Electric Vehicles

BMEVIVEM263

Dr. Gyuláné Vincze
Gergely György Balázs
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### Appendix A. List of quantities

<table>
<thead>
<tr>
<th>Name</th>
<th>Base unit</th>
<th>Used other units or Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>t</td>
<td>s</td>
<td>h (hour), 1h=3600s</td>
</tr>
<tr>
<td>v</td>
<td>m/s</td>
<td>km/h, 1m/s=3.6km/h</td>
</tr>
<tr>
<td>F</td>
<td>N</td>
<td>kN</td>
</tr>
<tr>
<td>Fₚ</td>
<td>N</td>
<td>kN</td>
</tr>
<tr>
<td>Fₚₚ</td>
<td>N</td>
<td>running resistance in horizontal road</td>
</tr>
<tr>
<td>Fₚ</td>
<td>N</td>
<td>maximum motive force without slipping</td>
</tr>
<tr>
<td>m'</td>
<td>kg</td>
<td>t=1000kg</td>
</tr>
<tr>
<td>g</td>
<td>m/s²</td>
<td>g=9.81m/s²</td>
</tr>
<tr>
<td>m'g</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>Θ</td>
<td>kgm²</td>
<td>accelerable rotating mass</td>
</tr>
<tr>
<td>α</td>
<td>rad</td>
<td></td>
</tr>
<tr>
<td>i'</td>
<td>%</td>
<td>i'=100tgα[%]</td>
</tr>
<tr>
<td>rₚ</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>P, p</td>
<td>W</td>
<td>kW, LE (Horse power), 1kW=1,36LE</td>
</tr>
<tr>
<td>η</td>
<td></td>
<td>η ≤ 1</td>
</tr>
<tr>
<td>M, m</td>
<td>Nm</td>
<td>small letter for instantaneous value</td>
</tr>
<tr>
<td>ϕ</td>
<td>Vs</td>
<td></td>
</tr>
<tr>
<td>Ψ</td>
<td>Vs</td>
<td>Ψ=Nϕ, where N is the number of turns</td>
</tr>
<tr>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U, u</td>
<td>V</td>
<td>small letter for instantaneous value</td>
</tr>
</tbody>
</table>
| \( I, i \) | electric current | \( A \) | small letters for instantaneous value
| \( R \) | electric resistance | \( \Omega \) |
| \( \omega \) | angular velocity | rad/s | \( n \) (angular velocity, \( 1/\text{min} \), \( \omega = \frac{2\pi n}{60} \approx n/9,55 \))
| \( \rho^* \) | magnetic pole pairs |
| \( f \) | frequency | Hz |
| \( \lambda \) | wave-length | m |
| \( s \) | slips |
Chapter 1. Introduction

The Electric Vehicles electronic lecture note is made for students of the BME Faculty of Electrical Engineering and Informatics, Electric Machines and Drives MSc branch. The main purpose of this lecture note is to give an overview of the electric vehicles’ drive system solutions, main structural principles, on-board and external joint electric equipments.

Generally the vehicles are the appliances of the public and cargo transportation that possess various size and comfort. The usual categorization with some typical vehicle types is listed as follows:

Vehicle categorization

The drive system solutions of the listed vehicles are disparate therefore these cannot be discussed generally together because these belong to different fields.

This electronic lecture note is only dealing with electric driven land-craft vehicles. Apart from the conventional vehicles it discusses in detail the novel levitated vehicles.

Only those vehicles are called electric vehicles which drive or moving is fully or partly performed by electric motor. Nevertheless all of the modern vehicles contain electric systems with different power level and various electric motor-driven on-board devices; there are numerous vehicles which are not driven by electric motor.

The vehicle design is one of the most complicated engineering creations moreover the vehicles’ electric drive system design is the top of the electrical engineering profession. This lecture note shows the variety, the special features and the specialty of the electric vehicles drive systems and for the easier comprehension it reviews the basic operation of the drive systems. It presents the most typical drive solutions and structures through the examples of concrete electric driven vehicles.

It is assumed that the students possess general electric engineering and basic drive technical knowledge, and they interested in this subject.

The lecture note consists of 8 main chapters.

The 1st chapter is dealing with the tractive requirements of the land-craft vehicles. It shortly summarizes the tractive force, the brake force and the tractive power demands requiring for moving of the vehicles, and other control functions need for safety moving.

The 2nd chapter summarizes the possible tractive methods, the mechanical drive system solutions and the electric motor implementation of the land-craft vehicles. The chapter gives an overview of the electric drive system sizing for given tractive demand.

The 3rd chapter presents the electric vehicles’ power supply methods. Larger part of this chapter is dealing with the overhead line power supply systems and the requirements of the network friendliness but other power supply methods are reviewed also, including the power supply of the levitated vehicles.

The 4th chapter presents the conventional brush-commutated DC motor driven public transport and rail vehicles through some vehicle examples.

The 5th chapter is dealing with the field orientated, inverter-fed induction motor drive systems, used for traction and presents some concrete vehicles equipped with modern drive system.
The 6th chapter presents the field orientated, inverter-fed synchronous motor drive systems, used for traction. The most interesting application, the linear synchronous motor traction is detailed.

The 7th chapter is dealing with the levitation methods and special problems of the levitated vehicles.

The 8th chapter is focusing on the drive system technics of the electric and hybrid-electric cars.

The following key words are used in this lecture note:

1. The vehicle electric drive performs the moving of the vehicle. The electric drive contains the electric motor, the power electronic circuit and the control and protective devices.

2. The main electric circuit consists of the electric circuits of each element required for the vehicle traction and operation.

3. The auxiliary devices are not involved in the vehicle traction. These devices are for signaling, controlling, protecting, information transferring and comfort, heating and cooling.

4. The auxiliary circuit consists of the electric circuits of each element performing operation of the auxiliary devices.
Chapter 2. Traction requirements, selecting vehicle drive

1. Forces influencing vehicle traction

Forces acting in vehicle movement can be divided into four groups:

1. forces pointing parallel to vehicle movement,
2. forces perpendicular to path of motion,
3. lateral forces acting on the vehicle,
4. inertial forces influencing the movement.

Forces a), b) and c) arise between the path (or medium of movement) and the vehicle.

Secure movement can be realized with strict monitoring and controlling the above forces. Main requirements of secure movement are:

1. vehicle moves with the expected constant speed and direction on straight-line path, it does not slip during acceleration or deceleration.
2. It does not (or with allowable degree) leave the planned path during change of direction.
3. canting, pitching and oscillation of vehicle body is damped properly and kept to acceptable level under operational circumstances.

Vector sum of active and passive forces pointing to movement direction determines whether vehicle accelerates, decelerates or moves with constant speed.

Active force in the movement direction can be:

1. motive force (pushing or pulling) $F$ acting in the movement direction controlled by the vehicle driving engine and
2. brake force $F_{\text{brake}}$ acting on opposite direction, controlled by several braking actions.

In vehicles rolling on wheels, motive and brake force acts between the path and the surface of the wheels and depends on the adhesive conditions. Such a limit does not appear with levitated, linear motor-driven vehicles.

Passive force in movement direction is the vector sum of forces acting against the movement. Force opposite to movement is so-called tractive resistance $F_m$. Most part of tractive force is air resistance (windage), which depends quadratically on vehicle speed, usually. Also, part of the tractive resistance is the rolling resistance and, in case of levitation, the so-called magnetic resistance depending on levitation mode. If the gradient angle of the path is $\alpha$ then gravitational force $m' g$ calculated from the vehicle mass $m$ has passive component $m' g \sin \alpha$ parallel to the movement, which is opposite to movement when climbing up and in the same direction (additional) when going down the slope. Gradient of the road is given by $i^* = 100 \operatorname{tg} \alpha [%]$. 

Figure 1-1. Forces acting parallel and perpendicular to movement path

Vector sum of active and passive forces in the movement direction determines acceleration of the vehicle $\frac{dv}{dt}$:
Traction requirements, selecting vehicle drive

\[ F \cdot (F_m + m^* g \sin \alpha) = m^* \frac{dv}{dt} \]

1-1

\( m^* \text{ red} \) is resultant accelerated mass of the vehicle. If we have to accelerate a rotating mass inside the vehicle, for example the motor with inertia \( \Theta \text{ m} \), resultant mass is \( m^* \text{ red} \geq m^* \), where \( m^* \text{ red} = m^* + (\omega \omega' \omega') \Theta \text{ m} \) (\( \omega \omega' \): rotational speed of motor).

1. If \( F = F_m + m^* g \sin \alpha \), which means that motive force equals to passive forces, then vehicle moves with constant speed, its acceleration is zero.

2. If \( F > F_m + m^* g \sin \alpha \), then vehicle accelerates, if \( F < F_m + m^* g \sin \alpha \), it decelerates.

3. If \( F \) goes to negative, then vehicle is in brake mode.

Forces acting perpendicular to movement path cannot be controlled in most of the land crafts, which transfer to road or rail. Exceptions are levitated vehicles.

Passive forces perpendicular to movement has two components, gravitational force pointing down, and lifting force pointing up. Gravitational force is usually much bigger. On horizontal surface, the whole weight of vehicle \( m^* g \) acts perpendicularly to path, on non-horizontal surface only its perpendicular projection \( m^* g \cos \alpha \), as can be seen in Figure 1.1.b. Lifting force is a component of air resistance and depends on the shape and speed of vehicle.

Controllable perpendicular active forces arise only in levitated vehicles. If active levitation forces equal to passive forces, then levitation distance is constant, otherwise the distance changes.

At traditional vehicles moving on wheels, sum of forces perpendicular to path \( (m^* g \cos \alpha - F_{lf}) \) play an important role. Part of this force \( G_w \) appearing on one wheel presses the wheel to the road, and this force determines the possible tractive and brake forces. Circumferential force \( F_a \) that can be transferred on one wheel depends on pressing force and grip coefficient \( \mu_w \) of the wheel (\( k \) is number of wheels):

\[ F_{tk} = \mu_w G_w, \quad \text{where} \sum_k G_k = \left( m^* g \cos \alpha - F_{lf} \right) \quad \text{and} \quad \sum_k F_{tk} = F_t \]

1-2

\( \mu_w \) grip coefficient depends on the conditions of the road and wheel, weather, velocity of the vehicle and is different for each wheel, usually. Sum of the transferable forces \( F_t \), is limited because of the limited gripping coefficient, \( F_t \leq F_{max} \). An ideal tractive (or brake) force can be calculated for vehicles with wheels, which can be transferred to horizontal road (\( \alpha = 0 \)) with low speed (\( F_{lf} = 0 \)), in good road conditions and dry weather. This ideal force is called gripping limit, \( F_{\mu} \).

\[ F_{\mu} = \mu_{max} m^* g \]

1-3

If tractive force of the motor or brake force of the brake system is lower than the limit, then traction is realized with normal rolling. If tractive force is higher than momentary transferable force \( F_{\mu} \), then wheel spins, if brake force if higher, then wheel blocks (see more details in Section 1.5). Such spinning or block effect does not appear in levitated vehicles.

Lateral forces cannot be controlled in most of land crafts, they are passive forces and are transferred to the road or rail. Rail or wheel counteracts these forces coming from turning or side-wind.

However active controlled lateral forces are needed to counteract lateral passive forces in levitated vehicles or to control lateral movement.

Inertial forces influencing movement of the vehicle body generate canting, pitching and oscillation of the body. Dumping of these forces is required for stabilization of the vehicle. There are special solutions for damping and stabilization.
2. Designing motive force

Acceleration of a vehicle $dv/dt$ with mass $m$ is determined by the vector sum of active and passive forces in the movement direction, as can be seen on equation (1.1). Force $m'gsina$ resulting from the gradient of the road depends on what terrain the vehicle is designed for. Tractive resistance $F_n$ is determined by the type and shape of the vehicle and increases non-linearly with velocity. Sum of the passive forces is called running resistance $F_e$. Running resistance vs. velocity for different road gradients are shown in Figure 1.2.a. Tractive resistance $F_n$ can be got from running resistance $F_e$ where gradient $i'=0\%$.

