed control.

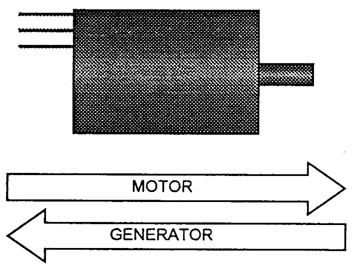


*Figure 6 Motor and generator mode.*

## 2.1 Torque production and induced voltage

Torque, or force, is normally produced by an interaction between current and magnetic flux. In a real electrical machine this is usually not physically true because the conductors are situated in slots and will therefore not be penetrated by the magnetic flux. The force is then actually created on the iron just like "a magnet attracts a piece of iron". However, regardless how the force is actually created inside the machine, it is sufficient to calculate the force from the interaction between current and magnetic flux.
The conductor in Figure 7 carries a current $I$ and is situated in a magnetic field with the strength $B$. The resulting force becomes

$$F = BIL \tag{2.1}$$

Where $L$ is the length of the conductor subjected to the magnetic field.

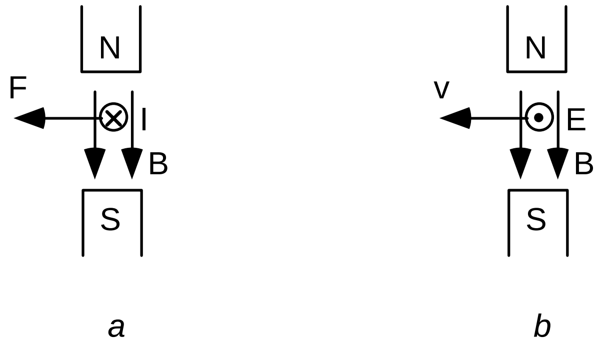


*Figure 7 Torque production and induced voltage.*

If the conductor is moving in the magnetic field, there will be an induced voltage $e$ according to

$$e = BvL \qquad (2.2)$$

where $v$ is the velocity.

## 2.2 The brushed DC machine

This type of motor is very widely used in applications such as portable tools, toys, electrically operated windows in cars, and small domestic appliances such as hair dryers, even if they are AC mains powered (but then referred to as the "universal motor"). However, they are also still used as traction motors, although the other types of motor considered later in this course are becoming more common for this application.
This chapter will explain the basic principles of the DC machine, which indeed is not an easy task. There are some pictures inserted to support the written explanations but still they are not as good as moving pictures would be. However, Chalmers has made available on the web animations of how the electrical machines work and it is strongly recommended that they are used as a complement to the description given below. The animations are found at:

http://www.medialab.chalmers.se/mdt/elkraft2001/

### 2.2.1 Basic operation

The classical DC electric motor is shown in Figure 8. It is a DC motor, equipped with permanent magnets and brushes. This simplified motor has one coil, and the current passing through the wire near the magnet causes a force to be generated in the coil. The current flows through brush X, commutator half ring A, round the coil, and out through the other commutator half ring B and brush Y (XABY). On one side (as shown in the diagram) the force is upwards, and in the other the force is downwards, because the current is flowing back towards the brushes and commutator. The two forces cause the coil to turn. The coil turns with the commutator, and once the wires are clear of the magnet the momentum carries it on round until the half rings of the commutator connect with the brushes again. When this happens the current is flowing in the same direction relative to the magnets, and hence the forces are in the same direction, continuing to turn the motor as before. However, the current will now be flowing through brush X, half ring B, round the coil to A and out through Y, so the current will be flowing in the opposite direction through the coil (XBAY).
The commutator action ensures that the current in the coil keeps changing direction, so that the force is in the same direction, even through the coil has moved.
Clearly, in a real DC motor there are many refinements over the arrangement of Figure 8. The most important of these are as follows.
• The rotating wire coil, often called the armature, is wound round a piece of iron, so that the magnetic field of the magnets does not have to cross a large air gap, which

would weaken the magnetic field.
- More than one coil will be used, so that a current-carrying wire is near the magnets for a higher proportion of the time. This means that the commutator does not consist of two half rings but several segments, two segments for each coil.
  Each coil will consist of several wires, so that the torque is increased (more wires, more force).
- More than one pair of magnets may be used, to further increase the turning force.

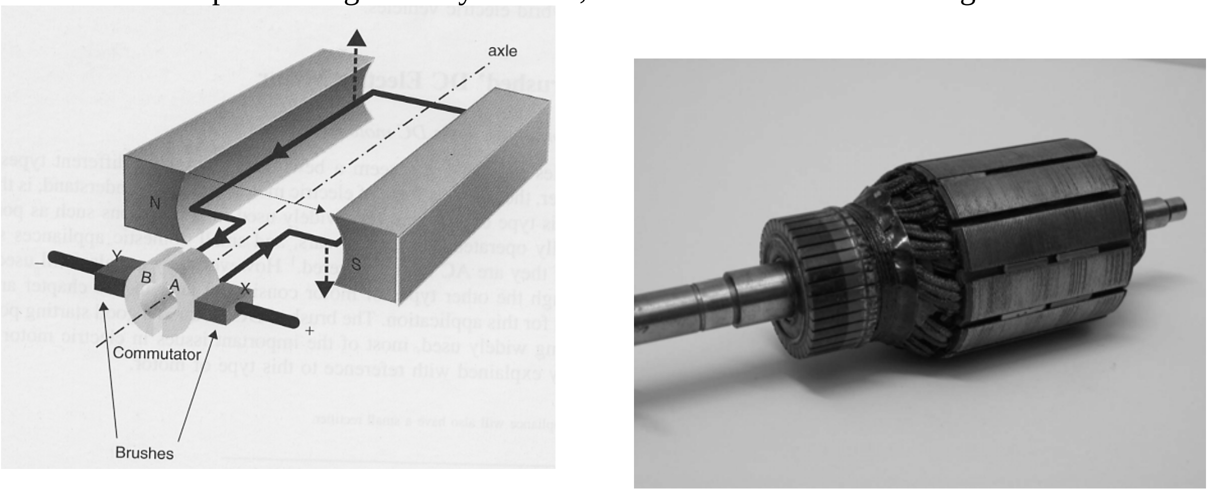


*Figure 8 DC machine. Schematic cross-section with one coil (left); real rotor winding with commutator (right).*

The picture to the right in Figure 8 shows a real rotor winding and commutator. The winding is made of several series connected coils that are placed in slots. The ends of each coil is connected to segments on the commutator that are displaced by one half turn. The sliding brushes will then always connect to the winding in such a way that conductors under pole is connected to one brush and conductors under the other pole is connected to the other brush. The commutator will hence act as a “rotating rectifier”.

### 2.2.2 Torque speed characteristics

If a wire in an electric motor has a length *L*, carries a current *i* and is in a magnetic field of strength $B$, then the force on the wire according to (2.1) is $F = BIL$.
If the radius of the coil is *r*, and the armature consists of *n* turns, then the motor torque *T* is given by the equation:

$$T = 2nrBIL \tag{2.3}$$

The term 2*BLr* = *B* x area can be replaced by $\Phi$, the total flux passing through the coil. This gives:

$$T = n\Phi I \tag{2.4}$$

However, this is the peak torque, when the coil is fully in the flux, which is perfectly radial. In practice this will not always be so. Also, it does not take into account the fact that there may be more than one pair of magnetic poles. So we use a constant $K_m$, known as the motor constant, to connect the average torque with the current and the magnetic flux. The value of $K_m$ clearly depends on the number of turns in each coil, but also on the number of pole pairs, and other aspects of motor design. Thus we have:

$$T = K_m \Phi I \tag{2.5}$$

We thus see that the motor torque is directly proportional to the rotor (also called armature) current *I*. However, what controls this current? Clearly it depends on the supply voltage $E_s$ to the motor. It will also depend on the electrical resistance of the armature coil $R_a$. As the motor turns the armature will be moving in a magnetic field. This means it will be working as a generator or dynamo. If we consider the basic machine and consider one side of the coil, the voltage generated is expressed by the basic equation:

$$E_b = BLv \tag{2.6}$$

This equation is the voltage form of (2.1). The voltage generated is usually called the back EMF, hence the symbol $E_b$,. It depends on the velocity $v$ of the wire moving through the magnetic field. To develop this further, the velocity of the wire moving in the magnetic field depends on $\omega$ the angular velocity and $r$ the radius according to the simple equation $v = r\omega$ . Also, the armature has two sides, so (2.6) becomes

$$E_b = 2BLr\omega \tag{2.7}$$

However, as there are many turns, we have:

$$E_b = 2nrBL\omega \tag{2.8}$$

This equation should be compared with (2.3). By similar reasoning we simplify it to an equation like (2.5). Since it is the same motor, the constant $K_m$ can be used again, and it obviously has the same value. The equation gives the voltage or back EMF generated by the dynamo effect of the motor as it turns.

$$E_b = K_m \Phi \omega \tag{2.9}$$

This voltage opposes the supply voltage $E_s$ and acts to reduce the current in the motor. The net voltage across the armature is the difference between the supply voltage $E_s$ and the back EMF $E_b$,. Neglecting the inductance of the armature winding, the equation for the armature circuit is

$$E_s = E_b + R_a I = K_m \Phi \omega + R_a I \tag{2.10}$$

The equivalent electrical circuit is given in Figure 9

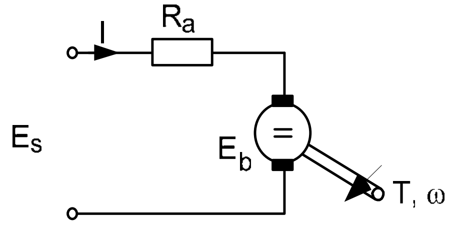


*Figure 9 Electrical equivalent circuit of a DC machine.*

The armature current can be found from:

$$I = \frac{E_s - E_b}{R_a} = \frac{E_s}{R_a} - \frac{K_m \Phi}{R_a}\omega \tag{2.11}$$

This equation shows that the current falls with increasing angular speed.
If we substitute (2.11) into (2.5) we get the equation connecting the torque and the rotational speed.

$$T = \frac{K_m \Phi E_s}{R_a} - \frac{\left(K_m \Phi\right)^2}{R_a}\omega \tag{2.12}$$

This important equation shows that the torque from this type of motor has a maximum value at zero speed, when stalled, and it then falls steadily with increasing speed. In this analysis we have ignored the losses in the form of torque needed to overcome friction in bearings, and at the commutator, and windage losses. This torque is generally assumed to be constant, which means the general form of (2.12) still holds true, and gives the characteristic graph of Figure 10.

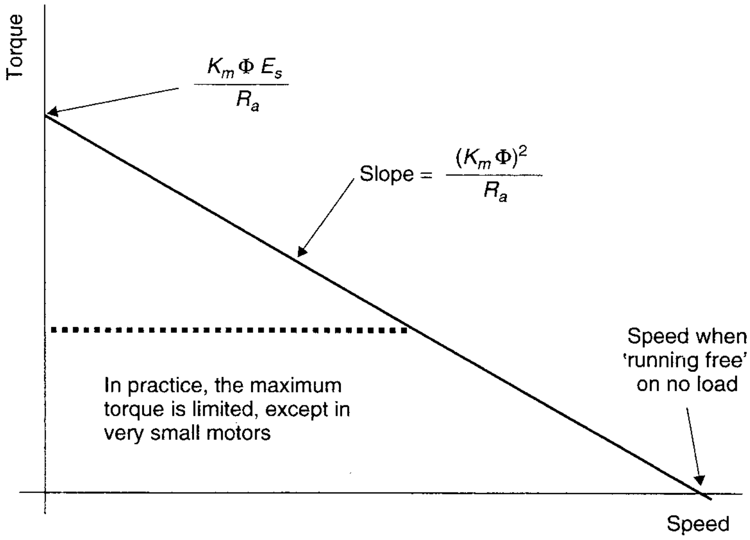


*Figure 10 Torque/speed graph for a brushed DC motor and constant supply voltage.*

When the DC motor is used in a variable speed system with a power converter, (2.12) can be rewritten to show the speed/torque relation instead

$$\omega = \frac{E_s}{K_m\Phi} - \frac{R_a}{(K_m\Phi)^2}T \qquad (2.13)$$

The equation indicates that the speed is closely related to the so called no-load speed $\omega_{n.l.} = E_s/K_m\Phi$ and when the torque increases, the speed will drop proportionally.

EXAMPLE

A DC motor for the propulsion of a small vehicle such as a go-kart might have the following data given in its specification:

• maximum power approx. 5 kW

• motor speed = 70 rpm/V

• armature resistance = 0.016 Ω

The motor speed information refers to the no load speed.

By converting the given motor speed specification to rad/s, the motor constant becomes

$$K_m\Phi = \frac{1}{2\pi \cdot 70/60} = 0{,}136 \ \text{vs/rad} \qquad (2.14)$$

If this motor were to be run off a fixed 24 V supply equation (2.12) for this motor would be:

$$T = 205 - 1{,}16\omega \qquad (2.15)$$

since $R_a$ is given as 0,016 Ω.. However, this would mean an initial, zero speed, torque of 205 Nm. This is a huge figure, but may not seem impossibly large until the current is calculated. At zero speed there is no back EMF, and so only this armature resistance $R_a$ opposes the 24 V supply, and so the current would be:

$$I = \frac{E_s}{R_a} = \frac{24}{0{,}016}1500\,\text{A} \qquad (2.16)$$

This is clearly far too large a current. A reasonable limit on current for this motor would be 250 A. We can use this information, and equation (6.4) to establish the maximum torque as:

$$T = K_m\Phi I = 0.136 \cdot 250 = 34\,\text{Nm} \qquad (2.17)$$

To limit the current and therby the torque, a series resistance could be used.

### 2.2.3 Controlling the brushed DC motor

Figure 10 and equation (2.12) show us that the brushed DC motor can be very easily controlled. If the supply voltage $E_s$ is reduced, then the maximum torque falls in proportion, and the slope of the torque/speed graph is unchanged. In other words any torque and speed can be achieved below the maximum values. As shown earlier in the course, by using power electronic converters the supply voltage can be controlled simply and efficiently.
However, reducing the supply voltage is not the only way of controlling this type of motor. In some cases we can also achieve control by changing the magnetic flux $\Phi$. This is possible if coils rather than permanent magnets provide the magnetic field. If the magnetic flux is reduced then the maximum torque falls, but the slope of the torque/speed graph becomes flatter. Thus the motor can be made to work at a wide range of torque and speed. This method is sometimes better than simply using voltage control, especially at high speed/low torque operation, which is quite common in electric vehicles cruising near their maximum speed. The reason for this is that the iron losses which are associated with high speeds and strong magnetic fields, can be substantially reduced. So the brushed DC motor is very flexible as to control method, especially if the magnetic flux $\Phi$ can be varied.

### 2.2.4 Motor efficiency

The major sources of loss in the brushed DC electric motor are the same as for all types of electric motor, and can be divided into four main types, as follows.
Firstly there are the copper losses. These are caused by the electrical resistance of the wires (and brushes) of the motor. This causes heating, and some of the electrical energy supplied is turned into heat energy rather than electrical work. The heating effect of an electrical current is proportional to the square of the current:

$$P = RI^2 \tag{2.18}$$

However, we know that the current is proportional to the torque $T$ provided by the motor, so we can say that:

$$\text{Copper losses} = k_c T^2 \tag{2.19}$$

where $k_c$ is a constant depending on the resistance of the brushes and the coil, and also the magnetic flux $\Phi$. These copper losses are probably the most straightforward to understand and, especially in smaller motors, they are the largest cause of inefficiency.
The second major source of losses is called iron losses, because they are caused by magnetic effects in the iron of the motor, particularly in the rotor. There are two main causes of these iron losses, but to understand both it must be understood that the magnetic field in the rotor is continually changing. As the rotor turns around one turn, a point on the rotort will pass a north pole, then a south pole, and then a north pole, and so on. As the rotor rotates the magnetic field supplied by the magnets may be unchanged, but that seen by the turning rotor is always changing. Any one piece of iron on the rotor is thus effectively in an ever-changing magnetic field. This causes two types of loss. The first is called 'hysteresis' loss, and is the energy required to continually magnetise and demagnetise the iron, aligning and re-aligning the magnetic dipoles of the iron. In a good magnetically soft iron this should be very small, but will not be zero. The second iron loss results from the fact that the changing magnetic field will generate a current in the iron, by the normal methods of electromagnetic induction. This current will result in heating of the iron. Because these currents just flow around and within the iron rotor they are called 'eddy currents'. These eddy currents are minimised by making the iron rotor, not out of one piece, but using thin sheets all bolted or glued together. Each sheet is separated from its neighbour by a layer of paint. This greatly reduces the eddy currents by effectively increasing the electrical resistance of the iron.
The iron losses are difficult to estimate due to the non-linearity of the iron.

Generally, iron loss calculations are conducted with various material constants based on experience, measurements and correction factors. A typical iron lamination used in electrical machines is the DK70 with a thickness of 0,5mm. For this material, the total iron losses i.e. hysteresis and eddy-current losses, can be calculated as

$$P = k_h B_{\max}^{\nu_h} f + k_e B_{\max}^{2} f^{\nu_e} \text{ [w/kg]} \tag{2.20}$$

where $B_{max}$ is the peak value flux density $f_s$ is the electrical frequency. Typical values at $B_{max}$ 1,2 T are $k_h$ = 0,04, $v_h$ = 1,6, $k_e$ = 0,0004 and $v_e$ = 1,9.

The third category of loss is that due to friction and windage. There will of course be a friction torque in the bearings and brushes of the motor. The rotor will also have a wind resistance, which might be quite large if a fan is fitted to the rotor for cooling. The friction force will normally be more or less constant. However, the wind resistance force will increase with the square of the speed and hence the total power becomes

$$P_{fw} = T_f \omega + k_\omega \omega^3 \tag{2.21}$$

where $T_f$ is the friction torque, and $k_\omega$ is a constant depending mainly on the size and shape of the rotor, and whether or not a cooling fan is fitted.