From the viewpoint of motive force, vehicle drive has to be designed so that motive force available is greater than running resistance characteristic used for design in the whole velocity range. Based on equation (1.1), acceleration reserve is the difference of momentary motive force and running resistance $F-F_e$. If the available motive force of the vehicle drive is that shown in Figure 1.2.a, then acceleration reserve is the greatest at starting and reduces to zero when $v=v_{max}$, on a horizontal $i'=0\%$ road. Final speed on a horizontal road is limited by this, as motive force $F$ is not greater than momentary running resistance $F_{e,v_{max}}$, i.e. the vehicle cannot accelerate. In this operating point, motive power required to keep velocity $v_{max}$ is:

$$P = Fv_{max} = F_{e,v_{max}}v_{max}$$

Drives are designed for this final $P=P_{motor,max}$ power, and this designed power is usually available in a wide range of velocity, as can be seen in Figure 1.2.b. Motive power is constant in a wide velocity range if $P=Fv$ is constant, which means that motive force decreases hyperbolically when increasing velocity. Constant power range can be used until maximal motive force $F_{start}$, i.e. between $v_{0}$ and $v_{max}$, $F_{start}$ is calculated from the required starting acceleration (according to equation 1.1). Gripping limit calculated in equitation 1.3 should also be taken into account when designing vehicles running on wheels, as motive force greater than grip limit cannot be transferred via wheels.

Such an ideal motive force characteristic can be seen in Figure 1.2.a. This characteristic, of course, is a limit characteristic. Under this curve, motive force has to be controllable freely, according to the demanded
momentary acceleration. A starting and acceleration process, which takes full advantage of the ideal motive force curve, can be seen in Figure 1.3. Motive force $F$ is set to value $F_{e,v_{max}}$ when final velocity is reached, and acceleration reserve decreases to zero. Dynamic behavior is usually described by starting acceleration value $v_{0}/t_{0}$. Acceleration that can be seen in the figure is used rarely; instead, softer acceleration is used that is more convenient to passengers.

Motive force and running resistance of different vehicle types are shown in Figure 1.4 and 1.5.

Figure 1-4. Specific tractive characteristics of urban vehicles

In the figure, specific motive force and power characteristics are shown, relative to vehicle mass $m_{v}$. Urban vehicles are designed for relatively low speed and high gradient angle. For example, angle $i_{v}=20-25\%$ is used for garage ramp, and this slope must be performed.

Figure 1.4 is prepared for urban vehicles and gives minimal motive force and power that have to be taken into account during design.

Figure 1.5 shows motive force characteristics of locomotive series V43, popular in Hungary, for two different gradient angles and pulled masses.

Figure 1-5. motive force characteristics of locomotive series V43.

Locomotive was designed for various applications (goods, slow and express trains). Allowable starting force $F_{\text{start}}$ is limited by grip limit $F_{\mu}$, in equation (1.3).

Characteristics of motive force of engines with maximal voltage and current are indicated by lines 1 and 2. Line 1 is for maximal excited motor, and line 2 is for maximal allowable field weakening ($42\%$).

Motive force range under line 3 can only be used for continuous and long time mode, under motive force $F_{\text{hour}}$. Constant motive power is used between points A and B. Motive force for momentary acceleration demand can be set with voltage regulation and field weakening under limit characteristics. Voltage of the motor and field weakening can be changed with steps for locomotives V43.

3. **Designing brake force in vehicles**

In every vehicle, at least three independent brake systems must be used for security reasons:

1. normal operation brake system,
2. security brake system,

3. arrester brake.

**Arrester brake** secures the vehicle in standing position without additional energy supply.

**Normal operation brake** in an electric vehicle is realized with controlling brake mode of the driving electric motor, almost without exception, despite of the fact that brake effect can only arise on driven wheels in case of vehicles running on wheels. (In case of levitated vehicles, brake mode of driving linear motor can affect along the whole length of the vehicle.) Brake mode of an electric drive can be lossy, or lossless, with regenerated energy. In modern vehicles, regeneration of braking energy plays an important role during design. Brake with loss (realized with resistance) is only used if regeneration cannot be used because of some reason. In regeneration brake mode, brake force is limited by maximal regeneration brake power and maximal brake force, just like during traction mode (Figure 1.6).

![Traction Characteristic Extended to Brake Mode](image)

**Figure 1-6.** Tractive characteristic extended to brake mode

Novel electric vehicles are designed so that the whole energy can be regenerated, i.e. regenerated power equals to the used power during traction.

Energy saving that can be realized with regeneration is 5…35% of the input energy, depending on the road conditions and number of stops.

**Security brake system** is always mechanical and not electric. Hydraulic or pneumatic frictional brakes are used in vehicles with wheels and they are mounted on all wheels. In levitated vehicles, air resistance is increased to provide mechanical brake, this solution is called aerodynamic brake.

**Normal mode and security brake systems** are separated in most vehicles, and can be operated jointly or separately. Brake control is designed so that joint total brake force by normal mode and security brake should be controllable, too, and brake force should be developed continuously, without steps.

**Control of brake** has several aims:

1. to stop the vehicle securely,
2. to set a comfort deceleration in time for the passengers,
3. anti-blocking of the wheels, in case of vehicles with wheels.

### 4. Operational modes of vehicle drives

Motive and brake force are opposite, as can be seen in Figure 1.6. In the figure it is not indicated, but most vehicles has to be able to move forward and backward. Operational modes needed for traction can be seen in Figure 1.7.
Traction requirements, selecting vehicle drive

Figure 1-7. Operation modes, 4/4 quadrant operation

In I and III quadrant of a general 4/4 quadrant mode, the motive power is \( P = Fv > 0 \), in this case drive operates as a motor. In II and IV quadrants \( P = Fv < 0 \), in this case drive operates in brake mode. Modern vehicle drives can change between quadrants without mechanical or electric switches, i.e. drive is also 4/4 quadrant. There are drives suitable only for less quadrants. For example, internal combustion engines can operate only in one quadrant, forward and backward reversal has to be done mechanically and brake is realized only mechanically, except power brake.

5. Spinning and blocking of wheels

Force that can be transferred on the surface of the wheels depends on force pressing the wheel to the road and the gripping coefficient, according to equation (1.2). There is a nonlinear relation between the motive force required for traction and force transferable with wheels, as can be seen in Figure 1.8.a.

Figure 1-8. Grip characteristics, a.) transferable motive force on wheels, b.) grip limit vs velocity

As the figure shows, transferable force follows the required value, indicated with dashed line, but curves separate sooner or later, depending on weather conditions. Until transferred force can follow the required force, the vehicle is in normal rolling mode (with small slip). In this case the difference of the two forces is the rolling resistance, which depends on wheel deformation, wheel and road conditions and speed of the vehicle. Increasing the required force (engine torque, brake force), rolling friction becomes slipping friction, and transferable force becomes smaller than required, and it has limit value. Momentary limit \( F_{\text{max}} \), indicated in Figure 1.8.a, highly depends on weather and other conditions. The biggest from these limits is the gripping limit \( F_\mu \), indicated in equation (1.3).

Gripping limit depends on vehicle speed, decreases when velocity increases, as can be seen in Figure 1.8.b. It has two reasons. One is that lifting force, ignored in equation (1.3), increases with higher speed, so force pressing the wheels on the road decreases. Another is that the effect of road rugosity becomes more and more higher when speed increases, wheels often move off the road. As gripping ability decrease with speed, and rolling resistance increases, a speed limit (300-350 km/h) has to be used for traditional trains.

In traction mode, force higher than transferable (shaft torque/radius) spins the wheels, and blocks the wheel in brake mode. Both effects are harmful, so control of traction and brake force has to be used. To characterize spinning and blocking, relative slip of a wheel is defined as follows:

\[
\mathcal{S} = \left( v_{\text{eff}} - v_{\text{vehicle}} \right) / v_{\text{vehicle}}
\]
where \( v_{cc} \) is circumferential speed of the wheel (Figure 1.9.b). To calculate slip precisely, we should know the speed of the vehicle even if spinning has already started. In practice, angular velocity \( \omega_w \) is measured and circumferential speed can be calculated as \( v_{cc} = r_w \omega_w \). Speed of the vehicle can be calculated with average angular speed \((\omega_{av})\):

\[
v_{vehicle} = r_w \omega_{av} = r_w \left( \omega_1 + \omega_2 + ... + \omega_k \right) / k_m
\]

1-5

where \( r_w \) is radius of wheel, \( k_m \) is number of measured wheels. Calculation is less accurate if more than one wheel slides and another uncertainty is the radius since wheel can deform during wear and load. \( v_{cc} > v_{road} \) (see Figure 1.9.b) and \( s > 0 \) during sliding, and \( v_{cc} < v_{road} \) and \( s < 0 \) during blocking, where \( v_{road} = -v_{vehicle} \). Figure 1.9.a shows the relation between the absolute value of relative slip and gripping coefficient. This relation is similar to all vehicles running on wheels, but \( \mu \) and \( s \) values can change significantly, for example for vehicles running on rail or road. A short slip range can be determined for a vehicle type where there is a linear relation between gripping coefficient and slip. This range is the range of normal rolling. If gripping worsens, relative slip goes outside of this range (as an indicator) in case of spinning or blocking.

![Figure 1-9. a) Grip coefficient vs relative slip, b.) spinning, c.) blocking](image)

**Anti-spin of wheels** operate in tractive mode and the torque of traction motor(s) is controlled (limited). Anti-spin system limits the torque so that relative slip is inside the narrow range shown in Figure 1.9.a, i.e. wheels can roll and transfer force to the road. The role of anti-spin is to prevent spin of wheels and, in case of rails, to protect rails and wheels. Wear of rails in case of spinning or blocking is a problem in high-speed trains at stations and places where stop and start happen often. To increase grip, sand technique is often used for vehicles running on rail.

**Anti-blocking of vehicles running on wheels** operates in brake mode and (total) brake force is limited in case of using several brake systems. There are two goals of anti-blocking. In case of rails anti-blocking is designed to prevent slipping to protect rail and wheels and to ensure rolling of wheels. In case of tyres, anti-blocking system limits brake force so that transferrable brake force on wheels should be maximal. This goal can be reached with about 5% relative slip where gripping is maximal. Such a brake force control is called ABS.

(References used in this section are: [1][5])
Chapter 3. Types of traction, location and types of traction motors

1. Electric vehicles with internal and external traction motors and linear motors

*In a vehicle with internal traction motor* one or more electric traction motors are placed “on-board” with all auxiliary mechanical elements (mechanical drive, gear, shock-absorber). Motor increases the mass of the vehicle. Most of the vehicles are equipped with internal and rotating motors.

*In a vehicle with external traction motor* the traction motor is placed into an engine room outside the vehicle body, its mass does not loads the vehicle body. Instead, engine room, traction mechanics, tow rope and suitable track is needed for the traction of the vehicle.

Traction motor of *linear motor vehicles* is placed partly on the vehicle and partly on the track. In this construction, mass of motor inside the vehicle can be much lower than in vehicles with internal motor. Contrary, trail needed for linear motor drive is more complicated and expensive than trail of traditional vehicles. Linear motor drive is usually used in levitated vehicles. Motive force arises between the two parts of the linear motor without mechanical connection.

2. Single motor and multimotor drives

Most of the land crafts roll on wheels and are driven by internal rotating motor. The number of wheels and mechanical solutions for traction are very different in vehicle constructions. Regarding the number of motors the vehicle can be driven by a single motor or multimotor.

*Single motor vehicle* can be designed if requirements for motion force and traction power can be fulfilled with one motor.

Single motor vehicles can be divided into three groups:

1. electric cars, hybrid buses, trolleys,
2. electric bicycles and other low power electric vehicles,
3. linear motor vehicles, as a special case.

The construction of the vehicles in the first group is usually similar to vehicles with internal combustion engine, and electric motor is connected to front or back wheel axles with cardan shaft and differential gear (Figure 2.1.a). Gearbox with variable transmission and clutch is not needed in electric vehicles.

If there is a fix transmission between the angular speed of motor and wheels then this transmission is required to fit the angular speeds. In low power vehicles even simpler, v-belt or chain-drive is used, or a wheel hub motor placed on the wheel with flat, disc-type shape.

![Figure 2.1. Drive of electric cars, a.) single motor drive, b.) wheel hub motor drive](image)

Vehicles with *linear motor drive* can be considered as special single motor vehicles where motor is along the whole body.
Multimotor drive can be used in low or high power vehicles, too.

An example for multimotor low power vehicle is an electric car with separately controllable wheel hub motors in every wheel (Figure 2.1.b). Usually, rpm of the motor and the wheel are the same. Motors drive the wheels directly and not the axle. Such a drive has mechanical problems as mass of wheels increase, and there is a flexible connection between rotor and stator of the motor.

There are several reasons to design high power multimotor vehicles:

1. One reason is electrical and is based on conventions. Voltage on one motor can be changed with serial or parallel connection of the motors. Changing serial and parallel connections of two motors is used in two-motor trams and underground trains, for example.

2. The other reason is mechanical. When using more motors construction can vary. Motive force can be divided to several wheels, power required for traction can be divided between motors, and more, smaller motors are easier to place inside the body.

Typical multimotor vehicles are electric locomotives where motors are placed on bogies, in several variations. A common sign system is used to indicate the mechanical solution. For example, B’B’ sign means vehicle with two bogies with two-two pair wheels and one motor per bogie, B.C., sign means two bogies with two wheel pairs on one bogie (sign B) and three on the other (sign C), and every wheel pairs driven by separate motors (index o), which means 5 motor drives altogether.

Figure 2.2 shows driving motor placed on wheel axle. There is a connection with rubber core and cardan shaft between the motor and axle which enables flexible displacement.

Point of interest of this solution is that there is a separate brake axle to place the brake discs which connects to the axle of the motor through the “big gear”. In this way, motor is not influenced by the heat of brake discs.

Novel multimotor drive solutions can be found in low floor urban/suburban vehicles. Because of low floor (350 mm or below step-in height), wheels on the left and right cannot be connected with axle, contrary to locomotives. Novel types axles are required.

A low floor vehicle with two-two wheels behind each other with common drive can be seen in Figure 2.3. Examples for this solution are Swiss made COBRA and Combino trams running in Budapest. There are electric motors on left and right sides which drive two wheels on the same side (indicated with yellow in the figure) with two-side cardan axles. There are seats above the wheels. A specialty of vehicle COBRA shown in figure 2.3 is that its axles are steered mechanically (automatically from the side of the vehicle), and this solution provides exceptional advantages in curves, regarding to wear and noise.
3. Fitting characteristics of rotating motors to traction requirements

Traditional cylindrical rotating machines are designed for high rotational speed so that their diameter would be the smallest possible. This rotational speed is 6-7000/min for vehicle motors, or 6-700 rad/s as angular speed. The fixed ratio \( r = \omega_m / \omega_w \) between angular speeds of motor \( \omega_m \) and wheel \( \omega_w \) must be set so that maximal motor rotational speed corresponds to final speed of the vehicle.

Calculating speed of vehicle \( v \) from angular speed of motor is shown in (2.1.a), where \( r \) is radius of the wheel. This calculation is for ideal conditions, assuming that there is no slip, spin, so circumferential speed of wheel \( r \omega_w \) equals to vehicle speed.

\[
v = r_w \omega_w = r_w \omega_m \left( \frac{1}{r} \right)
\]

2-1 a.

\[
F = \frac{1}{r_w} r M_{\text{f}}
\]

2-2 b.
The expression between the torque of motor $M_m$ and its motive force is shown in equation (2.1.b). Losses of the drive can be taken into account with efficiency $\eta < 1$. One motor can drive several wheels, in this case motive force (2.1.b) is distributed among the wheels, for example among the two driven wheels in Figure 2.1.

If several motors drive the vehicle then motive forces of the motors are summarized in a way that angular speed $\omega_w$ of the wheels are constrained through the road. A problem can be to distribute the load among the motors equally, there are different solutions for this in different vehicles.

Variable transmission gearbox used for internal combustion engine drives can be eliminated if the mechanical characteristic $M_m - \omega_m$ of the electric drive fits to traction need $F_v$ of the vehicle without modification. Fitted characteristic $M_m - \omega_m$ of the electric motor means that all of its points, calculated as above, suits to ideal traction characteristic, as shown in Figure 2.5. Load torque characteristics calculated from running resistance to motor axle is also indicated in Figure 2.5.b.

Electric power $P_m = M_m \omega_m$, required for traction can be calculated from tractive power $P = F_v$, taking into account drive losses:

$$P_m = \left( \frac{1}{\eta} \right) P$$

Power $P_m$ is the sum of the powers of the motors in case of a multimotor solution. In this case, we have to take into account that the distribution of loads among the motors are not even, for example load can be higher than average because of the wear of the wheel. Differences must be taken into account when designing the motors.

4. Types of electric vehicle drives

As can be seen above, drives with mechanical characteristic fulfilling the requirements indicated in Figure 2.5, can be used for traction without mechanical gear.

The following drives can be used:

1. series excited DC motor drive with commutator, extended with field-weakening range;
2. inverter-fed field-oriented controlled induction motor drive, extended with field-weakening range;
3. inverter-fed current vector controlled, permanent magnet, sinus-field synchronous motor drive, extended with field-weakening range (PMSM drive);
4. multi-phase, permanent magnet, rectangle field synchronous motor drive (so-called ECDC or BLDC drive);
5. switched reluctance motor (SRM) drive (rarely).

Earlier, one-phase commutator motor drives were also used, but not nowadays.

4.1. Using per-unit system for electric machines
To simulate the behaviour of electric machines, per-unit system is often used. With per-unit system, several behaviours and control modes can be compared easier, and it is also easier to evaluate the simulation results. The quantities in per-unit indicated with superscript comma express relative values related to nominal values indicated with index \( n \). Important per-unit quantities for DC machines are: 

\[ I' = \frac{I}{I_n}, \quad U' = \frac{U}{U_n}, \quad \phi' = \frac{\phi}{\phi_n}, \quad M' = \frac{M}{M_n} \]

where \( M_n \) is nominal torque determined by \( \phi_n \) and \( I_n \).

4.2. Park-vector method for investigating AC machines

This section summarizes the basics of Park-vector method used for three-phase AC electric machines, as it is required for the further parts of this book.

Three-phase electric machines are usually described by voltage, flux and torque equations. Original equations for phases \( a, b, c \) form an equation system where interactions between phases are also described. This equation system is hardly usable because of inductive couplings. As interactions are cyclic and symmetric in three-phase machines, a transforming method is available where vector based descriptions are available instead of phase quantities. The advantage of this transformation method is that three phase equations are simplified to two equations (without coupling between them): equations for Park-vectors and zero-sequence components. Equation for zero-sequence components can be eliminated if \( (i_a + i_b + i_c) = 0 \) is fulfilled with construction, for example in machines with star connected winding and not-connected star point.

Vector description is made with Park-vectors calculated with operators \((1, \tilde{a}, \tilde{a}^2)\), where \( \tilde{a} = \alpha e^{\frac{j\pi}{3}} = \frac{1}{2} + \frac{j\sqrt{3}}{2} \)

and \( \tilde{a}^2 = e^{\frac{j2\pi}{3}} = -\frac{1}{2} - j\frac{\sqrt{3}}{2} \).

Vector description of three-phase electric machines uses the vectors constructed in the way

\[ \vec{u} = \left( \frac{2}{3} \right) \left( u_a + \tilde{a} u_b + \tilde{a}^2 u_c \right), \quad \vec{i} = \left( \frac{2}{3} \right) \left( i_a + \tilde{a} i_b + \tilde{a}^2 i_c \right) \text{ etc.,} \]

where \( u_a, u_b, u_c, i_a, i_b, i_c \) etc. are instantaneous values of phase quantities. Using these vectors a Park-vector based equation system can be created.

Park-vector equations describe the system unambiguously if inner or outer zero-sequence component voltage \( u = (1/3)(u_a + u_b + u_c) \neq 0 \) cannot create zero-sequence current \( i = (1/3)(i_a + i_b + i_c) \), as \( (i_a + i_b + i_c) = 0 \) requirement is fulfilled with construction.

![Figure 2-6. Current Park-vector](image)

Park-vectors calculated as above are complex quantities resulting from the transformation, and their real and imaginary components, magnitude and angle can be calculated in every moment. Advantages of vector description are that vectors can be drawn in plane field, and momentary quantities are easy to calculate. For example, knowing current vector \( \vec{i} \) phase currents \( i_a, i_b, i_c \) can be calculated, as shown in Figure 2.6.

Instantaneous three-phase quantities can be calculated from a vector in every moment with a simple projection rule; they can be calculated from the projections to the \( a, b, c \) axes \((1, \tilde{a}, \tilde{a}^2 \) directions). In the example, \( i_a \) is positive, while \( i_b \) and \( i_c \) are negative and have almost half values, comparing to \( i_a \).

Transient processes of three-phase electric machines can be represented easily with Park-vectors, and vector description provides possibility to coordinate transformation, for example to rotating coordinate system.

Calculating electric power with Park-vectors

Instantaneous power described with phase voltages and currents is:
Types of traction, location and types of traction motors

\[ p = u_a i_a + u_b i_b + u_c i_c \]

2-3

Park-vector description of the same power, together with zero-sequent components \( u = (1/3)(u_a + u_b + u_c) \) and \( i = (1/3)(i_a + i_b + i_c) \), is:

\[ p = \left( \frac{3}{2} \right) \bar{u} \cdot \bar{i} + 3u_0 i_0 \]

2-4

In this equation dot means scalar product, i.e. \( \bar{u} \cdot \bar{i} = |\bar{u}| \cdot |\bar{i}| \cos \phi \), where \( \phi \) is the angle between voltage and current vectors. As \( i_0 = 0 \), usually, zero-sequent power component, the second part of equation (2.4) is often not indicated.

(References used in this section are: [6]...[9])
Chapter 4. Electric vehicles’ energy supply

1. External and internal energy source

The electric energy supply of the electric vehicles is performed by the following three methods:

- **External energy supply** is generally the national electric energy network directly or converted by intermediate devices. The vehicle is operable if the energy transmittance is fulfilled. The energy transmission can be fulfilled by a trolley contact at vehicles powered by overhead-line. At inductive energy supply the transmission is fulfilled by induction without connections. Basically there are three types of vehicles powered by overhead-line: electric vehicles of the urban public transport (tram, trolley), urban rail vehicles (metro, suburban railways) and railway vehicles. Inductive energy transmission can be found at high-speed linear motor driven vehicles. The solar cell is a special solution for the external power supply.

Most commonly the battery is the electric energy storage device that is delivered by the vehicle. The stored electric energy is applicable for the traction of the vehicle (electric car, forklift truck) or in most of the cases it powers just the auxiliaries. Apart from the batteries, ultracapacitors or fly-wheels can be applied independently, or as a secondary energy storage device. The conditions of the energy storage devices shall be continuously checked, the recharging should be provided periodically.