Finally, there are constant losses that occur even if the motor is totally stationary, and vary neither with speed or torque, e.g. losses due to the switching in the power converter. The letter C is used to designate these losses.

It is useful to bring together all these different losses into a single equation that allows us to model and predict the losses in a motor. When we do this it helps to combine the terms for the iron losses and the friction losses, as both are proportional to motor speed. Although we have done this for the brushed DC motor, the result is a good approximation for all types of motor,

$$P_{tot} = k_c T^2 + k_1 \omega + k_2 \omega^2 + k_\omega \omega^3 \tag{2.22}$$

where $k_1$and $k_2$ are recalculated values from (2.20).

However, it is usually the motor efficiency that is required which is obtained according to

$$\eta_m = \frac{P_{out}}{P_{in}} = \frac{T\omega}{T\omega + k_c T^2 + k_1 \omega + k_2 \omega^2 + k_\omega \omega^3} \tag{2.23}$$

Suitable values for the constants in this equation can usually be found by experimentation, or by regression using measured values of efficiency.

It is useful to plot the values of efficiency on a torque speed graph, giving what is sometimes known as an efficiency map for the motor, which gives an idea of the efficiency at any possible operating condition, see Figure 11 for a typical example.

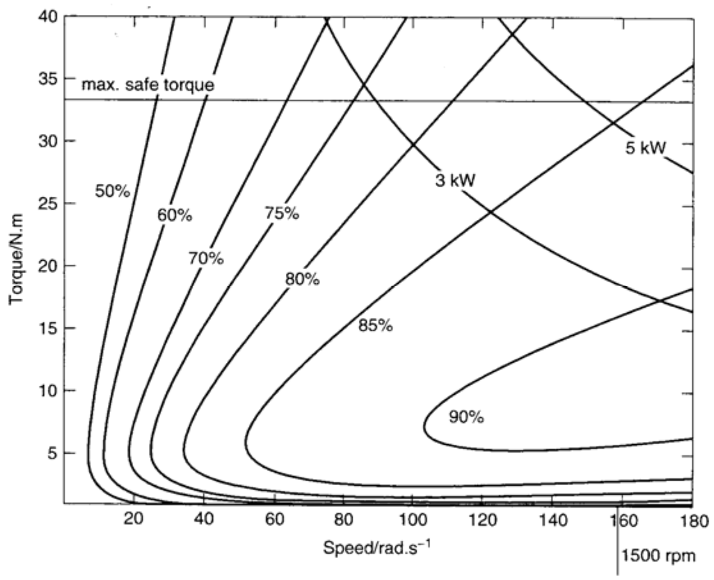


*Figure 11 Efficiency map for a typical permanent magnet DC motor with brushes.*

### 2.2.5 Motor losses and motor size

While it is obvious that the losses in a motor affect its efficiency, it is not so obvious that the losses also have a crucial impact on the maximum power that can be obtained from a motor of any given size. The power produced could be increased by increasing the supply voltage, and thus the torque. Clearly, there must be a limit to this, the power cannot be increased to infinity. One might suppose the limiting factor is the voltage at which the insulation around the copper wire breaks down, or some such point. However, that is not the case. The limit is in fact mainly temperature-related. Above a certain power the heat generated as a result of the losses become too large to be conducted, convected and radiated away, and the motor overheats. An important result of this is that the key electric motor parameters of power density and specific power, being the power per unit volume and the power per kilogram mass, are not controlled by electrical factors so much as how effectively the waste heat can be removed from the motor.

This leads to a very important disadvantage of the classical brushed DC motor. In this type of motor virtually all the losses occur in the rotor at the centre of the motor. This means that the heat generated is much more difficult to remove. In the motors to be considered in later sections the great majority of the losses occur on the stator, the stationary outer part of the motor. Here they can much more easily be removed. Even if we stick with air-cooling it can be done more effectively, but in larger motors liquid cooling can by used to achieve even higher power density.

This issue of motor power being limited by the problem of heat removal also explains another important feature of electric motors. This is that they can safely be driven well in excess of their rated power for short periods. For example, if we take a motor that has a rated power of 5 kW, this means that if it is run at this power for about 30 minutes, it will settle down to a temperature of about 80°C, which is safe and will do it no harm. However, being fairly large and heavy, a motor will take some time to heat up. If it is at, say, 50°C, we can run it in excess of 5 kW, and its temperature will begin to increase quite rapidly. However, if we do not do this for more than about 1 minute, then the temperature will not have time to rise to a dangerous value. Clearly this must not be overdone, otherwise local heating could cause damage, nor can it be done for too long, as a dangerous temperature will be reached. Nevertheless, in electric vehicles this is particularly useful, as the higher powers are often only required for short time intervals, such as when accelerating.

## 2.3 Electric machines as brakes

A drive system for a vehicle is normally required to operate in all four quadrants of the torque-speed plane, as shown in Figure 12. The motor drives the vehicle in the forward direction in quadrant 1, and in the reverse direction in quadrant 3. In both of these quadrants, the average power is positive and flows from the motor to the mechanical side. In order to brake the vehicle electrically, it is necessary to operate the system in the regenerative braking mode, where the direction of power is reversed so that it flows from the mechanical side into the electrical. In quadrant 2, the speed is positive but the torque produced by the motor is negative. In quadrant 4, the speed is negative and the motor torque is positive.

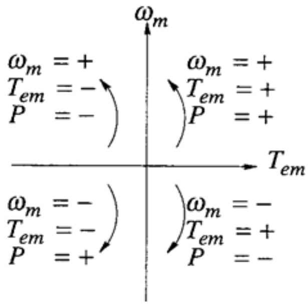


*Figure 12 Operating modes.*

The ability of an electrical motor to convert mechanical to electrical power is easy to understand in the case of the classical DC motor with brushes, but the broad principles apply to all motor types.

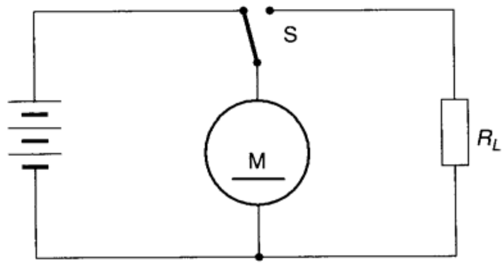


*Figure 13 Motor circuit with resistor for dynamic braking.*

Consider Figure 13. A DC motor is connected to a battery of negligible internal resistance, and voltage $E_s$. It reaches a steady state, providing a torque $T$ at a speed ω. Suppose the switch S is now moved over to the right. The motor will continue to move at the same angular speed. The induced voltage applied to the resistor $R_L$ in series with the resistance of the rotor coil (armature) gives a current of

$$I = \frac{K_m \Phi \omega}{R_a + R_L} \tag{2.24}$$

This current will be flowing out of the motor, and will result in a negative torque. The value of this torque will still be given by the torque equation. So, the negative torque, which will slow the motor down, will be given by

$$T = -\frac{\left(K_m \Phi\right)^2 \omega}{R_a + R_L} \tag{2.25}$$

We thus have a negative torque, whose value can be controlled by changing the resistance $R_L$. The value of this torque declines as the speed m decreases. So, if $R_L$ is constant we might expect the speed to decline in an exponential way to zero.

This way of slowing down an electric motor, using a resistor, is known as dynamic braking. Note that all the kinetic energy of the motor (and the vehicle connected to it) is ultimately converted into heat, just like normal friction brakes.

If the resistor of Figure 13 was replaced by a battery and power converter, then we would have a system known as regenerative braking. The converter unit is then able to control the armature current to a desired level depending on the braking effort needed.

## 2.4 Basic relations

The torque that a normal electrical machine with cylindrical rotor is able to produce is very much related to the levels of magnetic flux and current that can be handled inside the

machine. For the magnetic field which is conducted by iron laminations a reasonable limit is 1 – 1,5 T. For higher levels, the iron will saturate and the iron losses will increase substancially. The limit for the current is more a design problem. The more current that is put into a given size of a motor, the more losses will have to be dissipated. So the tolerable current level very much depends on the cooling method. Still, to get a figure of the current loading it is possible to state the *linear current loading,* which is a measure that corresponds to the amount of current that is flowing in the motor per length circumferintially.
In Figure 14, let us assume that we have a magnetic flux that is radially directed and of equal magnitude along the circumference,$B_{max}$. It is further assumed that the current is carried in conductors that are “smeared” around the surface in such a way that there is equal amount of current per length circumference; the linear current loading $A$ is uniform.
Conductors adjacent to the north pole carry current in one direction and of course the other conductors carry current in the opposite direction. The total torque can then be expressed as,

$$T = F_{tot}\frac{D}{2} = B_{\max} I_{tot} L\frac{D}{2} = B_{\max}\cdot A\cdot \pi D\cdot L\frac{D}{2} = 2V_r\cdot B_{\max} A \qquad (2.26)$$

where $F_{tot}$ is the total force on all conductors, $D$ the airgap diameter and $L$ the axial length and $V_r$ the active airgap volume.
In words this means that the torque that a machine can produce is closely related to its rotor volume (and of course the cooling arrangements).
The power that a machine can produce is

$$P = T\omega = 2B_{\max} A\cdot V_r\omega \qquad (2.27)$$

or

$$V_r = \frac{P}{2B_{\max} A\cdot\omega} \qquad (2.28)$$

i.e. the for a given power, the rotor volume and thereby the motor size will decrease inversely to the motor speed. On the other hand, the speed of the wheels of the vehicle is given so the reduced size that can be obtained by using a high-speed motor is counteracted by the gearbox that will be needed for the complete drive system.

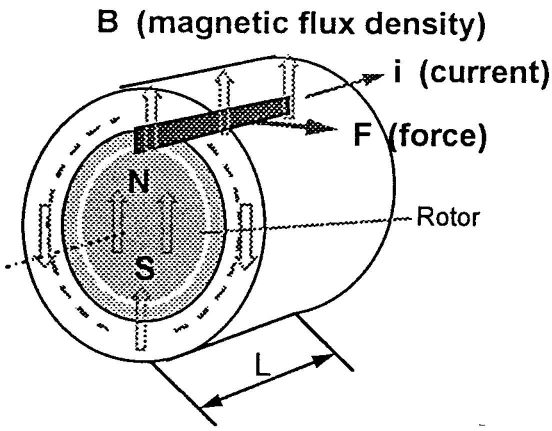


*Figure 14 Torque production in an electric motor.*

## 2.5 Machine structures

So far the classical DC machine with commutator has been used to exemplify the basics of electrical machines. The motor type is sitll widely used but especially when it comes to larger machines, the dominant types used today are AC machines. Among them the most promising type is the permanent magnet AC machines and it will be described in chapter 3.

Electrical machines can be designed in a variety of shapes and they are often referred to depending on the direction of magnetisation.

### 2.5.1 Radial flux

The previous DC machine has got a magnetisation that runs radially, it is a standard radial flux machine. If the magnets would be moved to the rotor and the electrical winding to the stator, there would be no need for a commutator any longer as the alternating current that flows in the winding could now be supplied from an AC source; it would become an AC machine. As the rotor is inside, the machine is referred to as an inner rotor machine. To have the magnets on the rotor, i.e. the inner part, is favourable due to thermal aspects. As there is no winding on the rotor there will be now copper losses to dissipate from the rotor. Furthermore, as there is a constant magnetisation on the rotor there will be no iron losses either on the rotor, at least at a first glance. Due to the switchings of power electronics, there can still be losses produced both in the magnets and the iron.
In some cases it is preferable to have the stator inside and the rotor outside and then the machine is referred to as an outer rotor machine, Figure 15.

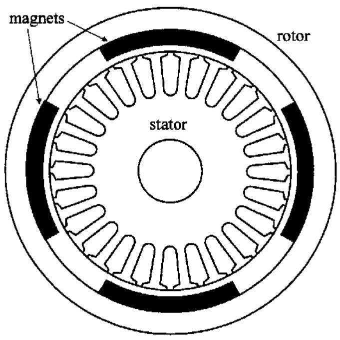


*Figure 15 Cross section of a 4 pole outer rotor pm machine.*

### 2.5.2 Axial flux

An electrical machine can also have its magnetisation in an axial direction, Figure 16. The axial flux machines are often suited for high torque and relatively low speed applications as direct drives or in-wheel drive of an electric vehicle. However axial flux machines have also been used in a high speed flywheel application. To increase the torque, with maintained induction and current loading, the outer diameter in relation to the inner diameter is increased. The axial length is not effected, since the thickness of the stator and the rotor backs are mainly determined by the number of poles. These types of machines tend therefore to have a much larger diameter to axial length ratio and consequently a high pole number. There are several topologies of this concept of which the Torus machine is one of the more interesting topologies, see Figure 16.

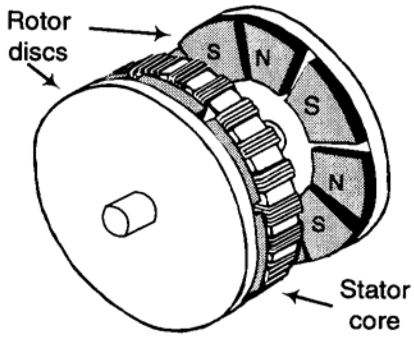


*Figure 16   Axial flux machine, "Torus".*

The Torus machine is an axial flux machine having two rotor disks and a strip wound stator core. The stator winding is a toroidal winding uniformly wrapped around the core. The stator winding has extremely short end-windings and both sides of the stator are used for torque production i.e. the material is efficiently used. The stator core can be constructed with iron powder or without the presence of iron. All designed Torus machines that are presented in the literature are of the type airgap-wound type i.e. no stator teeth and have therefore normally low inductances. Since they are airgap-wound they cannot operate with a large field weakening range. Torus machines have often high overload capability due to efficient cooling and low inductance. These machines have mostly been used for generator applications such as small generators, engine starter/generator and wind power generator. Torus machines have also been used in electric vehicle applications where they are mainly mounted in the wheel hubs. Most of the Torus machines were designed as BLDC machines but the ones for electric vehicle applications are PMSM.

### 2.5.3 Transversal flux

The main advantage of transversal flux (Figure 17) machines are their torque density which is in the range of 5-10 times higher compared to standard induction motors. The main drawback is their poor power factor which is in the range of 0.35 for surface mounted magnets and 0.55 for the less robust flux-concentrated machines. This can be compared with PMSM which reaches 0.9-1 in power factor. The price for a high torque density must be paid with a large inverter in the drive due the low power factor. Besides the low power factor, the stator structure usually results in large cogging.

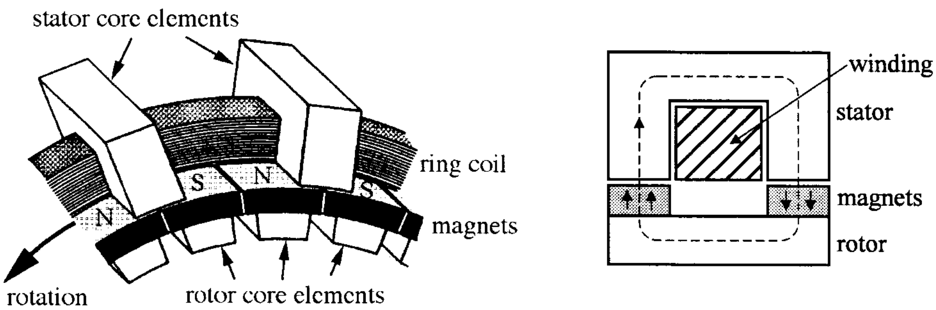


*Figure 17   Transversal flux machine.*

# 3 AC machines

The two most common AC motor types for EVs and HEVs are the permanent magnet (PM) motor and the induction motor. The permanent magnet AC motors have magnets on the rotor while the induction motors have short-circuited bars. The stator construction is in principle the same for both motor types.
The PM motor can be classified as sinusoidal type or trapezoidal type depending on the flux distribution in the air gap. Sinusoidal motors have a sinusoidal distribution of the winding. Trapezoidal motors have concentrated three-phase windings and are also known as brushless DC motors. The use of high-density rare earth magnets in PM motors provides high power density, but at the same time the cost of magnets is on the negative side for these motors. For EV and HEV applications, motor size is relatively large compared to the other smaller power applications of PM motors, which amplifies the cost problem. However, HEV motors are usually smaller than EV motors, and the performance and efficiency achievable from PM motors may be enough to overcome the cost problem.
Figure 18 gives an indication of the utilisation for the basic motor types.
Another candidate for traction motors is the switched reluctance (SR) motor. These motors have excellent fault tolerance characteristics, and their construction is fairly simple. The SR motors have no windings, magnets, or cages on the rotor, which helps increase the torque and inertia rating of these motors. The motor speed-torque characteristics are an excellent match with the road load characteristics, and performance of SR motors for EV/HEV applications have been found to be excellent. The two problems associated with SR motors are acoustic noise and torque ripple.