The diesel-electric locomotive is operated by chemical energy delivered on the vehicle. A diesel aggregator is the electric energy source of a diesel-electric locomotive. The hybrid-electric vehicle is similar. Its design is based on different combinations of internal combustion engine (diesel or Otto-engine) and electric generator. The fuel-cell can be the power source of a vehicle that is operating with hydrogen (sometimes with methanol). Gas turbine powered electric vehicles also exist. At the former mentioned vehicles the stored chemical energy is transformed to electric energy on-board. The refueling of these vehicles should be provided periodically.

The range of the vehicle is the maximum route that can be achieved by a “non-external energy powered” vehicle with one energy charge.

2. Energy supply of overhead line powered urban electric vehicles

The urban electric vehicles are operating with DC voltage network. The nominal voltage of the overhead line is different. For example in Budapest: 600V (tram), 825V (metro), 1100V (suburban train), 1500V (cog wheel train), the permissible voltage range from the nominal value is ±20%...-30%. In urban traffic conditions it is characteristic when the stops and the reasons that stop the vehicle are frequent therefore the load of the overhead line is dynamically varying. Between two stops launching, accelerating, coasting, braking, stopping, waiting phases are repeating. For energy saving purposes the power-off coasting - that has no energy demand - and at modern vehicles the regenerative braking is the often used. With regenerative braking the 20-30% of the energy consumption of the urban electric vehicles can be saved.
Figure 3-1.: Energy supply of urban electric vehicles a.) substation, b.) tram, c.) trolley.

The DC voltage of the overhead line is produced by a diode rectifier circuit connected to the three-phase public supply network through a transformer (Fig.3.1.a). Therefore the vehicles cannot recuperate the braking energy into the public supply network. Considering the fact that in urban traffic a few vehicles powered from the same contact line, the energy transmission can be achieved between the vehicles. Therefore the recuperated energy (current) of a braking vehicle can be consumed by other vehicles. In the aspect of the vehicles the regenerative braking mode can be achieved, if provided that the contact line voltage not exceeds the permissible value. If the maximum voltage level is reached, other braking mode should be selected e.g.: resistive braking.

The contact line is generally overhead line (Fig.3.1.b.), at trolleys two overhead lines (Fig.3.1.c.). The energy is supplied by a third rail at the metro and the millennium underground train. The contact line is distributed to segments that can be separately released, the energy supply of the segments can be unidirectional or bidirectional. The energy supply of the busy, radial-connected junctions causes problems for the urban vehicles.

### 3. Energy supply of overhead line powered railway vehicles

Public network connected high power substations are established along the railway track in defined distances for supplying the overhead line powered railway vehicles. All the switching, converter and protecting devices are in the substations that are required for the overhead line supply.

The following table summarizes the railway overhead line systems, the vehicle drive system solutions and the required energy converters. According to the table there are several solutions, each electric traction mode need several energy conversion processes, therefore for the traffic designers it is difficult to find the optimal solution.

Table 3-1.: Contact line voltages and electric energy conversion solutions.

<table>
<thead>
<tr>
<th>Main converters of the substations</th>
<th>Overhead line voltage</th>
<th>Internal energy consumption: electric drive and the required internal energy conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>transformer +</td>
<td>single-phase, standard frequency voltage</td>
<td>(each of the listed vehicle drives is equipped with built-in transformer, that has suited-voltage and galvanically isolated)</td>
</tr>
<tr>
<td>phase change among segments</td>
<td></td>
<td>1. DC motor with rectifier and split transformer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. DC motor with controlled rectifier</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. AC drive with DC-link frequency converter The DC-link can be:</td>
</tr>
<tr>
<td>transformer</td>
<td>single-phase, low-frequency voltage</td>
<td>The application is similar to the former</td>
</tr>
</tbody>
</table>
Electric vehicles’ energy supply

<table>
<thead>
<tr>
<th>Frequency converter</th>
<th>DC voltage</th>
<th>(nowadays the single phase brushed DC motor without rectifier is not used)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer + rectifier</td>
<td>three-phase voltage</td>
<td>(the vehicle drive is not galvanically isolated from the contact line)</td>
</tr>
<tr>
<td>1. DC motor with switchgears, resistor gears</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. DC motor drive with DC chopper</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. AC drive with DC-link frequency converter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transformer</td>
<td>three-phase voltage</td>
<td>induction motor drive with gear-switches (Italian Kandó-system, it is not used nowadays)</td>
</tr>
</tbody>
</table>

### 3.1. Railway electrification systems

Features of the overhead line powered systems: supply voltage amplitude, number of the phases and the frequency; at railway applications these three together is called “current type”. Several railway electrification systems exist all over the world. If a vehicle can operate in two different systems it is called dual-voltage vehicle. In Europe six different railway electrification systems have been evolved because in different countries the railway electrification had begun separately under various conditions:

1. DC, 850 V: England
2. DC, 1500 V: France, Netherlands
3. DC 3000 V: Spain, Belgium, Italy, Poland, Slovenia, Czech Republic, Slovakia
4. three-phase, AC: Italy (nowadays it is not used because of the problems of the current collection)
5. single-phase, AC, 15 kV, 16 2/3 Hz: Austria, Switzerland, Germany, Sweden, Norway
6. single-phase, AC, 25 kV, 50Hz: Hungary, France, Denmark, Great-Britain, Czech Republic, Slovakia, Croatia, Yugoslavia, Romania, Bulgaria

The content of the former list continuously changes because of the reconstructions and the installation of new systems. According to the list, in practice the voltage of the overhead line system is DC voltage or single-phase AC voltage (three-phase overhead line is already not used). Two different types of the single-phase system exist: the standard frequency and the low-frequency. It is possible when two different electrification systems can be found in one country. In each European country at the installation of the modern high-speed railways the 25kV, 50Hz supply system is used.

The following diagram presents the distribution of the European railway electrification systems. According to this diagram the ratio of the different systems is approximately the same, except the 850V DC system. This causes a significant problem at the transcontinental traffic because locomotive must be changed at the border of different electrification system that can take quarter an hour which increases the travel time.
Distribution of the European railway electrification systems

Installing a unified European railway electrification system is not feasible because of several reasons. If either system is selected at least 67% of the European electrified lines should be adopted. It requires significant cost; moreover numerous devices (converters, supplying systems, substations, etc.) would become unnecessary. Perhaps these devices operate at the beginning of their life cycle or could be expensive. More than 50% of the electric locomotives would become inappropriate to operate causing lack of locomotives; moreover it would result in disturbances of the railway traffic. Adopting needs extremely great cost; moreover it should be performed in a short time, just in a few days.

The cheaper solution is to buy tractive vehicles that can operate under different electrification systems. These are called dual-, triple- or quad-voltage locomotives. These shall stop for a short period at the border of the different electrification systems and switch to the proper system by keeping appropriate rules. This can be executed in one minute; therefore it does not cause significant loss of time.

3.2. Comparing DC and single-phase railway systems

The DC railway electrification system has been evolved for DC traction motors. The 1500V voltage value was defined by the maximum permissible nominal voltage of the DC motor commutator bar voltage. The 3000V DC overhead line voltage is applicable if at least two motors are always connected in series. The low voltage level is a great disadvantage of the DC system, therefore a few thousand ampere current supply shall be provided for the high power traction. While at direct current the voltage drop of the current conductors is resistive, such a large current causes large voltage drop even in increased diameter contact line (500-600 mm²). Therefore the energy supplying substations shall be installed relatively densely, at 1500V systems the distance between two substations is 10-15km.

In the past, at the substations the DC voltage was generated by synchronous motor driven DC generators. Nowadays it is generated by a diode rectifier connected to the public supply network through a matching transformer. Generally the contact line is at positive polarity, the rail is at negative polarity. If DC voltage supplying substation is installed by a rectifier, the braking energy cannot recuperated into the public supply network. The energy transfer is limited but it can be achieved by two vehicles connected to the same contact line. Therefore the recuperated energy (current) of a braking vehicle can be consumed by other vehicles connected to the same line and operating in motor mode.

The contact line is distributed to segments that can be separately released, the energy supply of the segments can be unidirectional or bidirectional.

Single-phase AC supply system can be operated with standard frequency or low-frequency. The nominal value of the overhead line voltage can be high (in Hungary: 25kV) and it is a great advantage of the AC systems. The built-in main transformer of a vehicle produces the most adequate voltage level for the electric drive. On the other hand the AC supply has a disadvantage, in addition to the resistive voltage drop on the overhead line there is a significant inductive voltage drop (at 50Hz the X/R~3, where X=2πfL). At high voltage transmission less current belongs to the transmitted power that causes less voltage drop in spite of the increased impedance. The substations can be installed in 30…50km.

The low-frequency (16 2/3 Hz in Europe) AC system was evolved based on the tradition of the single-phase series commutated motor traction and nowadays it still remains in several countries. It has a disadvantage, because of the low-frequency the iron core size and the weight of the vehicle’s main transformer shall be designed for a much larger value then it would be necessary at standard frequency. It has another disadvantage, the substations shall be built with frequency converters capable of the low-frequency energy supply.

Kálmán Kandó was a pioneer in applying and wide-spreading the standard voltage railway traction system. The single-phase voltage of the overhead line is produced by transformers installed in the substations that connect to one of the three-phase public supply network’s line voltage. The two phase load of the network causes asymmetry that is reduced by cyclically connecting the transformers – that supply consecutive segments – to different line voltage of two phases of the public network (Fig.3.2.).
Figure 3-2.: Standard voltage traction system.

Simple segment isolator cannot be applied between rail segments supplied by different line voltage, because if a vehicle powered by two pantographs is running through a simple segment isolator, it can cause line-to-line fault. If the segment boundary is a phase boundary as well then no-voltage isolated overhead segments must be installed, the vehicles run through with their momentum. If the vehicle accidentally stops under a no-voltage, isolated segment then it can be connected to the next supplied segment temporarily. The standard frequency system has more advantages: the connections to the public supply network and the energy recuperation at braking can be easily achieved. The network-friendly operation and the requirement of the regenerative braking are important aspects at the design of the standard frequency railway network based modern vehicles.

### 3.3. Elements of the energy flow at overhead line powered vehicles

At the electric railway traction the supplied current of the substation flows through the contact wire and the pantograph and it closes through the wheels and the grounded rail (Fig.3.2.).

*The rail* is the part of the supplied current circuit, therefore the metallic contact, the protection against increase of the potential and in constant distances the grounding of the rails must be ensured. At DC supplying systems significant current can flow out of the rail, if the resistance of the parallel current paths is less or comparable with the resistance of the rail. Particularly dangerous if the leak current flows through conductive pipes or metal-sheathed cables because if the ground is wet the current can perform electrolysis at its entrance and exit places on the metallic parts that causes corrosion. This phenomenon does not exist at AC voltage systems, because of the high impedance of the parallel current paths.

*Wheel-rail circuit.* Without any measure the motor current would flow to the rail through the bearings and the wheels. The bearings can be damaged, therefore generally the current is conducted to the wheels through a slip ring – brush installation by bypassing the bearing box, the number of the slip rings depends on the amount of the current.

*The pantograph* has a sliding shoe connector that is pressed to the contact line by a sprung, armed and hinged mechanism. It can flexibly adapt to the instantaneous height of the contact line (the sag is 15-25cm). The lever apparatus is flat if it is folded and always possesses with an element that can break if the pantograph get stuck by accident. Two kinds of current collector is widespread the pole and the pantograph. The pantograph is used at railways. The pantographs have two different types: Z-shaped (asymmetrical) and diamond-shaped (symmetrical). The icing, the frosting and the pollution influence the life cycle and operational reliability of the pantographs.

*The overhead wire* generally consists of a contact wire and a catenary wire. The *catenary wire* is produced from a high mechanical strength material and it suspends the contact wire. The catenary wire and the contact wire is not isolated, this make a parallel current carrying branch. The *contact wire* contacts with the pantograph, it is approx. 120 mm² solid copper wire in Hungary at 4.8...6.5m above the vehicle. If the contact and the catenary wires are viewed from above, their tracing is zigzag shaped and has a symmetrical ±0,5m deviation from the center line of the track to even the wear on the pantograph’s shoe.

The contact line is distributed to segments that can be separately released. The rails are grounded and cannot be distributed to segments. The current can leave the rail and can flow in the ground as leak current until the return wire.
The contact wire shall be selected according to the mechanical and electrical features. If the mechanical aspects are considered, the contact wire shall be bearing, weather proof, well-mountable, and shall possess with adequate strength to endure the stress caused by the moving pantograph. If the electrical aspects are considered the contact wire shall have the better conductivity. The voltage level defines the insulation and the breakdown strength that shall be kept. The designed current stress of the rail line defines the diameter of the overhead line.

3.4. Multi-voltage locomotives

The realization of the long-distance transnational rail traffic is difficult because of the different railway electrification systems. If the locomotive can only operate in one kind of system, then it shall be changed on the border of the system. Multi-voltage locomotives can operate in different railway electrification systems, the change between the systems can be performed by an electric switch.

*In the locomotives operating in two DC voltage systems* (e.g. from 1500V or 3000V) two exactly the same drive systems are built that are designed for 1500V supplying voltage. The two drive systems are connected in parallel if the locomotive is powered from the 1500V overhead line, and these are connected in series if the locomotive is powered from the 3000V system.

*In the locomotives operating in two AC voltage systems* (e.g. from 15kV, 16 2/3Hz or 25kV, 50Hz) an on-board special transformer or a group of transformers is connected to the overhead line. The voltage ratio can be changed by the transformer; the change remains undetected for the electric drives. Two different solutions of the switching between two voltage systems are presented in Fig.3.3.

![Figure 3.3: Switching methods for dual-voltage locomotives operating in standard and low-frequency AC voltage system](image)

Fig.3.3.a. presents a solution operating with switching the primary number of turn. The iron core and the primary number of turns of the transformer shall be designed for 16 2/3Hz, 15kV supplying system. The nominal primary current of the transformer shall be also defined for the 16 2/3Hz, 15kV supplying system. The transformer secondary voltage shall not change at 50Hz, 25kV supply, therefore an increased primary number of turn coil (ratio: \(N_2/N_1 = 25kV/15kV\)) shall be connected to the overhead line. Therefore the secondary voltage does not change, but the magnetic stress of the iron core, its flux density is only 1/3 at 50Hz supply. If same vehicle power and phase constant is assumed, at 25kV, 50Hz supply, the transformer primary current will be reduced with the rate: 15kV/25kV. The \((N_2 - N_1)\) additional turns can be designed for this reduced current. Compared to the 50Hz supply, the transformer shall be significantly overdesigned, considering the flux density and the current also.

Fig.3.3.b. presents a solution operating with switching the secondary number of turn. In this case, similarly to the switching the primary number of turn, the transformer shall be designed for 16 2/3Hz, 15kV supplying system. The three times higher frequency 25kV voltage can be switched to the primary coil without difficulties and the magnetic stress of the iron core will be even approximately 50% at 50Hz (25kV). The secondary voltage would increase at 25kV supply; therefore on the secondary coil a 15kV/25kV ratio tap change is required, at 25kV from K1 to K2 shall be changed. The switches are on the secondary part; therefore a separate switch is required to each secondary coil. The switches shall be designed for much higher secondary current than then primary current. Other solutions exist, but the presented two switching methods are the most common.

*In the locomotives operating in two AC and one DC voltage systems* the switch between the 15kV, 16 2/3Hz and 25kV 50Hz supplying system can be performed by transformer switch that was detailed above. The third voltage system - that the vehicle can be made suitable for – is e.g. the 1500V DC supply. It can be realized if the
vehicle drive system is operating with a DC-link, and its voltage is designed for the DC overhead line voltage level. In this case the DC-link can be connected directly to DC overhead line.

3.5. Network-friendly operation for AC voltage powered rail vehicles

The network-friendly operation is a general requirement of modern standard- or low-frequency AC voltage powered vehicles. Those devices are called network-friendly consumers which cause minimal harmonic distortion on the network, and consume the \( P_1 = U_1 I_1 \cos \phi_1 \) active power - required for their operation – with minimal \( I_1 \) current (index 1 refers for the fundamental harmonic quantities), i.e. the \( \cos \phi_1 \) power factor well approximates the \( \cos \phi_1 \approx \pm 1 \) value. This involves that the motor mode is optimal if the phase angle is \( \phi_1 = 0^\circ \), i.e. the consumed current is in phase with the network voltage, and the regenerative braking mode is optimal if the phase angle is \( \phi_1 = 180^\circ \), i.e. the current is in antiphase with the network voltage.

In the past the control for the optimal power factor could be solved by rotating machines, e.g. in single-phase synchronous motor driven, DC generator powered Ward-Leonard type locomotives, because the built-in synchronous motor – that was connected to the network - is able to correct the phase angle with the control of the excitation. The Ward-Leonard type locomotives were withdrawn from the traction, but they are still applied for phase compensation (as a synchronous compensator) in busy railway junctions.

Nowadays the network-friendly operation is solved with electronics, with a 4qS (four-quadrant-supply) converter, that is connected to the network. It is a single-phase voltage source inverter type an AC/DC converter which is controlled by pulse width modulation (PWM). Generally the 4qS is applied with voltage source inverter fed induction motor driven vehicle drive system, as it is detailed afterwards in the examples.

Fig.3.4.a represents the simplest circuit of the IGBT transistor based 4qS converters.

![Fig.3.4.a](image)

Figure 3.4.: 4qS network-friendly supply a.) electric circuit, b.) time function of main electric signals

The input of the 4qS is connected to the secondary voltage of the vehicle’s main transformer, and the output is connected to the DC-link voltage of the vehicle, that feeds the inverter powered vehicle drive. The 4qS converter is responsible for the network-friendly operation in motor and brake mode, and for controlling the DC-link voltage. The reference value of inverter powered drive DC-link voltage is \( U_{e0} \) that is approximately 1.2...1.5 times higher than the secondary voltage peak value \( (u_{sz}) \). If the \( u_z \) voltage of the \( C \) capacitor is smaller than the reference \( U_{e0} \) value, then the FSZ voltage controller gives charging command, if the \( u_z \) is higher than \( U_{e0} \), then the FSZ gives discharging command. It is realized indirectly by a cascaded current control circuit. The controller output does not specify directly the \( i_{e} \) DC current required for the change of the \( (i_d - i_z) \) charging current, but it specifies the \( i_{e0} \), current through the AJK reference signal generator. Based on the amplitude and
sign of the voltage controller output signal, the $AJK$ specifies the network current reference signal for the $\dot{ASZ}$ current controller, that has a sinusoidal shape and its phase angle is $\varphi = 0^\circ$ if $C$ has a charging demand (i.e. in motor mode), and its phase angle is $\varphi = 180^\circ$ if $C$ has a discharging demand (i.e. in brake mode). So the phase angle specification depends on the required power flow direction for the DC voltage control.

![Figure 3-5: Simulated results of 4qS voltage and current time functions (brown: $u_{st}[V]$, blue: $i_{st}[A]$, green: $U_e[V]$, red: $i_e[A]$)](image)

The first part of Fig.3.5 shows motor mode, the $C$ shall be charged to keep the DC-link voltage level, the consumed $i_{st}$ secondary current is in phase with $u_{st}$, $P>0$. The second part of Fig.3.5 shows regenerative braking mode, where $i_{st}$ is in antiphase with $u_{st}$, $P<0$.

In the $4qS$ circuit (Fig.3.4.a) the $i_{st}$ secondary current control is fulfilled by PWM modulation, where the feasible switching configurations of the IGBT transistors are as follows:

1. if $T1-T4$ are switched on → $u_\approx = u$, and $i_\approx = i_\approx$, independently of the current direction,
2. if $T2-T3$ are switched on → $u_\approx = -u$, and $i_\approx = -i_\approx$, independently of the current direction,
3. if $T1-T3$, or $T2-T4$ are switched on → $u_\approx = 0$ and $i_\approx = 0$.

The current control is performed by these switching cases. Fig.3.4.b presents typical time functions of the control purpose fulfillment in motor mode, where $i > 0$ (charging current direction), the consumed power from the network is $P>0$. The harmonic content of the controlled $i_{st}$ secondary current depends on the switching frequency and the value of the $L$ filter choke. If the vehicle drive consists of a twin drive connected to two individual secondary coils ($u_{st}$ and $u_{st2}$) as it is shown on Fig.3.4.a, shifting the PWM pattern of the two individual 4qS converters can be applied for the reduction of the network harmonics.

According to the figure, the $i_\approx$ charging current of the $C$ capacitor is pulsating with $2f_n$ frequency, therefore the $u_\approx$ voltage is pulsating with the same frequency. For reducing the pulsation, in some vehicles a $L_\approx -C_\approx$ filter is built in, tuned for $2f_n$ frequency (at 50Hz frequency for 100Hz).

Nowadays there are still several vehicles powered from the single-phase AC electrification system that do not possess network-friendly, controlled supply, but in these vehicles it is tried to reach more favorable features for the network.

### 4. Energy supply of levitated vehicles

For the levitated and generally high-speed vehicles the overhead line energy supply cannot be applied. Non-contacting electric energy supply solutions should be found instead of the sliding pantograph, rolling wheels, rail circuit.
At levitated vehicles, the problem of the **traction energy supply** is solved by **linear motor** drive, where the active coil of the motor is installed on the track, the energy - required for the traction – shall not be conducted into the vehicle. Electronic device - installed along the track - supplies the stator coils of the motors with controlled current. For economic reason, the linear motor coils are supplied segment-by-segment, always those segments, where the locomotive is running.

Contactless solution should be designed for the **energy supply of the auxiliaries**, for supplying the electro magnets (magnets that create the levitating and pole flux), the air conditioning, and other consumers.

One solution is the **linear generator** built in the vehicle that takes the feature of the linear motor driven vehicle, that apart from the main flux, magnetic harmonics are generated because of the stator iron core slots installed along the track. The harmonic change of the flux density caused by the vehicle movement induces voltage in the linear generator coil, and it provides the energy supply of the auxiliaries. The linear generator energy source is always completed with battery energy storage. The transmittable energy of the linear generator depends on the vehicle speed. At low speed it does not transmit enough power, at standing position it transmits nothing.

At the stations or close to the stations, at low speed, additional energy supply shall be ensured. For this purpose traditional current supply could be applied with mechanical contact, powered by a third rail. However the **moving transformer** (so-called **IPS** system) is a much more intelligent solution. The primary side of the moving transformer is a part of the track, and the secondary side moves together with the vehicle. To reach high efficiency and small space demand, the moving transformer is designed for high-frequency transmission without iron core. The stator of the **IPS** (Inductive Power Supply) is a long primary loop installed along the track (e.g. at Transrapid vehicle 20 kHz, 200A sinusoidal current generator supply, shown in Fig.3.6.) the moving part is an on-board receiving-loop.

The nominal air gap between the primary- and receiving loop is approximately 40mm. The moving energy transmission is independent of the vehicle speed. In the primary loop there are two tuning capacitors, therefore the installation is not recommended in tunnels.

![Figure 3-6.: IPS energy transmission with moving transformers near to stations.](image)

**5. Energy supply of electric cars and road vehicles**

The battery and fuel-cell cars have DC supply. The operating voltage level is very different in 42V…2x288V range, but there can be higher value. Chapter 8 is dealing with the energy supply of the electric cars.