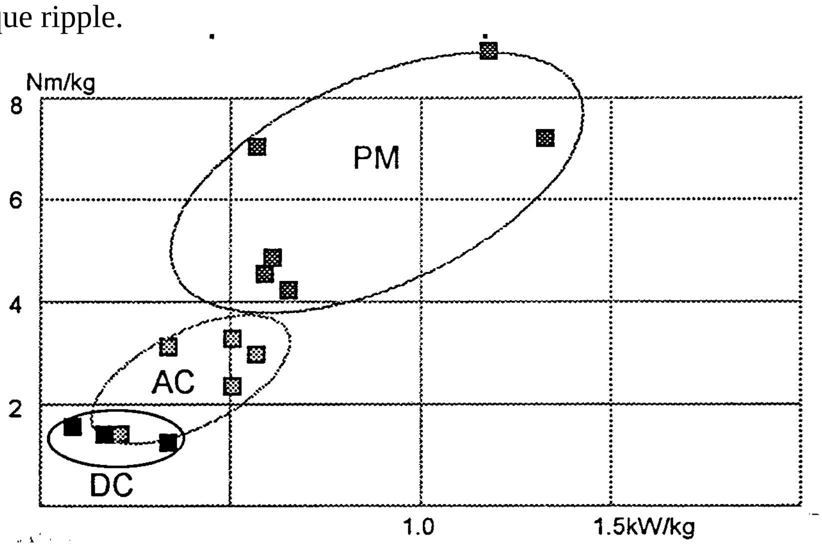


*Figure 18   Maximum torque and continuous power densities.*

## 3.1 Induction machine

The induction machine is the most common electrical machine. It is the work horse of industry and it is commonly used for constant speed applications such as pumps and fans. Due to energy conservation reasons, many of these constant speed drives are today converted into systems with variable speed.
In traction, it can be used as motor for the main propulsion but due to heating problems it is not looked upon as the most promising candidate.

### 3.1.1 Operating principle of the induction machine

A detailed description of the operating principles and characteristics of induction machines is outside the scope of this course. The purpose is only to briefly explain its operating principles in order tounderstand its basic characteristic.
Figure 19 shows the principle design of an induction machine. The stator consists of a three-phase winding where the phase windings are situated 120° from each other. The rotor is normally made as a so called rotor with squirrel cage meaning that all the rotor bars are short-circuited at the end and forms a "conducting sheet" around the rotor.

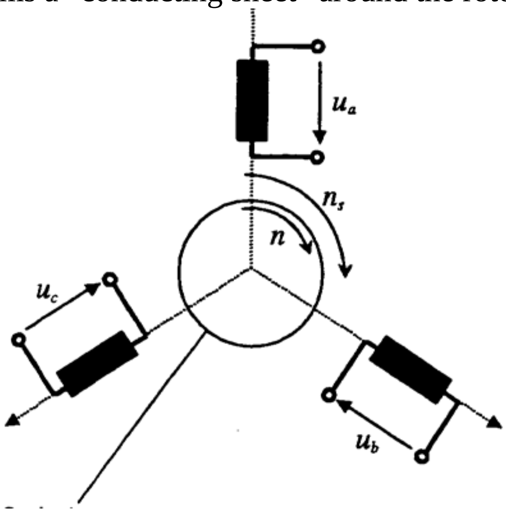


*Figure 19 Schematic representation of an induction machine.*

When a three-phase winding (a,b,c) distributed in *space* with a 120° phase shift according to Figure 19, is fed with a three-phase voltage where the three voltages, are phase shifted 120° *in time*. that is $u_a = \hat{U}\sin\omega t$, $u_b = \hat{U}\sin\left(\omega t - 120^\circ\right)$ and $u_c = \hat{U}\sin\left(\omega t - 240^\circ\right)$ a rotating field is produced in the air gap. The speed of the rotating field is determined by the frequency of the supply voltage, $f_1$ and the pole number of the machine $p$. The synchronous speed of the machine becomes

$$n_s = \frac{f_1}{p/2} \text{ [rps]} \tag{3.1}$$

From here on, hte pole number $p$ is assumed to be 2 for simplicity. The rotating flux wave induces a voltage in the rotor winding. Since the rotor winding has very low impedance a rotor current is obtained. The rotor current and the flux wave produce torque acting on the rotor.
The voltage induced in the rotor varies with the rotational speed of the rotor

$$U_2 = sU_1 \tag{3.2}$$

where the slip $s$ is defined as

$$s = \frac{n_s - n}{n_s} \tag{3.3}$$

The slip is a measure of how much the rotor speed differs from the synchronous speed of the rotating flux wave. Obviously, if the speed of the rotor is equal to the synchronous speed no currents are induced in the rotor and the machine produces no torque. As a consequence the induction machine has to operate with a speed that differs from the synchronous speed, i.e. $s \neq 0$, to produce a torque. If $s$ = 1 the machine is standing still, that is, the speed is zero.

### 3.1.2 Single phase equivalent circuit

Figure 20 shows a common single-phase equivalent circuit for an induction machine. The stator resistance is denoted $R_1$, $X_m$ is the magnetising reactance, $X_k$ is the leakage reactance and $R_2^{'}$ is the rotor resistance. The mechanical power is represented by an equivalent resistance $\frac{1-s}{s}R_2^{'}$. Observe that the mechanical power is depending on the slip. To obtain a better understanding of the characteristics of the induction machine it is often possible to simplify the equivalent circuit further by neglecting the stator resistance and the magnetising current, that is assuming that the magnetising reactance is infinite (straight line equal to the y-axis in a B-H curve).

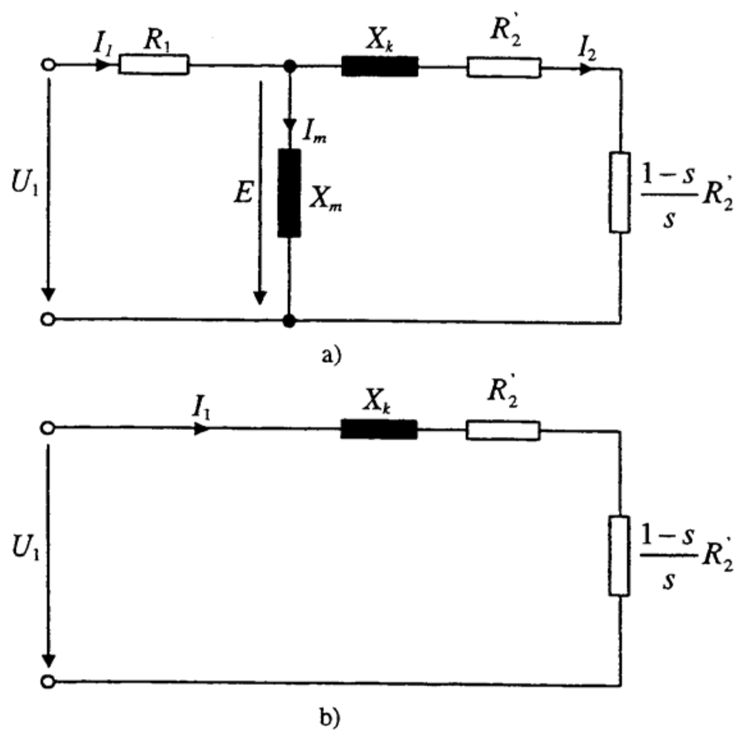


*Figure 20 Single phase equivalent circuits of the induction machine.*

The steady-state torque of the induction machine is derived from the equivalent circuit by dividing the calculated mechanical power with the angular speed $\omega$.

$$T \frac{P_{mech}}{\omega} \tag{3.4}$$

The mechanical power, that is, the power produced in the resistance $\frac{1-s}{s}R_2^{'}$ becomes

$$P_{mech} = (1-s)P_{12} = 3(1-s)\frac{R_2^{'}}{s}I^2 = 3(1-s)\frac{R_2^{'}}{s}\frac{U_1^2}{\left(\frac{R_2^{'}}{s}\right)^2 + X_k^2} \tag{3.5}$$

where $P_{12}$ is called the airgap power, that is, the power that is transmitted from the stator to the rotor (when operating as motor). Combining the torque expression and $\omega_{mech} = (1-s)\omega_s$ yields,

$$T = \frac{P_{mech}}{\omega} = \frac{(1-s)P_{12}}{(1-s)\omega_s} = \frac{3}{\omega_s}\frac{R_2^{'}}{s}I^2 = \frac{3}{\omega_s}\frac{R_2^{'}}{s}\frac{U_1^2}{\left(\frac{R_2^{'}}{s}\right)^2 + X_k^2} \tag{3.6}$$

Calculating the torque as function of speed or slip gives the torque characteristic shown in Figure 21.

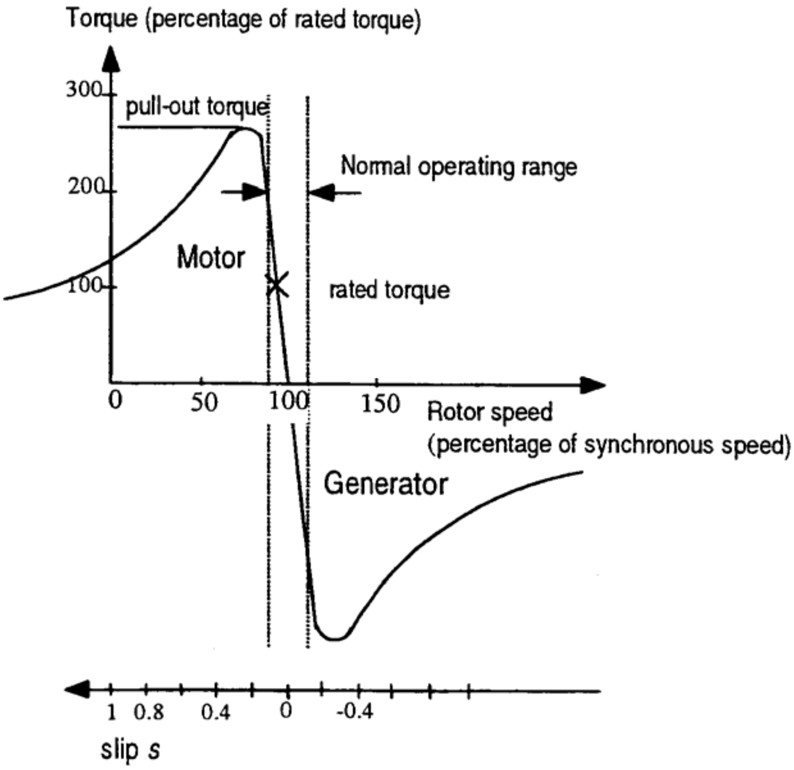


*Figure 21 Torque characteristic of the induction machine.*

The peak torque of the machine, the so called pull-out torque, is obtained by maximising (3.6) with respect to the slip s. The pull-out torque becomes

$$T_p = \frac{3U_1^2}{2\omega_s X_k} \tag{3.7}$$

which occurs at the so called pull-out slip

$$s_p = \frac{R_2^{'}}{X_k} \tag{3.8}$$

As shown in Figure 21 the induction machine will operate as generator if the slip is negative (s<0), that is, the rotating flux wave is rotating slower than the mechanical speed of the rotor.

## 3.2 PM-motor

Permanent magnet motors are usually referred to as synchronous motors but often also as brushless DC motors even when it is basically the same type of motor. The vocabulary is not very strict, but the most widely accepted definition is that the PM synchronous motor is fed with sinusoidal stator currents while the PM brushless DC motor is fed with square wave currents (see sec. 3.2.2).
The shape of the currents is determined by the motor controller. The advantage with square wave currents is a somewhat larger integrated current and thus a larger maximum torque in a specific motor. The disadvantage is a larger amount of

harmonic currents resulting in higher losses, more noise and a risk for torque pulsation.

### 3.2.1 Magnet materials

A magnetic field can be created either by electrical currents or by a permanent magnet. In a permanent magnet the microscopic “current” that the movement of the electrons of the atom make acts as a source for a magnetic field and therefore a permanent magnet creates a magnetic field although the actual current source is not visible.
Figure 22shows a typical magnetisation curve of a permanent magnet. The two importan proporties of the material is the coercive force $H_c$ and the remanent flux density $B_r$. The larger these two are, the stronger and better the magnet is. The product of $H_c$ and $B_r$ indicates the the strength of the magnet and is often referred to as the energy product of the magnet.
The development of commercially useful permanent, magnet materials began in the

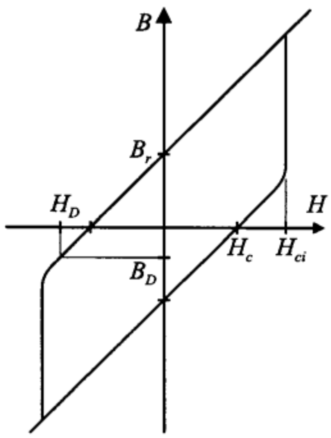


*Figure 22 Magnetisation curve of permanent magnet material.*

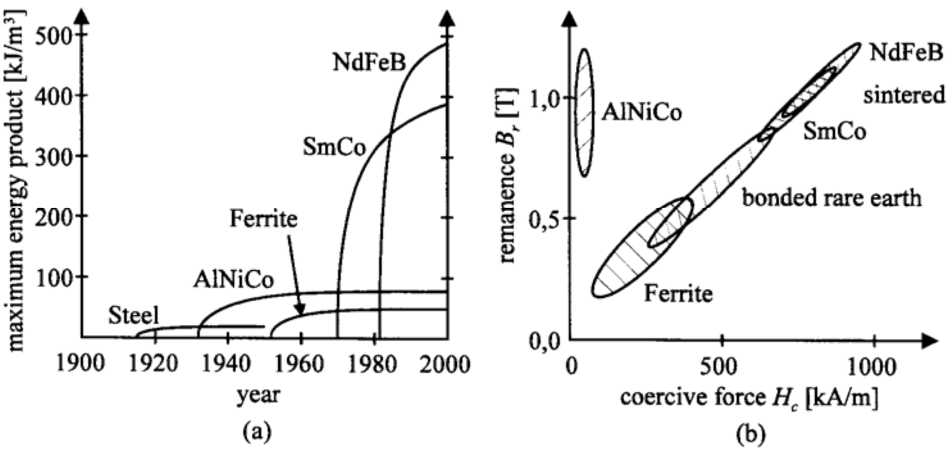


*Figure 23 Development of magnet material.*

early 20th century, first with magnetic steel, see Figure 23. In the 1930's the first material was developed which was useful for electro-mechanical devices. In the 1950's the ferrite permanent magnets were developed which were cheap and had remarkably high coercive force and energy product. Until today this is the leading magnet material due to its superior price-performance ratio. Well known applications are for instance loudspeakers and small DC motors.

The next milestone in advances of permanent magnetism was the development of sintered rare-earth cobalt magnets around 1970, in particular samarium-cobalt alloys SmCo. These offered high remanence and high coercive force resulting in a significantly higher energy product than ferrites can achieve. These properties and the large reversible demagnetization range (high intrinsic coercive force) made these magnets to be the superior choice for high performance machines. However, the high price of the raw materials has prohibited a large scale use. Hence major efforts were undertaken to find a magnet material with as good properties but constituted of cheaper raw materials. This research led to the, nowadays well known, neodymium-iron-boron NdFeB magnets, introduced in 1983. Although cheaper than SmCo and of even higher energy density, NdFeB is not always superior due to its lower thermal stability, caused by the lower Curie temperature, and its reactivity which leads for instance to corrosion problems. In contrary to ferrites the conductivity of rare-earth alloys can yield eddy current losses. Some of these problems can be overcome by embedding the rare-earth powders in a matrix, for instance resin or, for flexible magnets, rubber (also used with ferrite powder).
Besides the further increase of maximum energy product and remanence the topic of recent research is also to increase the Curie temperature of NdFeB alloys. This results in improved properties at elevated temperature which is particularly important in high performance motor applications.
The temperature in a motor with NdFeB magnets must be kept well below 150C while SmCo magnets will not restrict the motor operating temperature.
A problem of NdFeB magnets is their reactivity. This leads to corrosion and subsequently loss of magnetic properties. Therefore these magnets are often coated, for instance with nickel, increasing the costs for the magnets. An alternative is to ensure complete sealing in the motor production process. This can for example be achieved by embedding the magnets entirely in resin. In this case it is however important to avoid too much exposure to air and moisture for a period of time starting from the production of the magnets to their assembly which complicates the handling remarkably. McCaig and Clegg gave an example for the corrosion of NdFeB magnets.
In most properties SmCo magnets are superior to NdFeB magnets. Only the maximum energy product at room temperature is higher for NdFeB. However, the high price of SmCo normally prohibits its use in larger commercial drives. For special applications the increased price can be justified, for instance in high performance servo drives.

### 3.2.2 Operation principles

3-phase PM motors are usually divided into synchronous PM machines (or brushless AC BLAC) and brushless DC (BLDC) PM machines. This terminology is somewhat confusing since both types have no brushes and operate in synchronous mode. The actual difference is rather the operation principle than the machine itself. Their principles of operation will be briefly described in the following.

## Synchronous PM machine (brushless AC)

The synchronous PM machine is characterized by a permanent magnet excited rotor and the operation with sinusoidal stator currents. This implies that all phases are energized at all times. If also the voltage induced from the magnet flux in the stator windings is sinusoidal a constant power and thus constant torque is achieved. To be able to control the currents sinusoidally and synchronously with the rotor it is necessary to know the angular rotor position at all instants. This angular position is also often called rotor angle. Hence a position sensor with high resolution, for instance a resolver, is required. From the known rotor angle the instantaneous current reference values can be computed. The phase currents are then controlled using a pulse width modulation (PWM) scheme.

Figure 24 shows a typical cross section of a 2-pole synchronous PM motor.
Typical advantages of this type of PM motor are comparably low torque ripple, excellent low speed and positioning performance, low losses due to low harmonics, and that existing manufacturing facilities can easily be employed for the stator because it is very similar to that of a standard asynchronous motor. The major disadvantage is usually the requirement of a complex shaft-mounted sensor. Hence it is mostly used for larger drives where a low torque ripple is important and many stator slots are common. But also many servo drives use this operation mode when accurate positioning is demanded and a high resolution sensor is anyway needed.