(The literature used for this chapter: [10]…[15])
Chapter 5. Commutator motor driven conventional electric vehicles

The conventional electric vehicles are driven by rotating machines. Among the uncontrolled electric rotating machines the series wound commutator motors have the most suitable $M\omega$ mechanical characteristic curve for the tractive requirements. This justifies that almost exclusively series wound commutator motors were applied in electric vehicle drives for long decades. Nowadays several vehicles are still driven by such motor.

Interesting feature of the series wound commutator motor that it can be operated from DC and single phase AC network with relatively few changes. The $M\omega$ mechanical characteristic curve of the motor is similar at both supplies. The AC commutator motors are much more sensitive and more disposed for brush sparking than the DC motors. On the other hand at the beginning of the electrification the lossless change of the single phase supplying voltage could be achieved by split transformer, while there was not any device for changing the DC voltage with no-loss. Therefore at the beginning of the electrification in several countries the single phase commutator motor driven technologies were preferred and low-frequency AC railway electrification systems were selected to improve the motors operation. The single phase commutator motors are not applied since long time ago (this lecture is not dealing with these), however nowadays in some countries the low-frequency (16 2/3Hz, 15Hz or 25Hz) rail systems are still remaining.

1. DC commutator motor drives for traction

Until recently the series wound DC motors were most commonly used in vehicle drives. The magnetic flux of the series wound machine is generated by such excitation coil which $I_g$ current is proportional to the $I_a$ armature current: $I_g = c I_a$. The $c$ factor represents the degree of the field weakening that can be in $c_{\text{min}} \leq c \leq 1$ range. The value of $c_{\text{min}}$ is depending on the machine, it is determined by the habit of the brush sparking. Common solution that the field weakening can be varied with some ratios and it is made by an $R_s$ shunt resistor connected in parallel with the excitation coil (Fig.4.1.a). If the resistance of the excitation coil is $R_g$, then the degree of the field weakening is $I_g = I R_s / (R_g + R_s) = c I_a$. If there is no field weakening, then $R_s = \infty$, $I_g = I_a$, $c = 1$.

![Figure 4-1: DC commutator motor, a.) with series excitation, b.) with compound excitation](image)

In traction the compound wound DC motors are relatively frequently used also, the one of the excitation coils current is $I_g = I$, while the $I_g$ current of the other excitation coil is independent of the armature current (Fig.4.1.b). In the compound wound DC motor the flux is generated by the $I_g N_s + I_{g_2} N_k$ resultant excitation, where the number of turns of the series excitation coil is $N_s$, and the number of turns of the separated excitation coil is $N_k$. Fig.4.1 does not presents, but the DC motors can be separately excited, where the series excitation coil is missing, or permanent magnet excited. The latter motor types are applied in some vehicles generally in low power vehicles, in cars. The basic voltage, torque and speed equations of the DC commutator motors are:

$$u(t) = R i(t) + L \frac{di(t)}{dt} + u_b(t), \quad U = U_b + IR$$

$$u_b = k \phi(t) \omega(t), \quad U_b = k \phi \omega$$

$$m(t) = k \phi(t) i(t), \quad M = k \phi I$$

$$m(t) \cdot m_b = \Theta \frac{\delta \omega(t)}{dt}, \quad M = M_t$$

4-1
The left column shows the transient equations valid for time functions. The right column contains the quantities described with the operating point values and valid at steady-state. The lower case letters represent the transient values, while the capital letters represent the operating point values. In the equations the meaning of the quantities and parameters are: the terminal voltage: \( u \), \( U \), the internal voltage: \( u_b \), \( U_b \) (internal induced voltage), the armature resistance: \( R \), the armature inductance: \( L \), the magnetic flux of the motor: \( \phi \), the machine constant: \( k \), the motor torque: \( m \), \( M \), load torque of the motor: \( m_t \), \( M_t \), moment of inertia to be accelerated: \( \theta \).

### 1.1. Characteristic curves of the series wound commutator DC motor

The \( \phi \) magnetic flux of the machine is a non-linear, saturation-like function of the \( I_g \) excitation current. Fig. 4.2. represents (in per unit system) the characteristic curves of a series wound machine that has an assumed magnetization curve. The armature current range is \( 0 < I' < 2 \), i.e. it is varied between zero and twice the nominal value (\( I_n \)).

**Figure 4.2.:** Simulated results of series wound DC motor with per unit quantities, a.) flux and torque as the function of armature current, b.) \( M-\omega \) mechanical characteristic curves.

The per unit quantity of the armature resistance is: \( R' = 0.05 \) \( (R' = R/R_n) \), the per unit quantity of the torque is: \( M' = k \phi I/(k \phi n I_n) = \phi' I' \). The calculation of the speed is based on equations (4.1): \( \omega = (U - IR)/k \phi \), with per unit quantities: \( \omega' = (U' - I'R')/\phi' \).

Fig.4.2.a shows the flux and torque which are the function of the armature current. The two upper curves (\( I_g = I \)) are valid for the mode without field weakening, the lower curves (\( I_g = 0.5I \) and \( I_g = 0.35I \)) are valid for field weakening mode. Fig.4.2.b represents the \( M-\omega \) mechanical characteristic curves of motor mode (\( M > 0, \omega > 0 \)) that approximates well the ideal traction requirements which is presented in Fig.2.5. The lower four curves represent the mode without field weakening (\( I_g = I \)), where the maximum torque can be achieved, the speed can be varied by the motor terminal voltage within the upper boundary curve, marked with \( U' = 1 \) (the \( U \) voltage cannot be increased above the nominal value). The range limited by the previous boundary curve can be extended by applying field weakening that is presented by the two curves: \( I_g = 0.5I \) and \( I_g = 0.35I \). The loadability of the motor (\( M_{max} \)) is decreasing in field weakening mode, but its speed can be increased. This effect is utilized in traction, the traction characteristic curve of the V43 locomotive (Fig.1.5) is an example for this.

### 1.2. Control methods of the series wound DC motor in motor mode

Based on the previous description, it ensures that the torque and the speed of the series wound DC motor can be controlled by varying terminal voltage and field weakening. There are several solutions for varying the terminal voltage (Fig.4.3):
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Figure 4-3.: Basic voltage varying methods.

In most of the solutions continuously variable voltage is generated by electronic converters with DC/DC converter (vehicle examples in Chapter 4.2.2) or with AC/DC converter (Chapter 4.2.4), but in some vehicles only step-like, discrete voltage values can be selected (vehicle example in Chapter 4.2.3). The variation of the field weakening can be continuous (examples in Chapter 4.2.2.) or discrete (vehicle examples in Chapter 4.2.3).

In older vehicles instead of the electronic converters, step-like series resistor variation is used (4.3.c), the motor voltage can be varied with these resistors according to the expression $U_{\text{mot}} = U_T - IR_e$, where $U_T$ is the supply voltage. To reduce the loss ($I^2R_e$) of the series resistor ($R_e$), the driving technique of these vehicles is controlled, so that the series resistors are in the circuit for a short period only (at acceleration). In multi-motor driven vehicles the series-parallel connection combinations are also applied in combination with the resistance varying. In two-motor drive e.g. the supply voltage can be halved by connecting the motors in series (Chapter 4.2.1).

Figure 4-4.: Reversal of polarity a.) in armature circuit, b.) in excitation circuit, c.) simplified diagram.

For backward running the polarity of the armature or the excitation circuit of the series wound motor should be reversed. In Fig.4.4 the E switches are closed at forward operation while the H switches are closed at backward operation, and the selection is performed at standstill.

1.3. Electric braking mode of the series wound commutator motor

During braking, the kinetic energy of the motor and the vehicle can be reduced in two ways: recuperate the energy back to the electric network, or convert into heat (dissipate). The recuperating braking is equivalent to the generator mode of the electric machine. The dissipation brake can be electrical or mechanical based on friction. The electric solution is the resistive electrical brake, when the kinetic energy is converted into heat.

Compared to the advantages of the series wound motor from the feasible traction characteristic (Fig.4.2.b), the braking mode is relatively difficult to achieve. For braking, the $M=kJ\phi I$ torque direction of the traction motor can only be reversed by the changing of the $I$ armature current direction or the $I_s$ excitation current direction (flux direction). Therefore the armature or the excitation circuit reversing switch (Fig.4.4) should be also applied in braking mode. The function of the $E$ and $H$ switches changes to driving and braking switch. The reversing of the $E$ driving mode switch to $H/F$ braking mode switch is possible only in no-current state. At series wound machine it means that before the switching the motor is de-excited because of $I=0, I_s=0$ current, i.e. the flux is reduced to the remanent value ($\phi_{\text{rem}}$). After the switching, the internal voltage of the still rotating machine is excited-up by this remanent flux, i.e. reaches the $U_s=kJ\phi_{\text{rem}}$ operating voltage required for the formation of the brake current. Only such braking mode switch is operable, that helps this exciting-up process. Fig.4.5 represents an example for such braking circuit, where after the switching the direction of $I_s$, $\phi$ and $U_s$ remain unchanged, also at reversed direction $I_s$ braking current compared to $I$ direction. The braking current is generated by $U_s$ through the resultant resistance of the circuit. (Beside the $R_s$ braking resistance the armature and the excitation circuit resistances are negligible.)
Figure 4-5.: Steps of series wound motor resistive braking mode. a.) driving mode with E switches, b.) no-current state, c.) braking mode after exciting-up process with F switches.

After changeover switching the stable operating point is set to such brake current where \( I_{\text{fek}} R_{\text{fek}} = U_b = k \phi \omega \) (where \( \phi \) is generated by \( I_{\text{ge}} = I_{\text{fek}} \) current). The energy converted into heat is \( \int \dot{I}_{\text{fek}}^2 R_{\text{fek}} \, dt \).

Chapter 4.2.2 presents vehicles that are capable for regenerative braking. The vehicle example of chapter 4.2.1 represents the solution for circle-connected or cross-connected resistive braking mode (Fig.4.10).

1.4. Compound wound commutator DC machines for traction

For traction purpose the series wound machines are the most commonly used from the DC machines. Sometimes the compound wound machines (Fig.4.1.b) are applied to eliminate the disadvantages of the series excitation. The \( \phi \) flux of the machine is generated by the \( I_{\text{g1}} N_s + I_{\text{g2}} N_k \) resultant excitation, which is the sum of the \( I_{\text{g1}} N_s = I_{N_s} \) series excitation and the \( I_{\text{g2}} N_k \) separate excitation.

The compound excitation can be utilized well if \( I_{\text{g2}} \) is continuously controllable. The following purposes can be reached by controlling the separate excitation current (\( I_{\text{g2}} \)):

The previous excitation boost can be applied also with series excitation coil, it is called pre-excitation (for example in Chapter 4.2.1).

1.5. Separately excited commutator DC machine for traction

For traction purpose the “purely” separately excited DC machine is generally applied in low-power vehicles. In these drives separate controllers are built in for controlling \( I \) armature current and \( I_{\text{g}} \) excitation current (vehicle example in Chapter 4.2.5). Two ranges can be distinguished for \( I_{\text{g}} \) control:

Figure 4-6.: Characteristic curves of separately excited motors, a.) flux generation, b.) mechanical M-\( \omega \) characteristic curves.

Fig.4.6.b presents simulation results of the mechanical characteristic curves in per units that can be achieved by the previously described excitation control.

If Fig.4.6.b is compared to Fig.4.2.b, it can be observed that the \( M-\omega \) boundary characteristic curves of the separately and series excited motors are similar, but there are some differences:

The steep characteristic curves can cause problems in cases, when a vehicle is driven by two or more electrically parallel connected motors at the same time, and these motors are forced to approximately the same speed because of their mechanical connection on the wheels. The terminal voltages of the motors are the same because of the parallel connection, but their characteristic curves can be slightly different. Because of the steep \( M-\omega \)
characteristic curve, at same speed the torque distribution of the motors may vary much more than at series motor. Moreover the unequal load can cause unequal warming of the parallel connected motors. Fig.4.7.a presents this phenomenon for the two motors (motor 1 and 2) (slightly enlarged effect).

Figure 4-7.: Problems of parallel connected motors’ load distribution a.) if the motor characteristics are slightly different b.) if the speed is different because of the wheel wear.

Unequal load distribution can also happen in case of same motor characteristic curves, if the speeds of the parallel connected motors are not exactly the same e.g. because of wheel wear. Such difference is higher if the characteristic curve – belongs to the same terminal voltage - is steeper. It can be seen in Fig.4.7.b.

In low power electric car drives permanent magnet DC machine can be applied because of its simplicity. The field weakening (can be seen in Fig.4.6.a) cannot be achieved by this type of machine, i.e. the motor can only operate in $\omega \leq \omega_{\text{on}}$ range.

2. DC motor driven concrete electric vehicles

This chapter presents some concrete electric vehicles. These are currently in traffic and have a typical drive system.

2.1. DC motor driven vehicles operated by series resistance variation

The Hungarian product GANZ articulated tram is a good example for a vehicle operated by series resistance variation, and several runs in Budapest on the BKV (Budapest Transport Company) lines. The Millennium Underground has almost the same drive system as the GANZ articulated tram.

Each vehicle is connected to the 600V DC overhead line network. The vehicle is driven by four series wound traction motor, there are two motors in each bogie. In driving mode motor 1 & 2 and motor 3 & 4 (Fig.4.8) are always connected in series, because the motors were designed for half-voltage (i.e. 300V).

Fig.4.8 illustrates the complexity of the traditional series wound commutator motor driven vehicles operated by series resistance variation. This figure represents the whole circuit diagram of the main circuit.
Commutator motor driven conventional electric vehicles

Figure 4.8: Whole circuit diagram of the main circuit.

The diagram contains all the usual elements in the vehicle from the pantograph to the rail: overvoltage arresters, fuses, main switches, connections to the auxiliaries, and the complicated switching system of the motors.

For understanding the circuit, Fig. 4.9.a represents the simplified circuit diagram of the driving mode circuit.

Figure 4.9. a: Series resistance driving mode, simplified circuit

Figure 4.9. b: Series resistance driving mode, b.) effect of series-parallel switch to the \( M-\omega \) characteristic curve (with reduced number of sections).

The \( R_A \) and \( R_B \) series resistors can be varied by sections, moreover two motors can be connected in series or in parallel. In series mode the number of resistance sections is 12, in parallel mode: 10. At the end of the parallel
mode sections even two level field weakening can be applied. Therefore to reach the maximum speed (and \( \omega_v \)) of the vehicle, the number of the sections in driving mode is 24. The first six sections – as a pre-section – ensure hitchless start. During the start the tractive force is pulsating in ±9% range. Fig.4.9. represents the characteristic of the motor starting torque with reduced number of sections.

In the first part of the starting, all the four motors (also the series resistors) are connected in series, at first with \( K_2 \) switch, then after disconnecting each resistance section, with \( K_5 \) switch. When the \( \omega_s \) speed is reached the parallel mode of the 1-2 and the 3-4 motors start. (In Fig.4.9.a the current of the first branch is signed with simple arrow, the other is signed with double arrow). The parallel mode is developed by \( K_3 \) and \( K_4 \) switches, then the \( R_A \) and \( R_B \) series resistors are disconnected in section-like mode from the maximal value. In the GANZ articulated tram there is not a \( D \) diode connected in series with \( K_5 \) switch (can be seen in Fig.4.9.a), but it can be found in several similar circuits e.g. in the drive system of the Millennium Underground. During the switching, the \( D \) diode none of the motor currents are interrupted, therefore the transition is continuous from the series mode to the parallel mode. With series mode only \( \omega_s \) speed can be reached, with parallel mode: \( \omega_p \). The increase of the speed can be achieved by field weakening (with \( c \) and \( d \) switches).

The whole brake system of the vehicle consists of:

The electric brake of the vehicle is resistive brake; the number of the brake sections is 16. Fig.4.10 represents the electrical circuit of the braking mode.

![Resistive and cross-connected braking mode circuit.](image)

**Figure 4-10.:** Resistive and cross-connected braking mode circuit.

Motor 1-2 and motor 3-4 form two independent brake circuits with \( R_A \) and \( R_B \) resistors. Two motors are cross- or circular-connected, e.g. motor 1 feeds the excitation winding of motor 2. The cross-connection is advantageous, because the braking current is more evenly distributed between the two machines. In both bogies the resistive electric brake is complemented with a mechanical disc brake (\( SZ \)) operated by electromagnet. The \( SZ \) coil current is proportional to the current of the resistive brake as long as the braking current of the motors vanishes close to the low speed. The current of the disc brake – proportional to the braking current – is achieved by the voltage drop of \( R_u \) resistor connected in series with \( R_A \) and \( R_B \) brake resistors. If the voltage of \( R_u \) decreases under the battery voltage, than the disc brake uninterruptedly changes to battery supply, and brakes until stop. At the beginning of the brake mode, pre-excitation circuit helps the faster excitation-boost of the motors through \( R_s \) resistor (current drown with dashed line).

### 2.2. Chopper fed DC motor driven vehicles

For the lossless control of the DC voltage fed DC motor driven vehicles DC/DC converters are applied, that can be built with thyristor, GTO, and recently IGBT elements.

#### 2.2.1. Thyristor chopper controlled DC motor driven vehicle

The Ganz-Ikarus IK 280 trolley is a typical example for a thyristor chopper fed vehicle. Fig.4.11 represents the main circuit diagram of the vehicle.
The traction motor of the vehicle is series wound DC motor with \(M\) armature and \(G\) excitation winding. The \(LS\) smoothing choke is for smoothing the motor current.

The main element of the circuit is the chopper formed by the \(TF\dot{O}\) thyristor with turn-off circuit; this is the main control element for controlling the driving and braking mode of the vehicle. \(TG\), \(TF\) and \(TE\) thyristors are performing additional functions. The control of these elements is synchronized to the control of the \(TF\dot{O}\) chopper, their conduction states end when the \(TF\dot{O}\) chopper is turned-off.

The two \(E\) switches are operating at driving mode, while the \(H/F\) switches are for selecting the braking mode in forward operation. (The braking mode is achieved by reversing the armature current direction). The backward operation is not a normal operation; therefore there is no brake circuit for backward operation. The DC voltage is stabilized by the \(C\) capacitor. At start a charging resistor limits the charging current of the capacitor that is short-circuited by a charging contactor in normal mode. Fig.4.12 represents the switching states of the \(TF\dot{O}\) thyristor and the time functions of the motor terminal voltage and current in forward operation, traction mode.

In the range \(0 \leq u_s = bU_H \leq U_H\) the average value of the motor voltage can be continuously varied by the turn-on ratio \((b = t_{\text{be}}/(t_{\text{be}} + t_{\text{ki}}))\) of the \(TF\dot{O}\) thyristor chopper. The motor current, speed, i.e. the tractive force, the acceleration and the speed of the vehicle can be controlled by varying the voltage. The influence of the voltage change can be seen in Fig.4.2.b. The speed range can be expanded by the field weakening mode that can be achieved by \(TG\) thyristor, and relatively to the main thyristor the switching of \(TG\) is synchronized but delayed, i.e. the excitation winding is short-circuited periodically.

In traction mode the vehicle consumes \(P_H = U_H i_H\) power from the network. The \(i_H\) current is flowing during the turn-on period of the main thyristor. According to the motor mode, \(i\) armature current of the motor has the same direction as the \(u_s\) internal voltage. The developed power and torque on the motor shaft are: \(p = u_s i = k \phi\omega i=M\phi>0\) and \(M=k\phi i>0\).

Fig.4.13 shows the time functions and the switching states of the regenerative braking.
Main feature of the brake circuit is that the motor excitation current is remaining in the same direction during the switching from the driving mode to the braking mode. This is a necessary condition for the excitation boost process that was described in Chapter 4.1.3. Due to the switching of the armature terminals, \( i \) armature current of the motor has opposite direction as the \( u \) internal voltage, and the motor operates in braking mode. The measurable brake power and brake torque on the motor shaft are: \( p = u \cdot i = k \cdot \phi \cdot o \cdot \omega \cdot 0 < 0 \) and the motor torque direction reverses \( (M = k \cdot \phi \cdot i < 0) \), because the armature current direction has changed. If the direction of the network current \( (i) \) is taken according to \( i \) direction, it can be observed that comparing with the driving mode the network current direction reverses and the recuperated power is: \( p_n = U \cdot i \). The \( i_n \) network current only flows during \( t_n \) turn-off time.

Similarly to the driving mode, the braking current is controlled by the turn-on ratio of the \( TFÖ \) chopper. If \( u_s < U_n \) than \( TE \) thyristor is continuously in turn-on case, as it is represented in Fig.4.13.a. The regenerative braking is operating if \( u_s > U_n \) caused by e.g. too high speed, but is this case the \( TE \) should be turned-off, that connects the \( R_s \) series resistor into the braking circuit. The voltage of \( R_s \) resistor has an opposite direction to \( u_s \), therefore it allows that the circuit of Fig.4.13 is operable with the \( u_s \cdot iR_s < U_n \) conditions.

*If the network is not suitable for regenerative braking*, then the circuit is switching to resistive braking, as in Fig.4.14. The operation of the circuit is similar to the regenerative braking operation, but the braking current closes through \( TF \) thyristor and \( R_f \) braking resistor. The breaking kinetic energy is converted into heat in \( R_f \) braking resistor.

This trolley equipped with thyristor chopper is driven by a *single motor*; the electric circuit is clear and simple. On the other hand it has a disadvantage. For the appropriate operation of the different driving and braking modes (can be seen in Fig.4.12...4.14) the main thyristor should possess safety turn-off circuit - that cannot be given in the previous figures - i.e. it must not remain unduly in turn-on state. The \( TFÖ \) main thyristor sign means the thyristor system with built-in turn-off circuit, its first control input starts the turn-on process, while the second input starts the turn-off process.
At junctions of two trolley lines, the poles can temporary switch reversed polarity voltage to the vehicle that cause problems at trolley supply. The vehicle circuit of Fig.4.11 would fail by the effect of reversed polarity, therefore before the junctions it must be switched-off from the overhead line. In modern vehicles a rectifier is built-in between the poles and the $C$ filter capacitor. The inverter fed trolley (Fig.5.9) is an example for this, where the rectifier is amended with two IGBT switching elements to achieve the regenerative braking at normal polarity despite the rectifying.

2.2.2. IGBT chopper fed DC motor driven vehicle

The still operating DC motor driven vehicles: trams, trolleys, metros are successively modernized to IGBT chopper fed drive system. Fig.4.15 represents the main circuit diagram of a DC motor driven, IGBT chopper fed T5C5K type tram (T5C5K is the modernized version of the Czechoslovakian Tatra T5C5 type tram).

The elements of the IGBT chopper perform functions similar to the thyristor chopper, and the same notations are used as in Fig.4.11. The operation of the chopper is similar to Fig.4.12 … 4.14 in driving mode and in several electric braking mode, but IGBT switching elements are used instead of the thyristors.