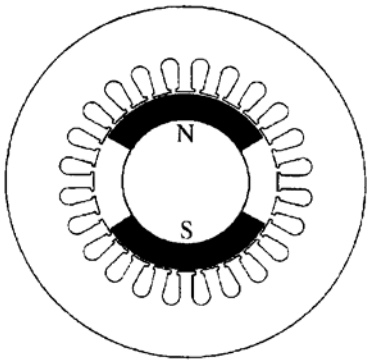


*Figure 24   Typical cross section of a 2-pole synchronous PM motor.*

## Brushless DC PM machine

The BLDC PM machine is characterized by a permanent magnet excited rotor and the operation with square wave currents according to Figure 25. This implies that always two of the three phases are energized. If the induced voltage is trapezoidal with 120° flat tops a constant power and thus constant torque are obtained as in the synchronous PM machine. This is, however, often difficult to realize with the result that BLDC machines have usually a higher torque ripple. The major advantage of this type of machine is that much simpler rotor position sensors can be used because the only instances that must be detected are when the currents are switched to the next phase. The current magnitude is commonly controlled by a PWM method. A drawback is that field weakening operation is difficult.

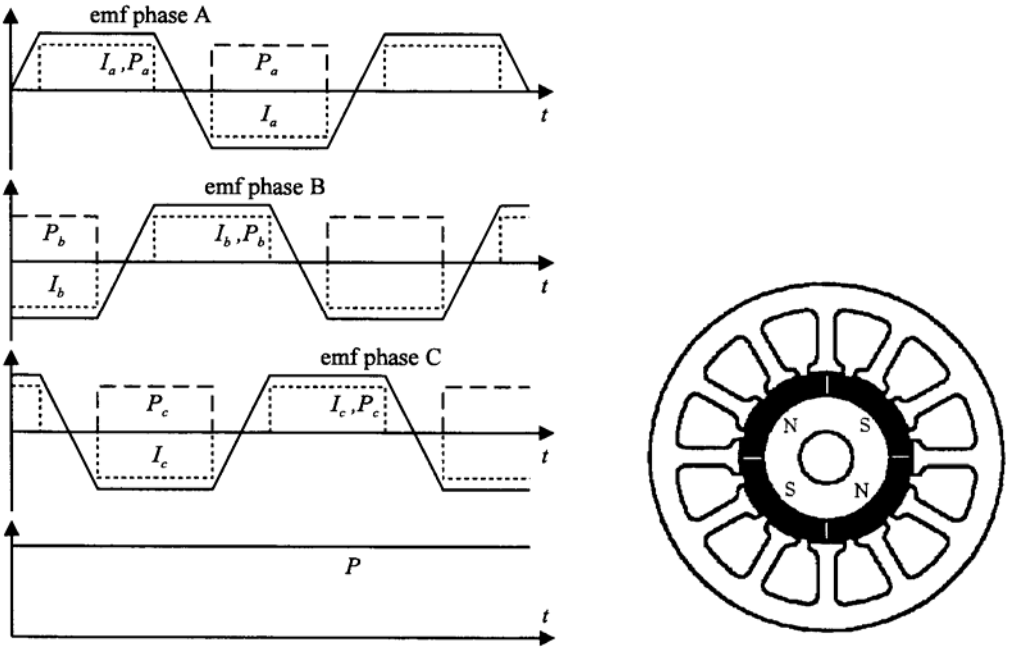


*Figure 25   Ideal waveforms (left) and cross section (right) for a 4-pole BLDC motor.*

### 3.2.3 Influence from pole number

As discussed earlier, the size of an electric motor (airgap diameter and active length) is determined by its rated torque, the magnetic flux density in the airgap and the so called linear current density in the stator winding,. The flux density is limited by the magnetic properties of the iron while the current density can be increased if the cooling is intensified. With the "airgap dimensions" given, the weight of the motor can be reduced through an increased number of poles. Figure 26 illustrates this by showing cross sections through the active parts of one 4-pole and one 16-pole motor.
The magnetic flux per pole is decreased approximately in proportion to the inverse of the pole number. Therefore the radial dimensions ("thickness") of the stator core and the rotor ring will be much smaller for a motor with high pole number, provided the same flux density is maintained in those parts. A higher pole number means a higher frequency provided the same motor speed. This requires special attention in choice of the stator core material and lay-out of the stator winding. Available materials and modern power electronics combined with small motor dimensions result in low

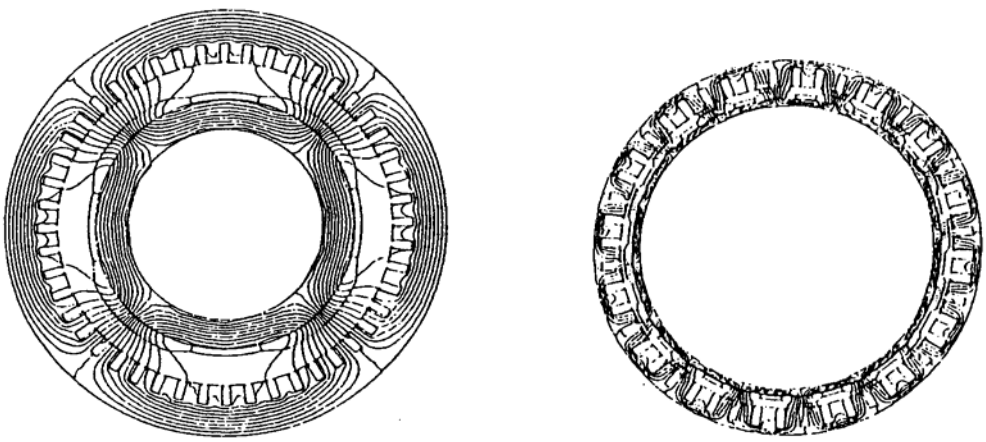

*Figure 26   Magnetic flux in 4- and 16-pole PM motors.*

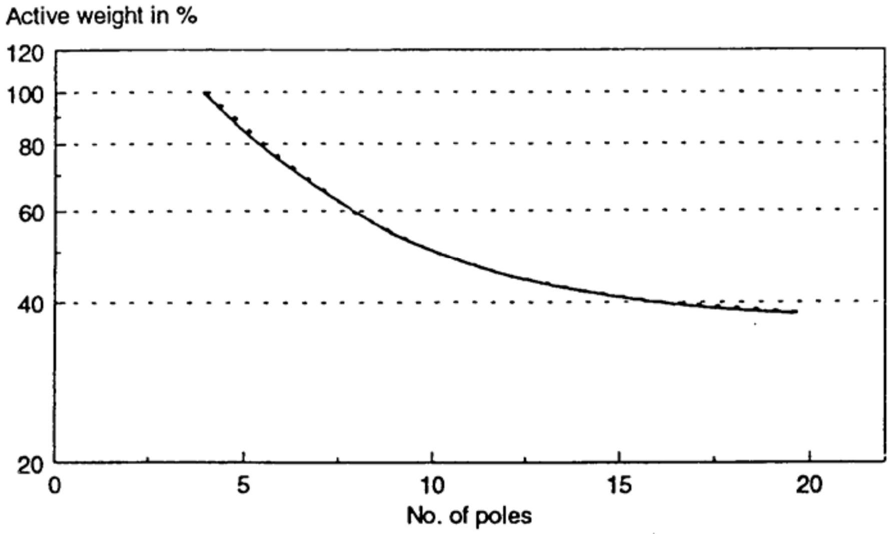


*Figure 27 Relative weight of motor vs. number of poles.*

losses in spite of the higher frequency. The weight of a PM motor as function of the number of poles is shown in the diagram in Figure 27.
The possibility to reduce weight through a high pole number is most pronounced for PM motors. An asynchronous motor with a high number of poles would have a very poor power factor and a reluctance motor would have to small difference between maximum and minimum reluctance in order to efficiently create the necessary torque.

### 3.2.4 Motor design

As outlined before, rhere are a number of various PM motor design concepts. Different number of poles has already been mentioned. The location of the magnets can either be surface mounted or interior in the rotor. The motors can be liquid cooled (usually water with anti-freezer) or air cooled. The motors can be long and slim or short with larger diameter. They can be designed for moderate speeds but also for extremely high rpm's.
One example is mady by the company Unique Mobility with support from BMW. It is a water cooled, high pole number, field weakened PM motor with very good properties for electric vehicle applications. In Figure 28 it is combined with a reduction gear into a so called trans-axle unit.

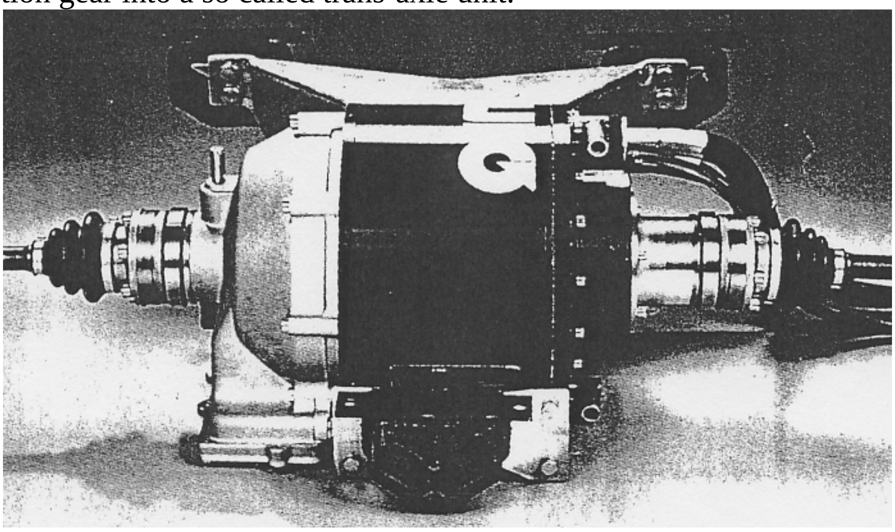

*Figure 28 32 kW, 8000 rpm, water cooled PM motor.*

| | PM synchronous | Induction |
|---|---|---|
| **Max. power, kW** | 32 | 32 |
| **Max. torque, Nm** | 140 | 140 |
| **Speed range, rpm** | 0 –2200 – 8000 | 0 –2200 – 8000 |
| **Base speed, rpm** | 3900 | 3275 |
| **Number of poles** | 18 | 4 |
| **Frequency range, Hz** | 0 – 1200 | 0 – 267 |
| **Outer diameter, mm** | 280 | 260 |
| **Length, mm** | 185 | 320 |
| **Weight, kg** | 38 | 57 |
| **Efficiency, % at** | | |
| **32 kW, 3000 rpm** | 91 | 85 |
| **32 kW, 5000 rpm** | 90 | 86 |

*Table 1 Motor design comparison.*

The rating and the performance of this prototype motor is summarised in Table 1. It includes a comparison with an asynchronous motor designed to meet the same specification.

The PM motor has mechanically a conventional lay-out (Figure 29), i. e. an inner rotor with the permanent magnets and an outer stator consisting of stator winding, stator core and a housing made from aluminium. The motor is liquid-cooled through water circulating through the housing. The outer housing as well as the shaft can be designed in various ways to match the transmission and the installation.

The rotor consists of the shaft, the hub and the rotor ring, the magnets and an outer retaining ring. The hub and the rotor ring is made from steel as one piece. The permanent magnets are high performance neodymium-iron-boron magnets (NdFeB). They get their final shape, corrosion protection and magnetisation after being fixed at the rotor. A thin, outer retaining ring is carrying the centrifugal forces acting upon the magnets.

The stator winding is placed in slots in the core, similar to other types of AC motors. The winding is made from thin copper wire, insulated and impregnated in order to give high strength and good thermal conductivity. The material used for the stator core is chosen with consideration to the high frequency.

A number of prototype system have been built by Unique Mobility and delivered to BMW for bench testing as well as installation and testing in electric cars. Figure 31 and Figure 31 shows results from a bench test and they indicate a very high system performance with efficiencies well above 90 % in a large part of the working range.

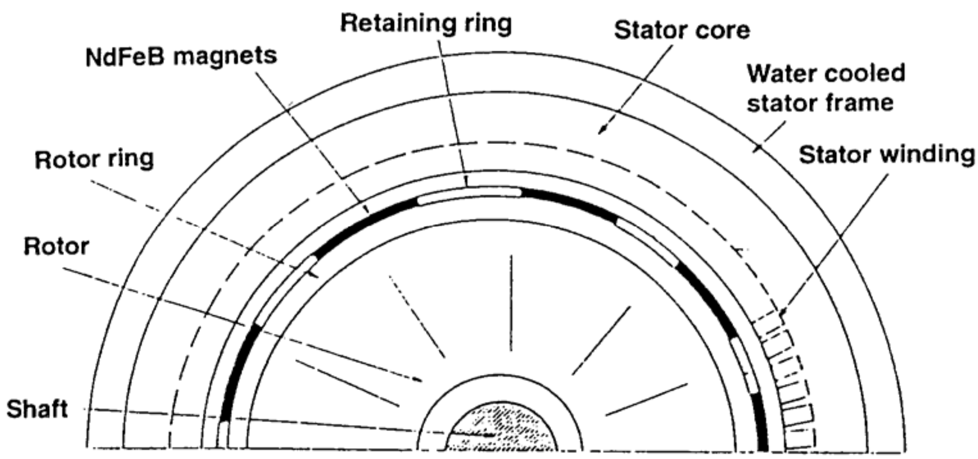


*Figure 29 Cross section through PM motor.*

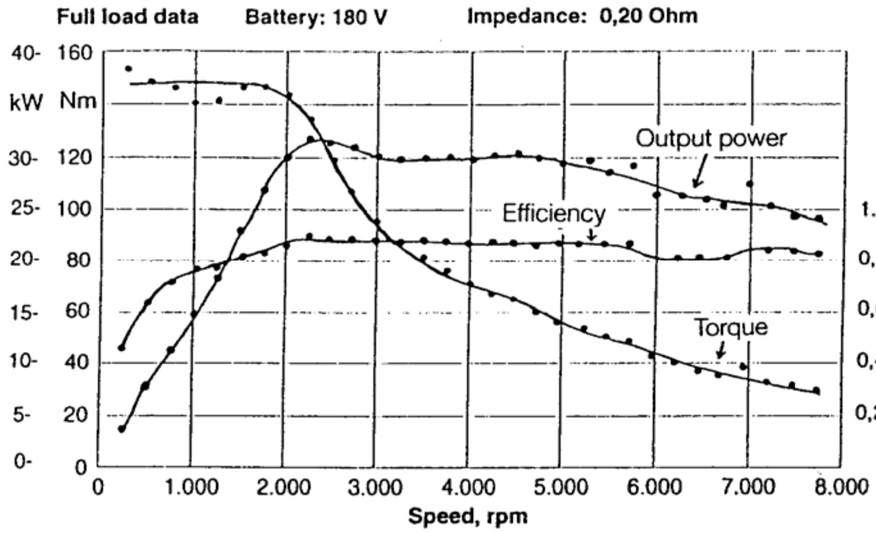


*Figure 30 Torque and power characterstics.*

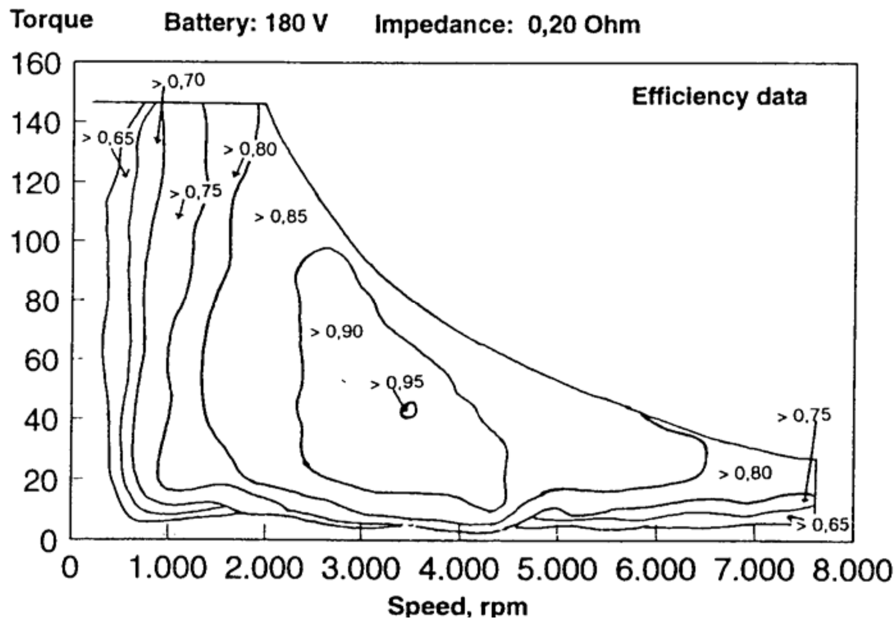


*Figure 31 Efficiency characteristics.*

Simulations, based on bench test results from various types of systems, have been carried out by BMW and they indicate a 15 % longer driving range with this type of PM motor drive system compared with a corresponding induction motor drive system.

## 3.3 Switched reluctance motor

Although only recently coming into widespread use, the switched reluctance motor (SRM) is, in principle, quite simple. It is salient both in stator and rotor and equipped with windings only in the stator, making this motor type potentially very easy and cheap to manufacture.

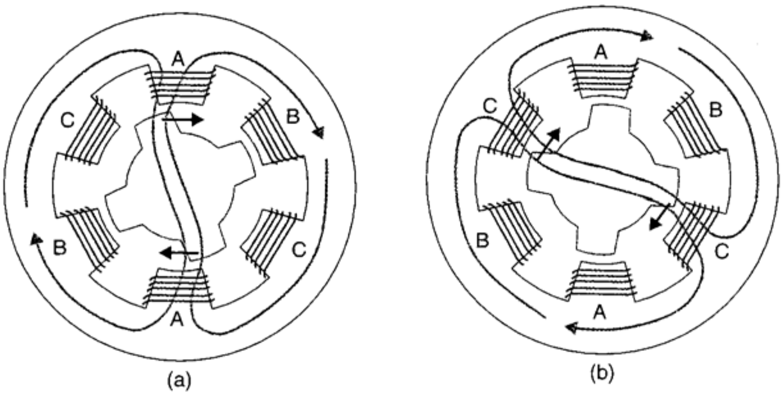


*Figure 32 Operation of a 6/4 switched reluctance motor.*

The basic operation is shown in Figure 32. Stator windings on diametrically opposite poles are connected in series to form one phase of the motor. When a stator phase is energized, the most adjacent rotor pole-pair is attracted toward the energized stator in order to minimize the reluctance of the magnetic path. By energizing consecutive phases in succession, it is possible to develop constant torque in either direction of rotation.

Several other combinations of the number of stator and rotor poles exist, such as 10/4 and 12/8, see Figure 33. Configurations with a higher number of stator/rotor pole combinations have less torque ripple.

Switched reluctance motors (SRM) possess unique features that make them strong competitors to existing AC and DC motors in various adjustable speed drives.

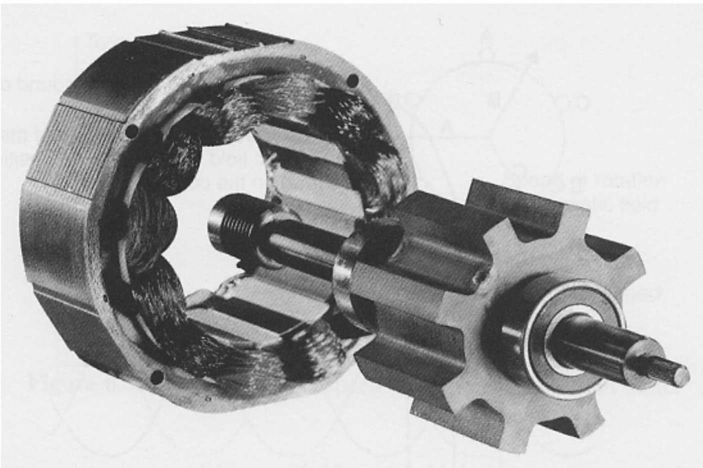

*Figure 33 Switched reluctance motor (SRM).*

The advantages of an SRM can be summarized as follows:

• Simple and low-cost machine construction due to the absence of rotor winding and permanent magnets.

• No shoot-through faults between the DC buses in the SRM drive converter, because each phase winding is connected in series with converter switching elements.

• Bidirectional currents are not necessary, which facilitates the reduction of the number of power switches in certain applications.

• The torque-speed characteristics of the motor can be tailored to the application requirement more easily during the design stage than in the case of induction and PM machines.

• The starting torque can be very high without the problem of excessive inrush current due to its higher self-inductance.

• The maximum permissible rotor temperature is higher, because there is no permanent magnet.
• They have low rotor inertia and high torque/inertia ratio.
• Independent stator phases enable drive operation in spite of the loss of one or more phases.

The SRM also comes with a few disadvantages, among which torque ripple and acoustic noise are the most critical. This is due to the fact that the torque is produced by shifting the current from one phase to the next which more or less automatically produces variations in the torque and thereby noise.

The absence of permanent magnets means that magnetic excitation solely has to come from the stator windings and converter, which increases the converter kVA requirement.

Compared to PM brushless machines, the per-unit stator copper losses will be higher, reducing the efficiency and torque per ampere. However, maximum speed at constant power is not limited by the fixed magnet flux as in the PM machine, and hence, an extended constant power region of operation is possible in SRMs. The control can be simpler than the field-oriented control, although for torque ripple minimization, significant computations may be required for an SRM drive.

# 4 Motor drives

There are a number of motors used in a modern vehicle. They are found almost everywhere: Starter, Door lock, CD shuttle, Windshield wiper,Windshield washer pump, Rear wiper, Sun roof, Defroster, Mirror remote control, Headlight position, Radiator cooling fan, Throttle control, Heat/air condition, Antenna lift, Seat actuator, Fuel pump, Window lift, etc.
Many of them are not required to operate with a variable speed and in such cases the preferred choice of motor is the standard DC motor. The main reason being that it is so easy to employ. But in some cases, like for the propulsion, the motor has to be controlled. Most often it is a speed that is requested, but of course it can also be the position or just simply the torque that is required. Regardless of application, there is a common system structure as outlined in Figure 34.

## 4.1 The production of torque, speed and position

The load of the motor can have different characteristic depending on the application but basically it consists of two parts, one for the inertia and one for the actual load and losses. The second part can have different characteristics but the most common are:
- constant, independent of speed like for hoisting
- linear to speed, the viscous friction
- quadratic to speed, like for fans.

Of course it can also be a mixture of all these. Summing all the components together gives the mechanical equation

$$T_{em} = J\frac{d\omega}{dt} + T_{em} + b_1\omega + b_2\omega^2 + ... \qquad (4.1)$$

where $T_{em}$ is the driving torque from the motor.

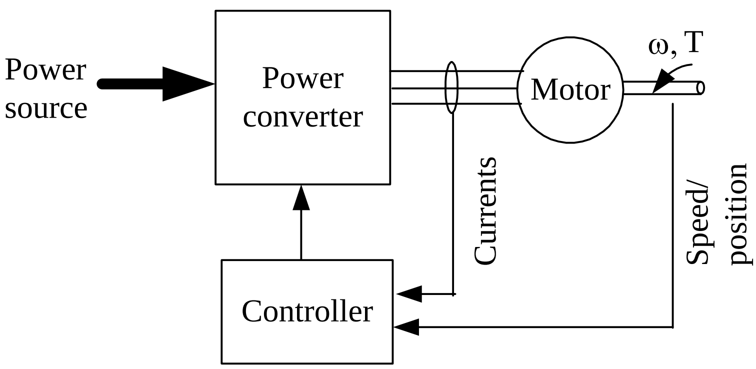


*Figure 34   Main components of an electrical drive system.*

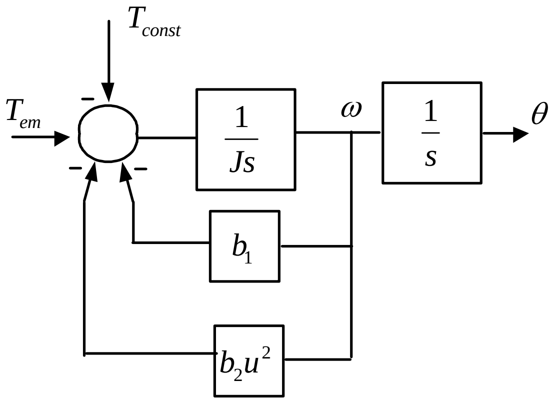


*Figure 35   Mechanical system. Torque to speed, speed to position.*

The speed is found by integration of the net torque. Then position can be found by integration of the speed. A block diagram showing this link of relations is shown in Figure 35.
The torque is created by the current in the motor and the current is in turn created by the applied voltage. Due to the inductance in a motor, the current cannot be increased infinitely fast. The relation between current increase and applied voltage is rather simple for a DC motor. The AC motors will in principle have the same relation if a suitable choice of controller frame is done. The resulting voltage equation will in principle look like

$$u_q = R_s i_q + L_s \frac{di_q}{dt} + \omega \psi_m \tag{4.2}$$

where a resistive voltage drop, an inductive voltage drop and an induced voltage is recognised. The electrical equation can be added to the mechanical system and this gives a block diagram according to Figure 36.
The chain of reactions – voltage to current to torque to speed to position – will later justify how the control system is normally designed.

## 4.2 The general control structure

Section 4.1 described how a voltage applied to an electrical motor would start a chain-reaction so that the motor started to move. In this system there are different time scales. It is fast to change the applied voltage and fairly fast to change the current and hence the torque.

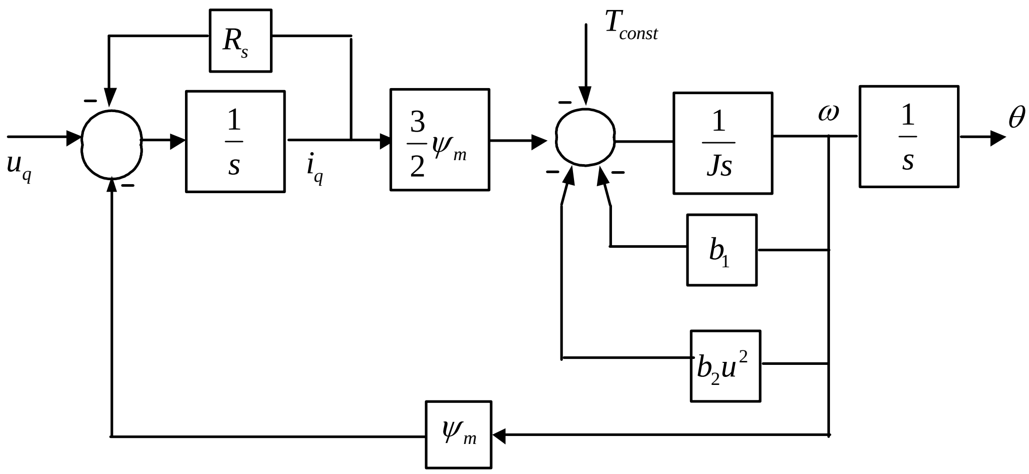


*Figure 36   Electrical and mechanical system.*

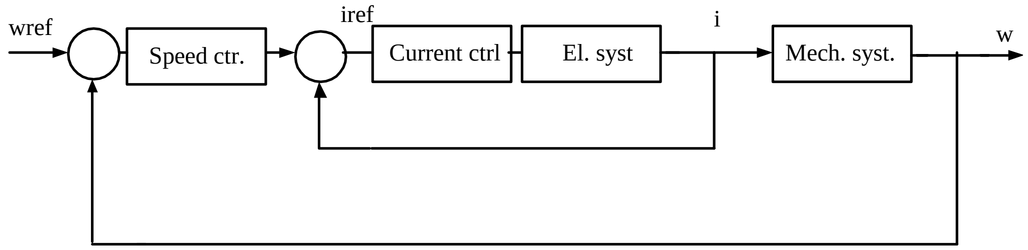


*Figure 37 Cascaded control structure.*

The torque will force the masses to move, i.e. to accelerate. However this acceleration is fairly slow compared to the build up of torque. Finally, once there is a speed, there can be a change in position, i.e. the motor starts to rotate.
This difference in time scales leads to a control strategy that is called cascaded control. The idea is that first the fastest process is taken care of, in the motor control case it is the control of current. Thereafter a control loop is employed that takes care of the next process in the time scale. In the motor control case it is the speed. Finally, if needed a loop for the position is also created. The structure is shown in Figure 37.
However, it is important to bear in mind that very often there are cross-connections that can disturb this idea with separated control loops. An example is the induced voltage in a motor. As seen in (4.2), the speed is also involved in the process to build-up current. This relation is shown as a dashed line in Figure 38 and the result is that control of the current is also influenced by the variation of speed. As a consequence, to get satisfactory performance from the system, the current controller might have to be changed to another type of controller.

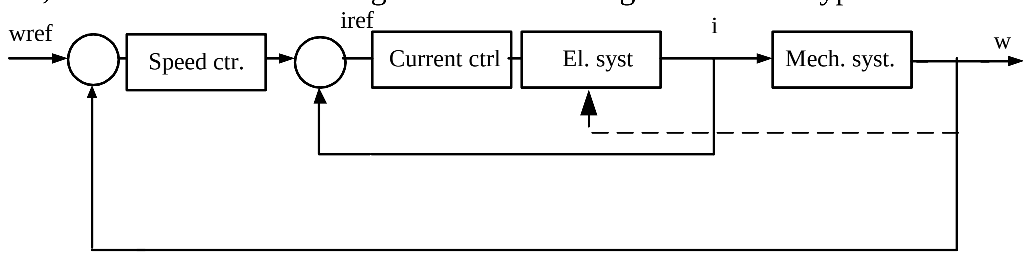


*Figure 38 Cross-connection between control loops.*

## 4.3 Sensors

The most important sensors in electrical drive systems are current and speed/position sensors.

### 4.3.1 Current sensors

The simplest current sensor consists of a small resistor inserted in series with the conductor where the current is to be measured. This is a cheap and fairly good sensor but it has a large disadvantage and that is that there is no galvanic isolation between the power circuit and the control circuit. In some cases expecially when cost is crucial, this can be handled when designing the system.
To get galvanic isolation, Hall-element based sensors are often used. They use the fact that a current will create a magnetic field around its conductor. By surrounding the conductor with an iron core the field is concentrated and can be measured. The measured value can either directly be translated into actual current value or it can be used in a special closed-loop technology to achieve a higher performance.

### 4.3.2 Speed/position sensors

For high performance drives, the two most common angular sensors are the pulse encoder and the resolver. Both of them will produce the angular position of the rotor and by time-differentiating the position, also the speed can be obtained.

## Pulse encoders

Pulse encoders are shaft mounted sensors that are equipped with a plastic disc with a pattern etched on it. There are two types of encoders: absolute and incremental. The principle of the absolute type is shown in Figure 39. The disc has several circular bands of etched patterns in such a way that a binary code is formed that indicates the angular position of the shaft. The etched pattern is decoded by means of a lamp/photo-transistor setup. Depending on the application, an encoder can be manufactured to produce up to several thousand positions per revolution.

The incremental encoder has a simpler etched pattern on the disc with only two bands, each containing the same number of sectors. However, the sectors on the two bands are displaced by 90º. To obtain the position the signals from the two bands are counted as the disc is rotated. Thanks to the phase displacement of the bands, it is possible to deduce the rotational direction so that the counter knows whether to cound up or down.

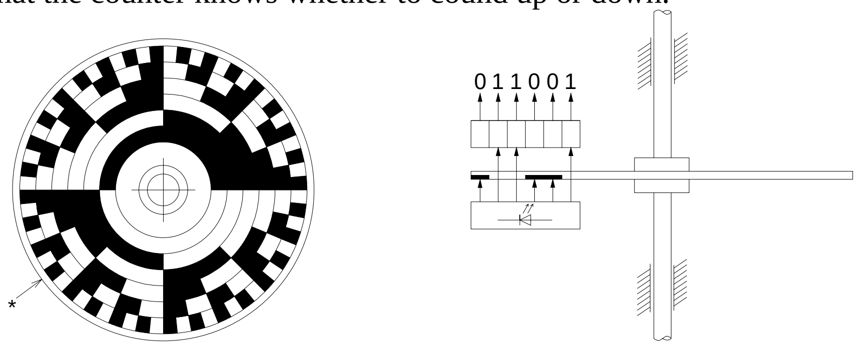


*Figure 39 Absolute position encoder.*

## Resolvers

The resolver, is an absolute encoder capable of producing a very accurate value of the rotor position, see Figure 40. The resolver is shaft/mounte on the machine and its rotor is equipped with a single winding that is supplied with a high-frequency carrier, 5 kHz or more.

$$u_s = \sin \omega t \tag{4.3}$$

The stator is equipped with two windings located 90° electrically from each other.
As the rotor is turned around, the signals in the stator windings will be amplitude modulated in accordance with the rotor position,

$$\begin{aligned} u_\alpha &= \cos\theta \sin \omega t \\ u_\beta &= \sin\theta \sin \omega t \end{aligned} \tag{4.4}$$

The position of the rotor can then be obtained from

$$\theta = \tan^{-1} \frac{u_\beta}{u_\alpha} \tag{4.5}$$

The demodulation of the information in (4.5) can either be done directly in an analogue circuit or the amplitudes can be supplied to a digital controller and the equation is evaluated.

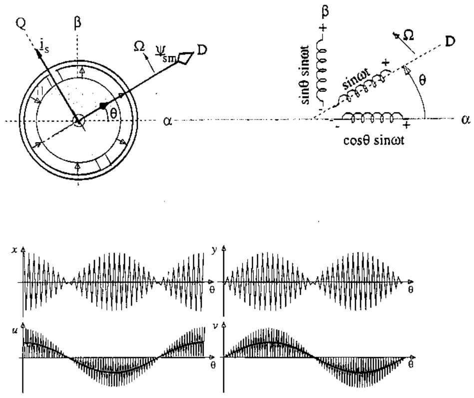


*Figure 40   Operating principle for the resolver.*

## 4.4 The non-controlled DC motor

As stated earlier, apart from the traction motor, the majority of motors in a modern vehicle are still DC motors. This is due to the facts that they are both cheap and easy to apply. A DC motor can be directly connected to the 12 V system and it will start and speed up to roughly a constant speed.

A model of the motor was discussed in chapter 2. However, it did not take into account a varying current. As the armature of the motor consists of a winding in the rotor, it will unevitably have a certain amount of inductance just like any coil. The nature of an inductance is to oppose a change in current. This can be understood from the basic electrical equation: the voltage across the inductance only determines the rate that the current changes. A more complete model of the DC motor is then given in Figure 41.

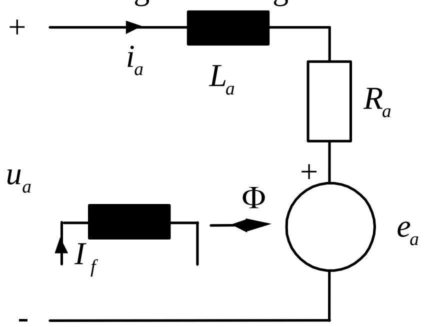


*Figure 41   DC motor model.*

In this model, the magnetisation of the motor is done with a so called field winding instead of permanent magnets. The reason for this will be explained in next section, discussing field weakening.

The induced voltage is proportional to the speed and the magnetisation. The magnetisation is up to a certain level proportional to the field current $I_f$. The electrical equation for the DC motor can be written as

$$u_a = R_a i_a + L_a \frac{di_a}{dt} + K_f I_f \omega \tag{4.6}$$

When a DC motor is connected directly to a DC voltage supply, like the 12 V in a car, there will be a high in-rush current in the beginning. The level is only limited by the armature resistance but due to the inductance it is usually limited to a bit lower level.

By combining the electrical and the mechanical equations, it is possible to simulate a start-up of the motor. A typical result is shown in Figure 42. The fast build-up of current is clearly visible. The peak current can be more than 10 times the normal value.
There are several drawbacks with this inrush current. The electrical supply has to be dimensioned to stand the current so e.g. fuses will generally have to be over-dimensioned. The big current will create a large short voltage drop and that might disturb other equipment that is also supplied from the 12 V. More over, the large current will produce a high torque on the shaft and thereby cause large forces in the mechanical load which might damage it or part of it.

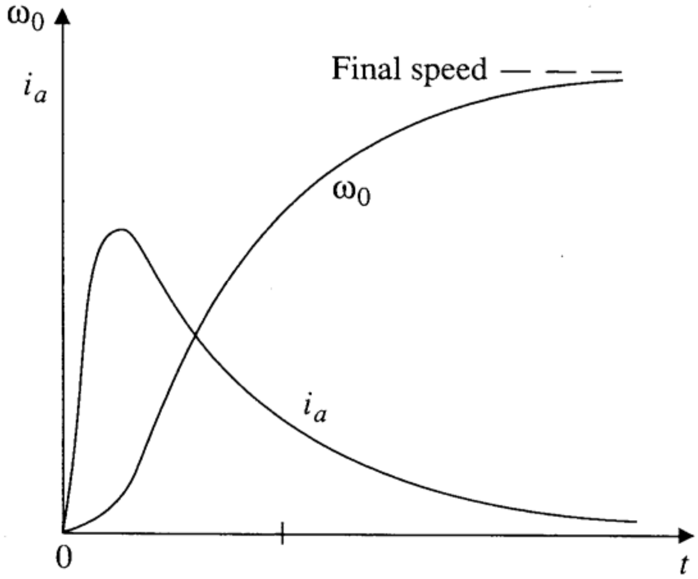


*Figure 42 Current and speed at start-up of a DC motor.*

A simple but costly method to reduce the inrush current is to have a resistor connected in series with the motor at start-up but then it will have to be disconnected or short-circuited once the motor has reached steady-state and this requires extra components that usually are hard to justify.
A better way is to make the system operate with variable speed, but that will then require a power converter for the variable supply and most often this can not be justified either.

## 4.5 Field weakening

The main application for a variable speed drive in a vehicle is for the propulsion. Back in the 70's, DC motors were used, During the 80's the induction motor became popular and today the dominating motor type for propulsion is the PM motor.
Regardless of motor type it is essential for the drive system to be able to run at high speeds, while at the same time, it is also important that the drive has a high torque capability at start. As power is proportional to speed and torque, it would be very inefficient to design a vehicle such that it would have the same torque capability at start as at maximal speed. The solution for this is something that is called *field weakening*. It will be explained by help of the simple DC motor.
As assumed in figure Figure 41, the magnetisation of the motor can be controlled by the field current $I_f$. The torque-speed characterstic at steady-state was derived in chapter 2 and can be written as

$$\omega = \frac{U_a}{K_f I_f} - \frac{R_a}{\left(K_f I_f\right)^2} T \qquad (2.12)$$

where the magnetic field has been replaced by $K_f I_f$.
The control strategy, see Figure 43, will now be that below base speed, the magnetisation is kept constant at its nominal value. This means that the armature voltage, $U_a$, has to be increased in accordance to the speed increase. But with the magnetic field at nominal value, the available torque is at its maximum. At base speed, the power converter has reached its limit and cannot produce any higher voltage. Equation (2.12) reveals that it is still possible to increase the speed if the field current $I_f$ is *reduced*. But as the field is reduced, the available torque will also be reduced as it is proportional to the product of the field and the armature current.
The armature current has the same limit regardless of speed and it is mainly determined by the current rating of the power converter.

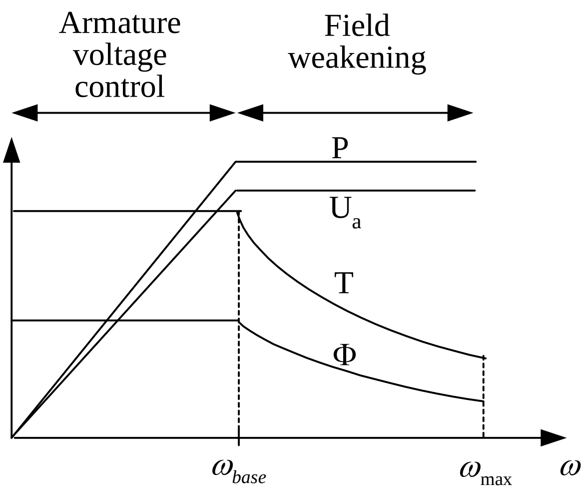


*Figure 43 Operating modes of a DC motor.*

Above base speed, the field will have to be reduced inversely proportional to the speed. The voltage and current can be kept at their rated values which means that the available power is constant in the so called field weakening range. The reduction of the field can not be continued to any value. For mechanical and stability reasons, there will still be a maximal speed that the drive can operate at.

## 4.6 The PM motor drive

A PM motor drive resembles a DC motor drive very much, *if* the internal control of the PM motor is disregarded. In the DC motor there is a fixed magnetisation in the stator and the commutator, or “mechanical rectifier”, distributes the current in the winding in the rotor.
A normal PM motor is constructed oppositely; there is a fixed magnetisation on the rotating rotor and the stator winding is supplied from a power converter that can produce the “rotating currents” in it.
But there is one big difference and that is that while the DC motor with a field winding is easy to operate with field weakening, it is more complicated to do this with the PM motor.
Ideally, if the magnetisation of the PM motor would be variable, a torque characteristic according to Figure 44 would be obtainable. The magnetisation though, is not variable. It is fixed as the motor is equipped with permanent magnets. In order to operate the motor at speeds higher than base speed, a field weakening has to be performed with help of the current

in the stator. Then using one component of the stator current to counteract the field from the magnets, means that there is less room for a torque producing component in the stator current.

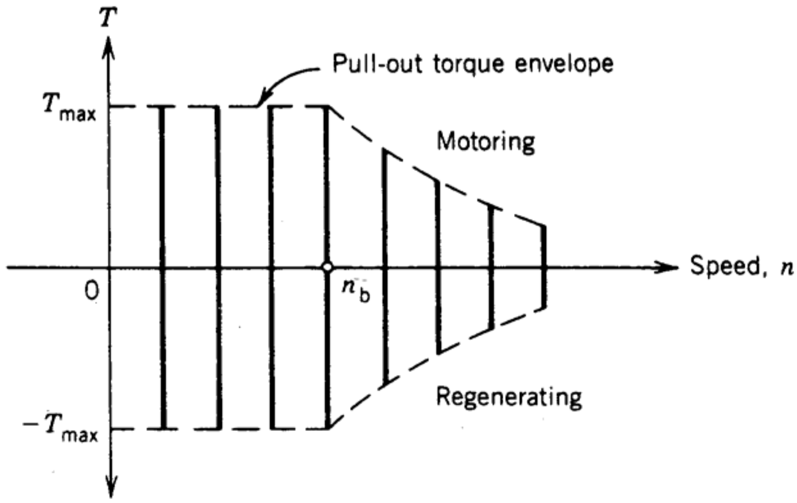


*Figure 44 Ideal torque characteristic for a synchronous motor with variable magnetisation.*

To be aböe to discuss the field weakening range of a PM motor, a new model of the machine has to be introduced; the space vector method

### 4.6.1 Space vector method

To deal with transient conditions in electrical machines, a model including the instantaneous quantities of all phases has to be used. In general the equations are fairly complex. By suitable transformations the equations can be simplified and written in a form that gives a good physical description of the machine. The method is called the *space vector method*. It can be used for almost all AC machines but here it will only be outlined for the permanent magnet synchronous motor (PMSM).

The method uses a complex quantity, a “space vector”, to represent the instantaneous values of currents, magnetic flux and voltages. The main benefit with the method is that it is easy to write the equations in such a form that they can be physically interpreted.

In a PMSM, there is a 3-phase winding in the stator and magnets on the rotor, see Figure 45 for the example of a 2-pole machine. The three phase windings in the stator are displaced in *space* by a 120°. Each of them produce a sinusoidal airgap magnetic field when energized.

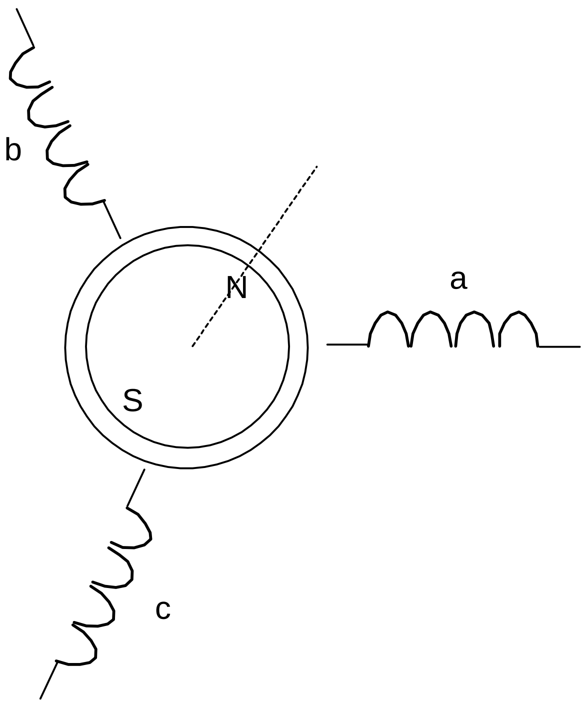


*Figure 45   Principle cross section of a PMSM.*

The magnetic field from each phase winding can be represented with a complex *space vector*. Phase a is then aligned with the real axis and the two other phases are displaced 120°. By combining the fields from the three phases the resulting field is obtained according to

$$\boldsymbol{\psi}_s = \frac{2}{3}\left(\psi_a + \psi_b e^{j120^\circ} + \psi_c e^{j240^\circ}\right) \qquad \text{----(4.7)}$$

where the 2/3 is just a scaling factor.

The interpretation of the magnetic field *space vector* is that the magnitude (length) of it corresponds to the peak value of the magnetic field and the direction of it corresponds to the direction of the field.

In an analogous way, complex space vectors for both currents and voltages can be defined,

$$\begin{aligned} \boldsymbol{i}_s &= \frac{2}{3}\left(i_a + i_b e^{j120^\circ} + i_c e^{j240^\circ}\right) \\ \boldsymbol{v}_s &= \frac{2}{3}\left(v_a + v_b e^{j120^\circ} + v_c e^{j240^\circ}\right) \end{aligned} \qquad (4.8)$$

The voltage equation for stator phase *a* is

$$v_a = Ri_a + \frac{d\psi_a}{dt}. \qquad (4.9)$$

For the other two phases, equivalent expressions are valid. By combining the voltage equations for all three phases, a very compact equation is obtained according to

$$\boldsymbol{v}_s = R\boldsymbol{i}_s + \frac{d\boldsymbol{\psi}_s}{dt} \qquad (4.10)$$

This equation can be visualised, for example by neglecting the stator resistance which results in

$$\boldsymbol{v}_s = \frac{d\boldsymbol{\psi}_s}{dt} \qquad (4.11)$$

This means that the direction of the stator voltage depicts in which direction the magnetic field is changing as shown in Figure 46.

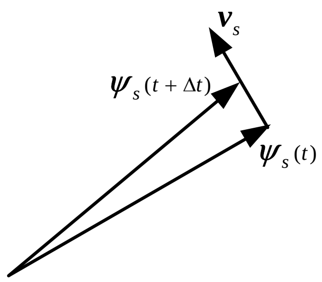


*Figure 46   Interpretation of space vectors.*

Inside the machine there are two sources for a magnetic field; the currents in the stator and the magnets on the rotor. Combining these two sources yields the total magnetic field in the machine

$$\boldsymbol{\psi}_s = L_s \boldsymbol{i}_s + \psi_m e^{j\theta} \tag{4.12}$$

where $L_s$ is the stator inductance that tells how much field is produced by the stator currents. $\theta$ is the angular position of the rotor.

Now, it is not the idea that the reader should “understand” the vector method from the very simple description given above. It was merely included to give the reader an illusion that the vector method can describe the inner nature of  AC machines.

The space vectors introduced above are given in the so called “stator reference frame” which meand that they will rotate as the motor rotates. By transforming the variables into a so called “rotor reference frame”, they will appear as “stand-still” during steady-state conditions. The reason is that the rotor reference frame is linked to the rotor and by doing so the magnetisation of the rotor, for example, will have a given and constant direction. The same holds true for the stator voltage and current as they “rotate” synchronously with the rotor speed.

In the rotor reference frame, the direction of the rotor magnetisation is called the d-direction (d for direct) and the perpendicular direction for the q-direction (q for quadrature). Any space vector can be divided into its components according to

$$\boldsymbol{x} = x_d + jx_q \tag{4.13}$$

which gives for the stator voltage $\boldsymbol{v} = v_d + jv_q$ .

Without a proper derivation, it is simply concluded that the voltage equation in the rotor reference frame becomes

$$\begin{cases} u_d = R_s i_d + L_s \dfrac{di_d}{dt} - \omega L_q i_q \\ u_q = R_s i_q + L_s \dfrac{di_q}{dt} + \omega L_d i_d + \omega \psi_m \end{cases} \tag{4.14}$$

The equation tells us that the stator voltage is used to overcome a resistive voltage drop, an inductive voltage drop and the induced voltage due to the rotation of the magnetised rotor.

In the rotor reference frame, there is a very simple expression for the torque that is developed by the machine. Again without a proper derivation, it is concluded that the torque is proportional to the q-current and the magnetisation of the machine,

$$T = \frac{3}{2} i_q \psi_m \tag{4.15}$$

### 4.6.2 Extension of speed range above base speed

In this section, the possibility of operating the PM motor at higher speeds will be discussed. First some simplifications will be made. It is assumed that the machine is operating at steady-state and that the stator resistance is negligible, which simplifies (4.14) to

$$\begin{cases} u_d = -\omega L_s i_q \\ u_q = \omega L_s i_d + \omega \psi_m \end{cases} \tag{4.16}$$

With increasing speed the back emf, $\omega\psi_m$, will increase and hence also the magnitude of the stator voltage $v_s = \sqrt{v_d^2 + v_q^2}$. Once the voltage is so large that it is equal to the maximum voltage of the converter $V_{max}$, it is not possible to increase the speed without a special method called *field weakening*. As the name implies, it means that the field $\psi_m$ is “weakened” whereby the speed can increase without exceding the maximal voltage.
The idea is that at lower speeds, below the so called base speed $\omega_{base} = V_{max}/\psi_m$, the machine is controlled in such a way that there is only torque-producing q-current. The maximal torque that can be obtained depends on the maximal current that is allowed, $I_{max}$.
At the same time, also the voltage limitation has to be checked

$$\left(L_s I_{max}\right)^2 + \psi_m^2 < V_{max}^2 \tag{4.17}$$

Above base speed, the field from the magnets is counter-acted by applying a *negative* d-current. As (4.16) then shows, the q-voltage will be reduced and thereby also the total stator voltage $v_s$ whereby the speed can increase without violating the voltage limitation. However, when introducing a d-current the level of the q-current has to be decreased in order not to exceed the maximal current allowed,

$$i_q = \sqrt{I_{max}^2 - i_d^2} \tag{4.18}$$

and if the q-current is decreased so is the torque.
Figure 47 shows how the tractive effort of a PM motor behaves, both in normal operation and field weakening.

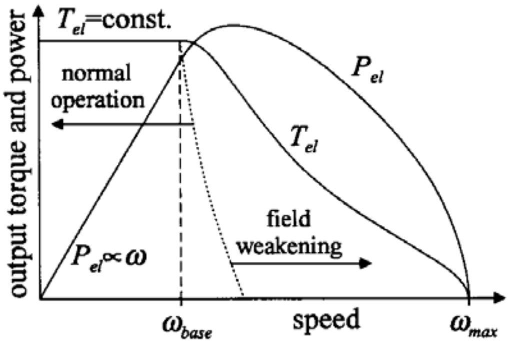


*Figure 47 Tractive effort of a PM motor drive.*

It is too lengthy to derive the exact relation between torque and inductance for the field weakening range but an example is shown in Figure 48. Above base speed the the torque capability follows rather fast if the inductance is low. So for a traction motor that is to operate in the field weakening range, the inductance should be adequately large. At the same time the graph shows that a large inductance reduces the available torque below base speed due to the voltage limit in (4.17). Another way of putting this is to say that the drawback with a large stator inductance is that the power factor of the motor is reduced and thereby a larger power converter will be needed than is indicated by the output power from the motor.
If the inductance is made fairly large, then the behaviour above base speed can be more less according to a constant power characteristica, just as is demanded in traction applications.

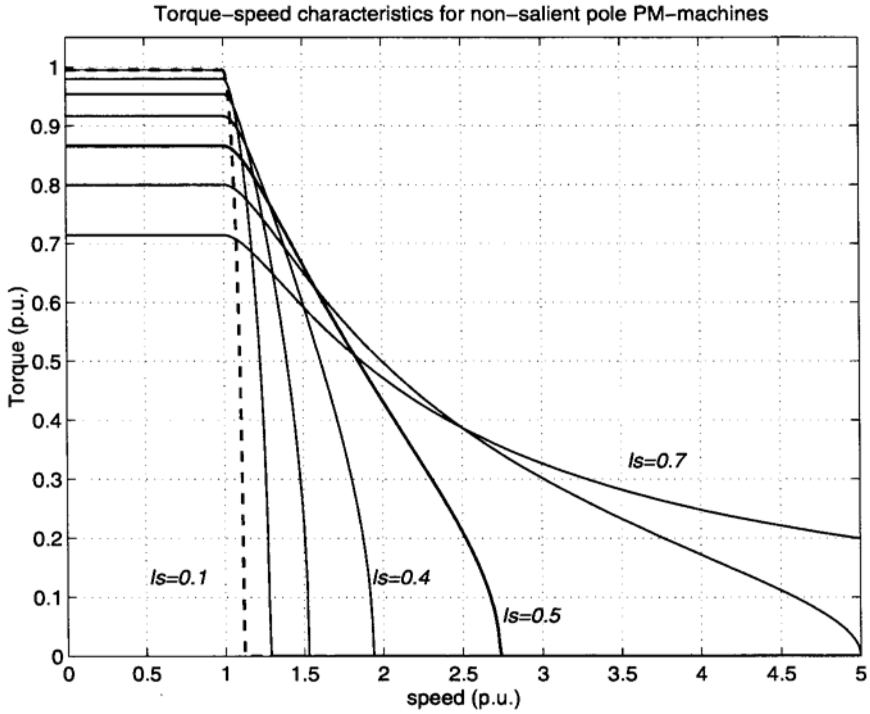


*Figure 48 Torque in the field weakened range as function of inductance $L_S$.*

## 4.7 The induction motor drive

The induction motor was historically the work-horse of industry. Again the same reasons as for the DC motor are valid; fairly cheap and easy to apply. The AC motor though, requires a three-phase supply to operate which is not that readily available in a vehicle. With a three-phase supply the motor can be directly connected to it and it will start-up automatically and thereafter it will run at almost constant speed. The basic relationships were given in section 3.2.

To make a variable speed drive possible with the induction motor, it has to be supplied from a power converter with variable voltage and frequency. Today the voltage source converters described in the power electronics section, are the completely dominating solution, Figure 49. The output voltage and frequency of the converter are controllable within a certain range.

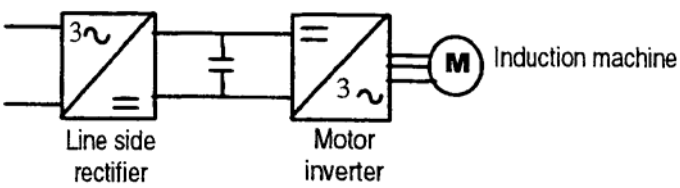


*Figure 49 Induction machine drive.*

The speed of the motor will roughly follow the frequency supplied from the converter, with just a small deviation due to the inevitable slip. It is not enough just to change the supply frequency in order to change the speed, the supply voltage also has to be adapted. This is due to the fact that the magnetisation of an induction motor is done from the supply side as there exists no magnets or field winding on the rotor. As for any machine the induced voltage is directly related to the field in the machine, so to keep the flux constant it is necessary for the voltage to vary linearly with the frequency

$$\Phi = k\frac{U_1}{f} \tag{4.19}$$

The machine operates at nominal (rated) flux in the range between standstill and base speed. Below base speed the pull-out torque is constant. In this region the torque the motor can deliver is then mainly determined by the current capability of the power converter.
At base speed, the converter has reached its voltage limit and as (4.19) shows, if the frequency is increased further the magnetic field will decrease inversely proportional to the speed. This is done so to say “automatically”, because if frequency is increased while the voltage is kept constant, there is less time to build a magnetic field and hence it will be lower. The machine is said to operate in the field weakening range. In the beginning of the field-weakening range the torque is reduced proportionally to the flux reduction, that is, as $1/f$. However, in the field-weakening range the pull-out torque decreases as $1/f^2$ and at high speeds the output torque has to be reduced proportionally to the pull-out torque, that is, $1/f^2$. The power above that speed is then not possible to maintain constant but decreases as $1/f$. Figure 50 concludes the most fundamental characteristics of a voltage source converter fed induction machine drive.

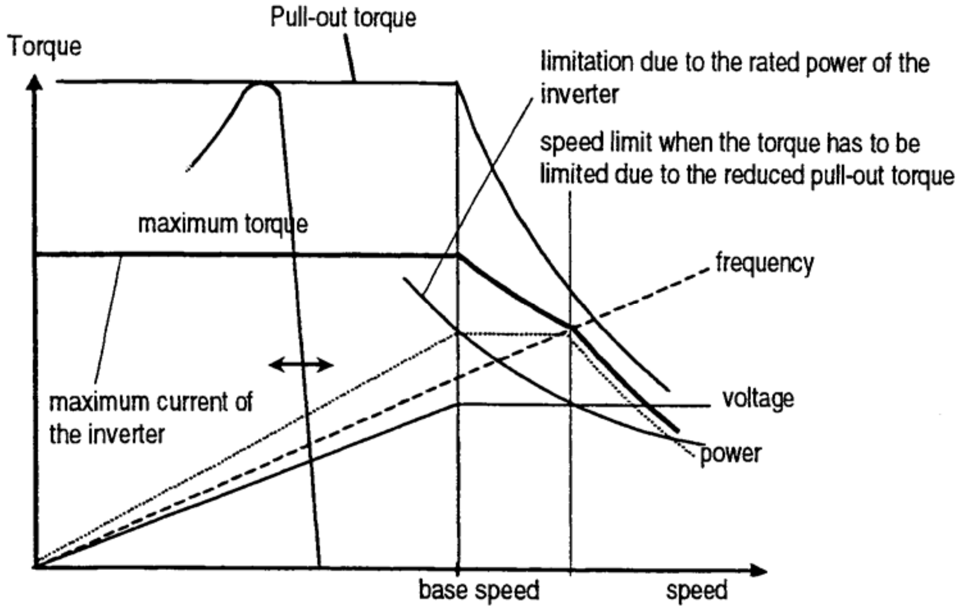


*Figure 50 Basic characteristic of an induction motor drive.*

### 4.7.1 Control methods for induction motor drives

Simple variable speed control schemes for the induction motor only controls the magnitude of applied voltage and frequency, see Figure 51. Basically the reference speed sets the applied frequency and voltage. However, with an increasing shaft load the required slip of the motor will increase. The torque is almost proportional to the active part of the current and therefore the applied frequency can be adjusted to a bit higher value so that the slip is compensated for.

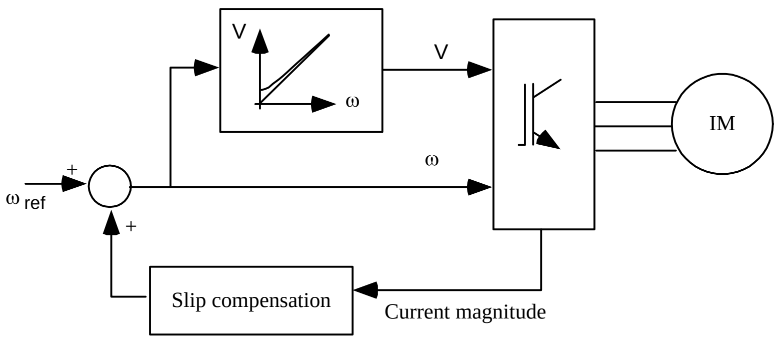


*Figure 51   IM drive with slip compensation.*

During the 80's, fast computers became available and that made it possible to use so called vector control, which makes the induction motor to appear as a DC motor. The torque production in the motor relies as usual upon an interaction between a magnetic field and a current. However, in the induction machine there is no easy relationshp between rotor position and field as it is in a PM motor. Therefore, a model is needed in which it is possible to keep track of the field and the current, this can be acheived by the vector control method. With this method, the current in to an induction motor is divided into two parts, one that controls the magnetisation and one that controls the resultant torque. The control method is outlined in Figure 52.

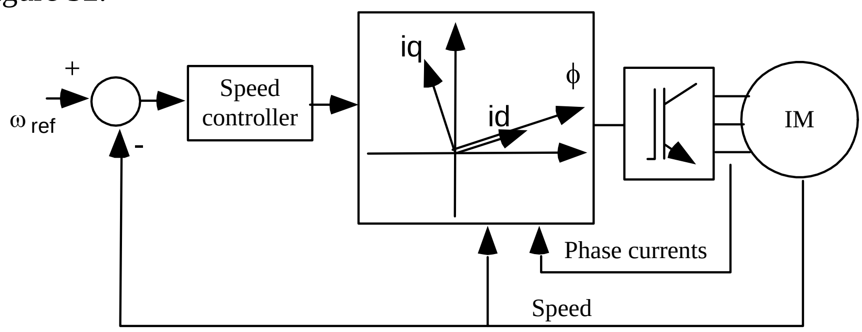


*Figure 52   Vector control of an induction motor.*

Finally for completeness, a method that is call Direct Torque Control (DTC) will be mentioned. It somewhat resembles the vector control but can be simpler to implement. In DTC there is no direct control of the magnetic field. Instead, the method uses a model of the motor to calculate the torque from applied voltage and current. The control idea is then to keep the torque within a tolerance band which in turn is controlled by the speed controller. If the torque becomes instantaneously too low, the magnetic field is advanced forward and thus "drags" the rotor forward and vice versa if the torque becomes too high, the magnetic field is stopped or retarded.
To summarise, the characteristic of a variable speed drive for the induction motor is very much dependent on the control and the power converter the system uses

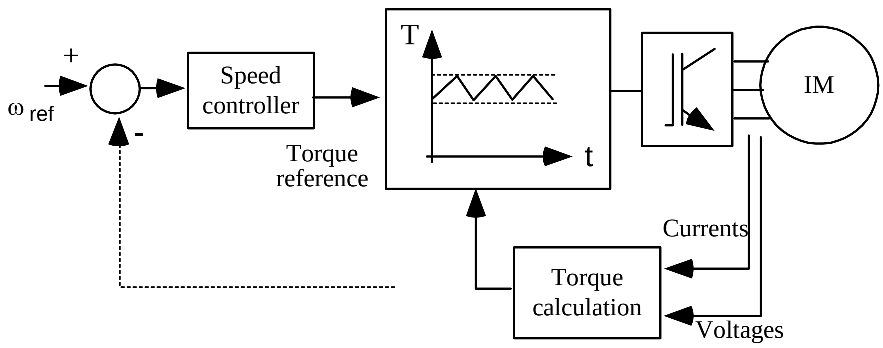


*Figure 53   Direct Torque Control (DTC).*

# 5 Special drive systems

There a many special drive systems developed for vehicle propulsion and in this chapter one of them, the 4QT system, will be described.

## 5.1 The 4QT-system

The 4QT system consists of, according to Figure 54, one internal combustion engine (ICE), two inverters, slip rings, a battery and the 4QT transducer. The 4QT transducer is an electric machine made up of two combined electric radial flux permanent magnet machines. It consist of one double rotor machine (DRM) and one conventional machine (Stator). The DRM consists of one inner rotor with windings fed through slip rings and one outer rotor with magnets. The Stator is a conventional stator with windings that interact with the outer rotor of the DRM. The magnets on the outer rotor are separated into one inner and one outer layer as shown in Figure 54.

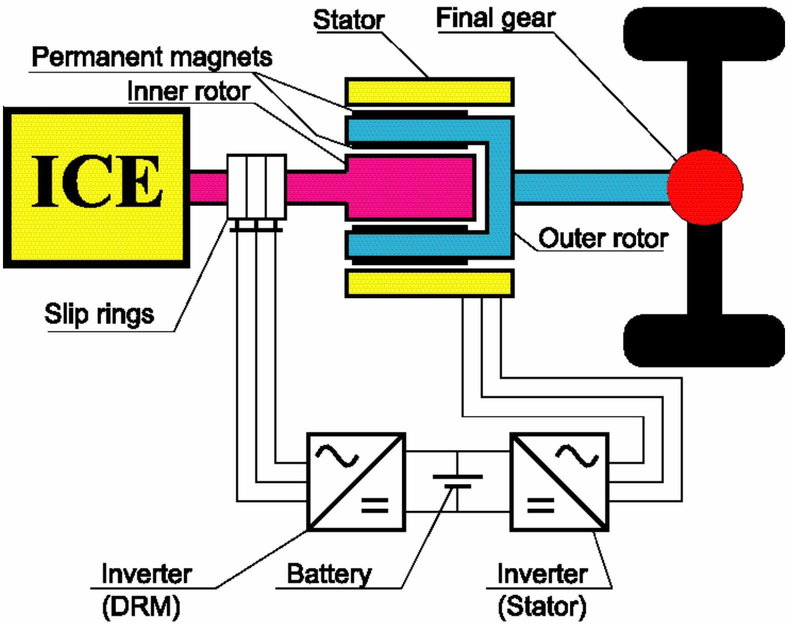


*Figure 54 The 4QT system*

Both machines are designed to work as motors and generators. The 4QT is mounted between the combustion engine and the final gear of a hybrid vehicle. Its function is to keep the operation of the ICE at maximum efficiency (Figure 55) during all driving conditions to minimize the fuel consumption. The 4QT changes both the speed and torque produced by the ICE at the optimal operation point to that required at the final gear. The DRM either increases or decreases the speed of the ICE to the speed required at the final gear. The Stator increases or decreases the torque produced by the ICE to the torque needed at the final gear. This enables the operation of the ICE at maximum efficiency at all speeds and loads of the vehicle. The 4QT replaces the gearbox, the clutch, and the flywheel in the vehicle but instead it needs a battery, two inverters and some control equipment. It is also possible to drive the 4QT-

equipped vehicle in pure electric mode but the driving range is then limited by the battery size.
As shown in Figure 55 the ICE efficiency is highest at high torques and at speeds that are not too high nor too low. The optimal operation line (OOL) is almost the same as the line of maximum torque. The two different lines are shown in Figure 55 as a solid line for the maximum torque and a dotted line for the OOL. The OOL is only used to obtain the maximum efficiency of the ICE, to obtain the lowest possible emissions the transient behaviour of the ICE has to be considered.

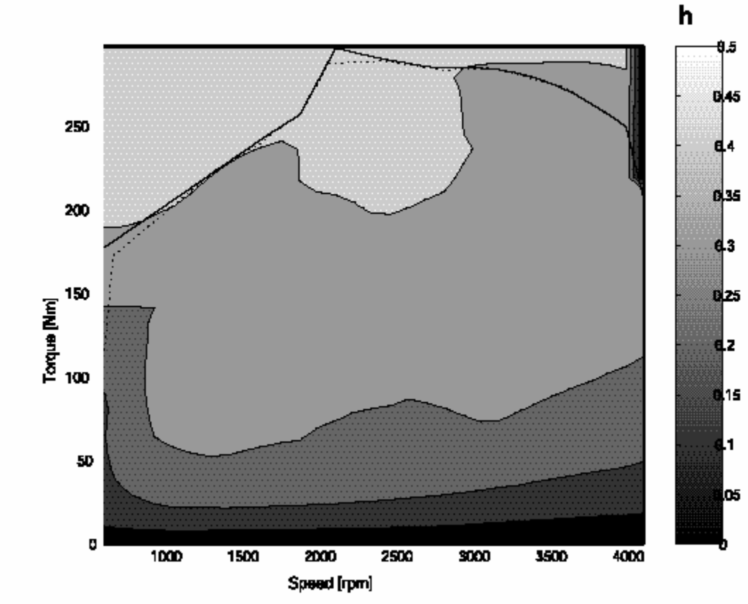


*Figure 55 ICE efficiency versus speed and torque. The solid line is the maximum torque and the dotted is the optimal efficiency line used in the simulations.*

To keep the ICE operation at the OOL the 4QT changes the speed and torque required at the final gear to the speed and torque along the OOL. This is shown in Figure 56. The required speed and torque at the final gear can be higher or lower than the OOL. In Figure 56 point A is the required torque and speed at the final gear. Point B is the equivalent operation point on the OOL of the ICE that produces the same power as required at point A plus the losses and the power for the auxiliary load of the vehicle. The 4QT changes the speed by  with the DRM from the speed required at the final gear to the optimal speed of the ICE. In the same manner the torque is changed by  in the stator. This behaviour maintains the operation of the ICE along the OOL. The 4QT is dimensioned for the difference in speed and torque between the ICE and the final gear and not as in a series hybrid vehicle where the electric machines are dimensioned for the maximum load.

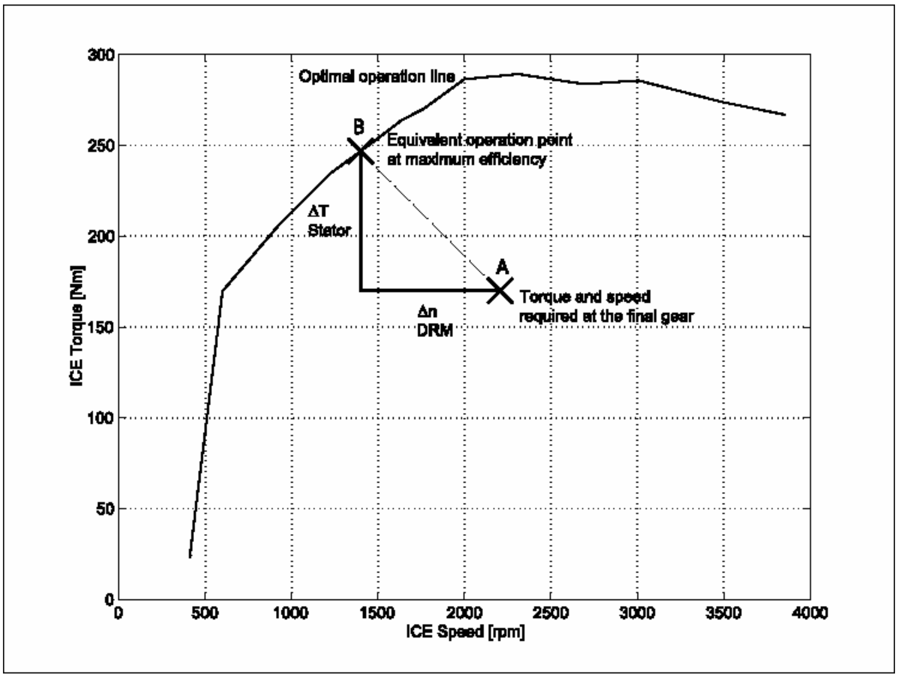


*Figure 56 The 4QT torque and speed changing strategy.*

## 5.2 Operation of the 4QT

Simulating a twelve-ton truck during the first 140s of the FTP75 drive cycle clearly demonstrates the operation of the 4QT. Figure 57 shows the vehicle speed and the speed and torque required at the final gear during the first 140 s of the FTP75 drive cycle. During this period the torque production in the ICE, DRM and stator are shown in Figure 58. Here it can clearly be seen that the ICE and DRM torques are the same because the DRM only changes the speed and transfers the ICE torque unchanged. The stator either increases or decreases the torque so it matches the torque required at the final gear. In Figure 58 the stator torque reaches very large negative values. In these cases both regenerative braking and conventional braking must be used

Figure 59 shows the speeds in rpm of the ICE, the inner rotor and the outer rotor. The DRM delivers the difference between the ICE speed and the speed at the final gear. The speed of the DRM can also be negative, even when the vehicle is moving forward. This can be mostly seen at low speeds when the optimal speed of the ICE is higher than that required at the final gear. The final gear speed in Figure 59 is the vehicle speed in km/h converted by the wheel radius and the constant final gear into the speed in rpm of the final gear input shaft.

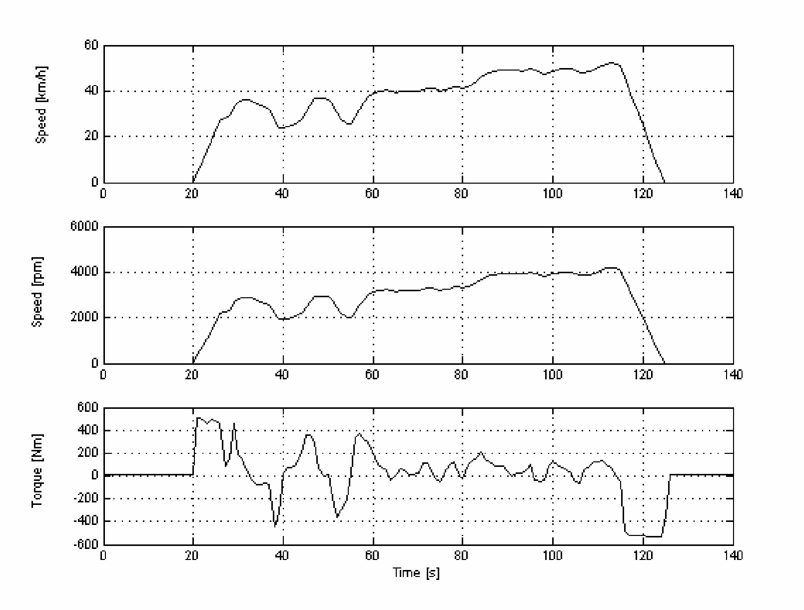


*Figure 57   Vehicle cruising speed, speed and torque at the final gear during the first 140s of the FTP75.*

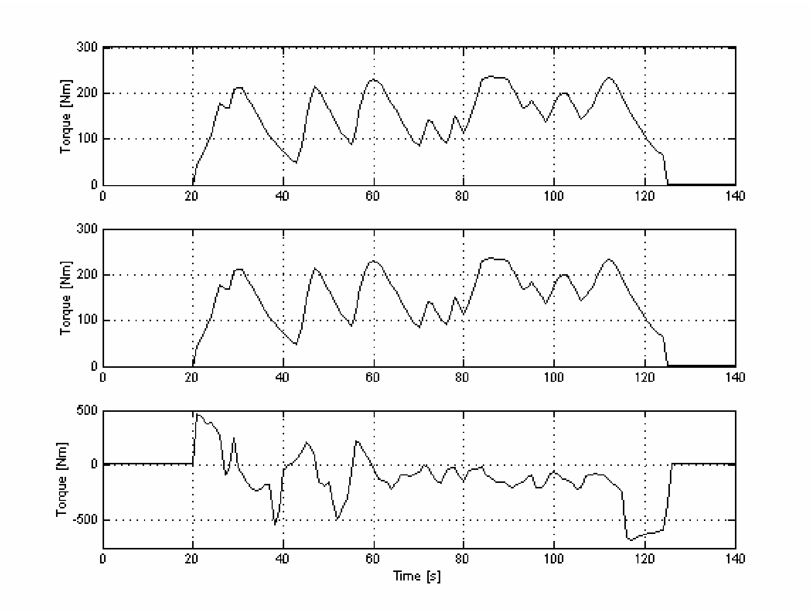


*Figure 58   ICE, DRM and Stator torques during the first 140s of the FTP75.*

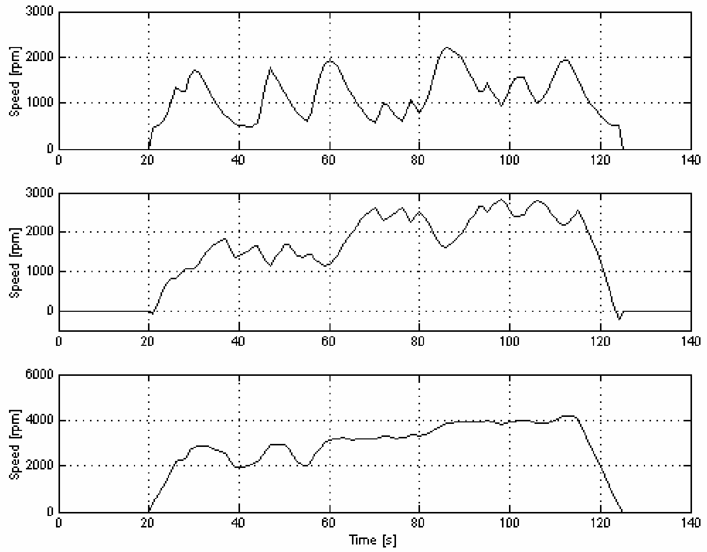


*Figure 59 ICE, DRM and outer rotor speed during the first 140s of the FTP75.*

In Figure 59the DRM speed is the speed difference between the inner rotor speed or the ICE speed and the outer rotor speed. As can be seen in the figures, for a vehicle equipped with a 4QT system the ICE should be dimensioned for the mean power consumption and the 4QT for the difference between the mean and the peak powers. The 4QT allows an optimal control of the ICE by changing the speed and the torque using the DRM and the Stator.

## 5.3 Different driving modes of the 4QT system

The 4QT system has its name from the four different driving modes it can operate in. Looking at a speed-torque diagram the 4QT can operate in all four quadrants defined with the origo at the operating point of the ICE.
These four modes can be described as:

- Increased speed and torque: The 4QT is taking power from the battery under heavy load. Both machines discharge the battery.
- Decreased speed and increased torque: The DRM decreases the speed and the Stator increases the torque. The DRM charges and the Stator discharges the battery.
- Decreased speed and torque: The DRM decreases the speed and the Stator the torque. Both machines are charging the battery.
- Increased speed and decreased torque: The DRM increases the speed and the Stator decreases the torque. The DRM discharges and the stator charges the battery.

All four modes will be further described in this chapter.

### 5.3.1 Increased speed and torque

In this mode, shown in Figure 60, both the speed and the torque are increased by the 4QT from the ICE to the final gear. This mode is for example used when the vehicle is driving at high speed and is accelerated. Figure 60 shows the power flow in the system. The power flows from the battery to both machines which lead to a decrease of the battery SOC (State of charge), so this mode of operation is time limited by the size of the battery.

### 5.3.2 Decreased speed and increased torque

In this mode, shown in Figure 61, the DRM decreases the speed and works as a generator feeding power to the stator and/or the battery. The Stator increases the torque from the ICE torque to the required torque at the final gear. The Stator gets power from the DRM and/or the battery. If this mode is used for a longer period of time all power that the Stator uses has to be produced by the DRM. This mode is used when the vehicle is driving at low speed and heavy load and when the optimal operation of the ICE is at a higher speed than the required speed at the final gear.

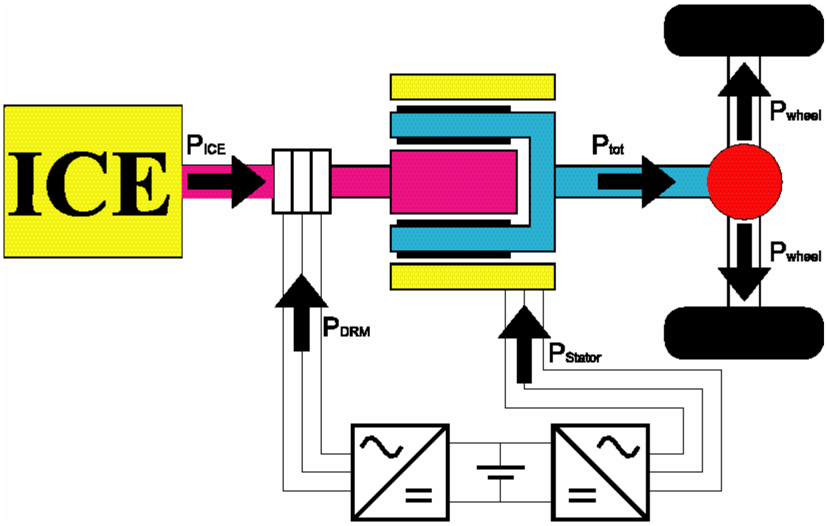


*Figure 60 Increased speed and torque.*

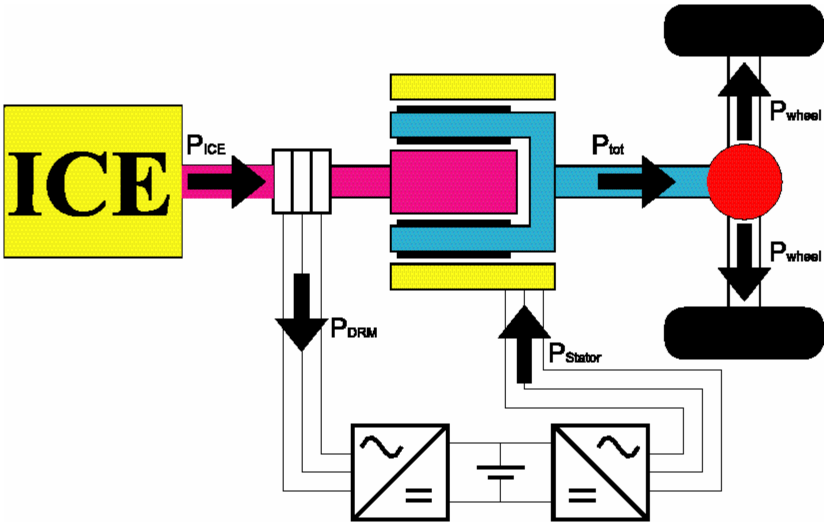


*Figure 61 Decreased speed and increased torque.*

### 5.3.3 Decreased speed and torque

If the SOC in the battery is low and the battery needs immediate charging both the DRM and the Stator can operate as generators at the same time. In this case the ICE is working with a higher speed and torque than required from the final gear. The DRM decreases the speed and feeds power to the battery via one inverter, the Stator decreases the torque and charges the battery with power via the other inverter. Figure 61 shows the power flow during this mode of operation. The ICE power is in this case the required power at the final gear plus power delivered to the battery through the DRM and the Stator.

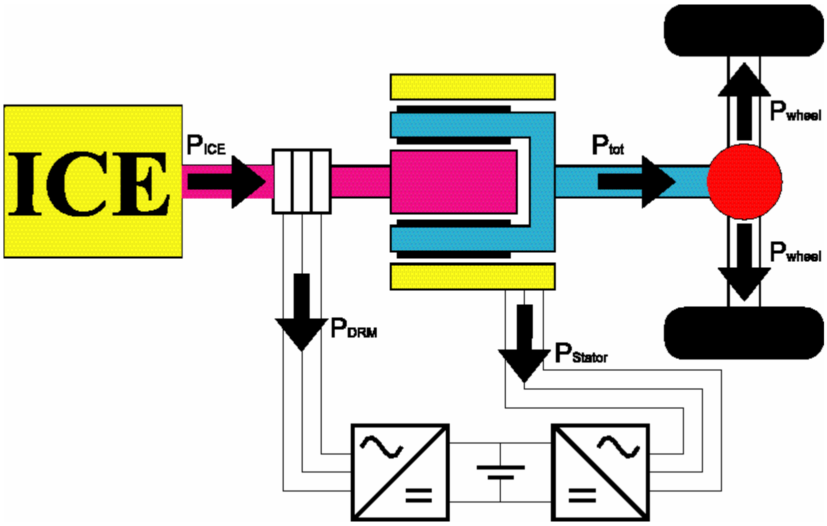


*Figure 62  Decreased speed and torque.*

### 5.3.4 Increased speed and decreased torque

The most common driving mode is increased speed and decreased torque, see Figure 63. This is because the ICE optimal operation is located at relatively low to moderate speeds but at high torques. During this mode the DRM takes power from the battery or from the Stator, which operates as a generator, and increases the speed. The Stator which, operates as a generator, decreases the torque. This driving mode gives at first sight the impression of a loop in the power flow, which is in fact true but the circulating power is very low compared to the power that flows straight through the system. As an example the circulating power is only 5% of the final gear power in simulations when driving a 12-ton vehicle at 100km/h on a flat road.

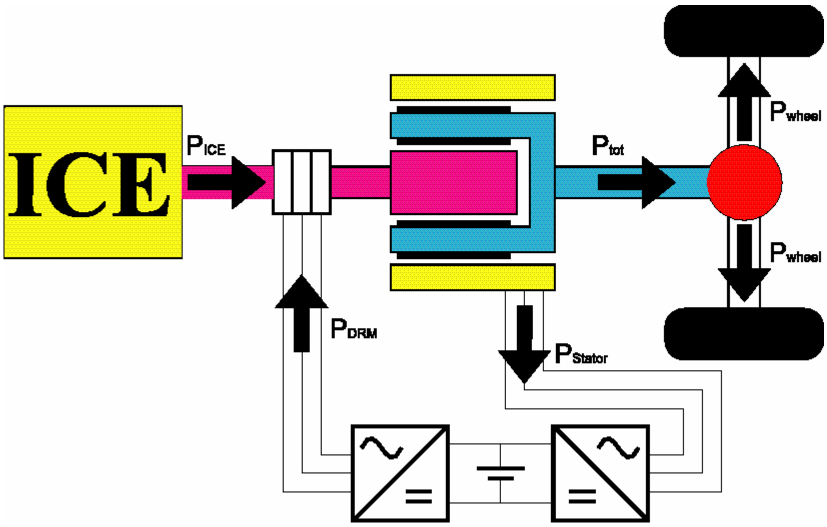


*Figure 63  Increased speed and decreased torque.*

### 5.3.5 Pure electric mode

There is in fact a fifth mode of operation, the pure electric mode, shown in Figure 64. Here the power from the battery is consumed by the two motors. When operating the DRM in this mode the torque that is produced by the DRM is also acting on the ICE shaft. This could lead to a situation where the ICE could start to rotate in the opposite direction to the normal operation because of the DRM torque. To avoid this a lock-up function of the ICE shaft is required when the DRM is operating in pure electric mode. This lock-up function should preferably be avoided as it gives one more component in the system and a minimum number of components is desired to get a low cost system.

One way to avoid this lock-up function is to use only the Stator during the pure electric mode operation. The drawback with this is that the electric performance becomes limited to the Stator power. This is not a big problem since the pure electric mode is mostly utilized at low speed and low power of the vehicle. The electrical power is also limited by the battery power and using both machines in pure electrical mode requires a battery with both high power and high energy capacities.

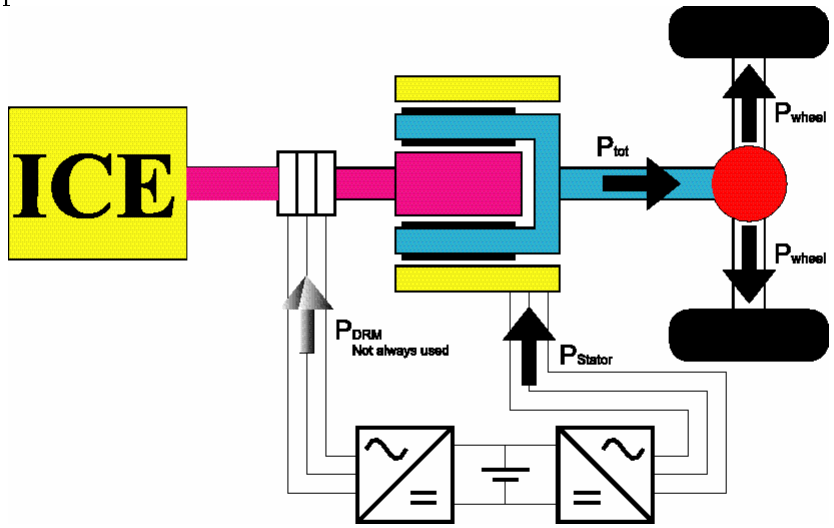


*Figure 64 Pure electric driving of the 4QT vehicle.*

The use of the 4QT system gives, the advantages of the 4QT system gives a more efficient vehicle compared to a conventional one.