![Figure 4-15.: Tram drive with IGBT chopper](image)

The switching on is more complicated than in the trolley, because these trams are equipped with four motor drive system similarly to the GANZ articulated tram (Fig.4.8.). In this drive two motors are always connected in series similarly to the GANZ articulated tram, because the motors are designed for half voltage (600V/2=300V). In multi-motor drives - consist of series wound DC motors – the cross- or circular connection is commonly applied as in Fig.4.15, where in driving mode the E switches while in braking mode the F switches should be turned-on.

Fig.4.16 explains the cross connection of the motors in driving and braking mode. (For the easier understanding, in the figure the two always series connected motor is signed with $I$ and $II$ index.) According to the figure, in driving mode $I$ and $II$ motors are connected in parallel, in braking mode these are connected in series, the current of one motor is the same as the excitation current of the other motor. This ensures simple braking circuit and smooth load distribution. Upto 95% duty-cycle the chopper operates with constant 1000 Hz frequency, further increasing the traction motor voltage is performed by decreasing the operational frequency of the chopper.
2.3. Diode rectifier fed DC motor driven vehicle

The V43 type diode locomotive (nickname in Hungary: Szili) has the simplest structure among the vehicles equipped with semiconductor converters, and still a large number of these are running in Hungary. This locomotive is driven by two motors. Fig.4.17 represents its schematic circuit diagram.

The motor terminal voltage cannot be varied by a diode rectifier, only if the AC voltage of diode bridge input side is varied. For this purpose a transformer - and the associated split switch - is built-in that has several splits on the high-voltage side. The faultless and interrupt-less transition between the splits is performed by $K1...K3$ auxiliary switches, synchronized to the moving sliding contacts. By handling the split-switch equipment, the driver of the locomotive can achieve such tractive characteristic that can be seen in Fig.1.5. The regenerative braking is not possible because of the diode rectifier. The output of the diode rectifier is a pulsating DC voltage that pulsates with 100Hz frequency. In these vehicles the aim is to smooth the current instead of filtering the voltage. The pulsation of the current remains relatively high ($\pm20\%$), despite of the $LS$ smoothing choke - built before the motors - that should be taken into account at the motor design ( laminated stator motors design to pulsating current).

In the schematic circuit diagram of the V43 locomotive a 16kV split can be seen on the primary side of the main transformer. The reason is that in the past 16kV overhead line voltage was used instead of the currently used 25kV.

Figure 4-16.: Motor connections in driving and braking mode

Figure 4-17.: Schematic circuit diagram of the diode rectifier fed locomotive.
2.4. Thyristor converter fed DC motor driven vehicle

Relatively large number of thyristor converter fed locomotives were manufactured. The most common is the V63 type locomotive (nickname in Hungary: Gigant). Fig. 4.18 represents its schematic circuit diagram.

![Schematic circuit diagram of the thyristor converter fed locomotive.](image)

Figure 4-18.: Schematic circuit diagram of the thyristor converter fed locomotive.

The vehicle is driven by parallel connected compound wound DC motor, and there are three motors in each bogie. Fig. 4.18 presents a drive of one bogie. The driving mode can be selected with E switch, while the braking mode can be selected with F switch. In driving mode the main circuit of the three motors is fed by a series connected TH-1 and TH-2 thyristor bridges. To reduce the pulsation of the DC voltage the two bridges are half-controlled, i.e. one branch of each bridge contains diodes that perform the function of null-diodes. The thyristors of TH-1 and TH-2 bridges are controlled with a shift. If less than half-voltage is required for controlling the motors, then only the thyristors of TH-1 bridge are controlled, and the circuit closes through the diodes of TH-2 bridge. Close to half-voltage the controlling of TH-2 bridge’s thyristors starts with a small overlap. If higher voltage is required the thyristors of the TH-1 bridge are operating with full control (as a diode bridge), the voltage control is performed by the thyristors of the TH-2 bridge. With this so called “follow-up control” method the phase angle of the consumed current can be improved.

The circuit does not allow regenerative braking; only resistive braking can be achieved by closing F switches. Simple braking force control can be achieved by the controllable separate excitation current. The separate excitation windings of each motor are connected in series, and their common current can be controlled by the THG excitation thyristor bridge. Generally Chapter 4.1.4 deals with the functions which can be achieved by the separate excitation of a compound wound motor. The resistive braking can be applied with limitation; the limits should be defined because of the heat generated on the braking resistor. Basically, the braking is mechanical.

2.5. Two quadrant transistor chopper fed DC motor driven electric car

In electric cars the separately excited DC motor drives were also used because of the simple controllability, e.g. with two quadrant chopper as in Fig. 4.19. In the circuit there is a separate chopper in the excitation circuit (with TG, DG elements), a separate chopper for driving mode (with TM, DM elements), and a separate chopper for regenerative braking mode (with TF, DF elements). The change between driving- and braking mode is performed electronically, without separate switches and without any excitation boost problems. The control operates according to the conventional GP accelerator pedal and FP braking pedal functions, i.e. basically it defines torque control. The forward or the reversed direction can be selected by E and H switches of the excitation circuit in standing position of the car.
Figure 4.19.: Separately excited DC motor driven vehicle, a.) construction, b.) M-ω boundary characteristic curve.

The circuit is clear and the functions can be easily separated from each other. If field weakening is applied by the excitation controller (as in Fig.4.6.a), in driving and braking mode the mechanical boundary curves of Fig.4.19.b can be achieved.

(The literature used for this chapter: [16]...[24])
Chapter 6. Induction motor driven electric vehicles

The induction motor has been known since almost the same time as the DC motor, but its role is increased only recently, since the drive technical features have been optimized and secured with inverter supply and field oriented control. The high power switching elements have enabled the development of the inverter technique, and high speed microcontrollers have enabled the development of the complicated control methods.

Slip-ring induction motors existed also in the past, for example the so-called Italian system vehicles powered by three-phase electrification system operating from 1902 to 1976 with rotor resistance change and mechanical brake. In addition the Ganz-Kandó-type locomotive with phase- and period shifter was a pioneering attempt that was produced with complicated rotating machine converters. The modern induction motor drive technique is a qualitative improvement.

The advantage of the induction motor application prevails at squirrel caged rotor motor without slip-rings. Comparing with the commutated vehicle drives it possesses robust design, smaller space demand and do not need any maintenance. There are some attempts for water-cooled vehicle drive too.

1. The field oriented current vector control theory and practical applications

The field oriented control produces a revolutionary change in the improvement of the induction motor drive features.

The basic quantity of the novel control: the rotor flux vector $\hat{\psi}_r$ of the induction machine, which is expressed in x-y stationary coordinate system in the following way (Fig. 5.1.a):

$$\hat{\psi}_r = \psi_r e^{i\alpha},$$

i.e. it can be represented as a vector with $\psi_r$ amplitude and $\alpha$ angle, and can be calculated quite complicatedly.

Figure 5.1.: Rotor flux and stator current vector a.) in stationary x-y coordinate system, b.) in α-β field coordinate system.

The field oriented control is a current vector control, fixed to the calculated rotor flux direction that is generally represented in α-β coordinate system, fixed to the $\hat{\psi}_r$ rotor flux vector as in Fig. 5.1.b.

The field oriented control is based on the two component of the motor supplying current vector ($i_\alpha$ and $i_\beta$), which can be controlled separately. The $i_\alpha$ current component is in direction of the rotor flux. The rotor flux amplitude can be controlled by $i_\alpha$, and the motor torque can be controlled by the perpendicular $i_\beta$ current component. The torque of the induction motor is determined by $\vartheta$ torque angle (see Fig. 5.1.b, $p^*$: number of the motor magnetic pole pairs):

$$m = \frac{3}{2} p^* |\hat{\psi}_r| |i| \sin \vartheta = \frac{3}{2} p^* \psi_r i_\beta, \quad i_\beta = \frac{2}{3} \frac{m}{\psi_r}.$$
According to the equation, if the magnitude of the rotor flux is constant, the torque depends only on the \( i_\beta \) current component. In this case the motor behavior is similar to the behavior of the separately excited DC motor. Negative torque can be developed with negative \( i_\beta \) component or \( \vartheta \) negative torque angle. To realize the control purpose - that is defined in \( \alpha-\beta \) coordinate system – for the \( i_\alpha \) and \( i_\beta \) current components, in x-y stationary coordinate system the corresponding

\[
\dot{i} = i e^{j \vartheta} = i e^{j (\omega_\varphi \vartheta)}
\]

current vector components \( i_\alpha \) and \( i_\beta \) should be controlled, as in Fig. 5.1.a.

**Discussion and equations of the field oriented controlled induction machine**

The rotor leakage eliminating modified equivalent circuit is the most suitable for the field oriented control as in Fig.5.2.a (\( L' \) is a so-called transient inductance).

![Equivalent circuit of the squirrel cage rotor induction motor](image)

**Figure 5.2:** Equivalent circuit of the squirrel cage rotor induction motor, a.) for fluxes, b.) for voltages.

To use voltage equations that contain the stator and rotor quantities, common coordinate system shall be selected rotating with \( \omega_k \) speed. The voltage sources of Fig.5.2.b represent the so-called rotating voltages that depend on the coordinate system selection. With quantities interpreted in common coordinate system – that rotates with \( \omega_k \) speed – the Park-vector, transient equations (valid for instantaneous values) of the induction motor are as follows:

**Voltage equations:**

\[
\dot{\hat{u}} = R \hat{\dot{i}} + \frac{d\vartheta}{dt} + j \omega_k \dot{\vartheta}
\]

\[
\dot{u}_r = R_r \dot{i}_r + \frac{d\vartheta_r}{dt} + j (\omega_k - \omega) \dot{\vartheta}_r = 0
\]

**Flux equations:**

\[
\dot{\varphi} = L_i \dot{i} + L_m (i + i_r)
\]

\[
\dot{\varphi}_r = L_m (\dot{i} + \dot{i}_r)
\]

**5-2**

The non-measurable rotor current can be eliminated from the rotor voltage equation by substituting \( \dot{i}_r \) from the flux equation \( \dot{i}_r = \frac{\dot{\varphi}_r}{L_m} - \dot{i} \):

\[
\dot{u}_r = \frac{\dot{\varphi}_r}{L_m} - R_r \dot{i}_r + \frac{d\vartheta_r}{dt} + j (\omega_k - \omega) \dot{\varphi}_r = 0, \text{ where } T_{r0} = L_m / R_r
\]

**5-3**

If a common, fixed to the rotor flux \( \alpha-\beta \) coordinate system is selected, then:

\[
\omega_k = \omega_\varphi = \frac{d\varphi_\varphi}{dt} \text{ and } \omega_k = \omega_\varphi - \omega
\]
Each quantity has \( \psi_r = \psi_{\alpha} = \psi_{\beta} \) nts. According to Fig. 5.1.b, the rotor flux is:

\[ \dot{\psi}_r = i_{\alpha} + j\dot{\beta} = i_{\alpha}e^{j\beta} \]

is fixed to the real axis, consequently the stator current is:

\[ \dot{i}_{\alpha} \]

the terminal voltage is:

\[ \dot{u} = u_{\alpha} + ju_{\beta} \]

The essence of the field oriented control can be presented from the equation (5.3), separated to \( \alpha-\beta \) components. The following equation is valid for the \( \alpha \) components of (5.3):

\[
\frac{\dot{\psi}_r}{\tau_{\alpha}} - R_i\dot{i}_\alpha + \frac{\dot{\psi}_r}{\tau_{\alpha}} = 0, \text{ rearranging: } \psi_r + T_{\alpha\alpha}\frac{\dot{\psi}_r}{\tau_{\alpha}} = L_{\alpha\alpha}\dot{\psi}_r
\]

5-4

It shows that the rotor flux vector magnitude depends on \( i_{\alpha} \) component only, \( i_{\beta} \) has no influence on it. The \( \psi_r \) magnitude can be slowly varied, it follows slowly the change of \( L_{\alpha\alpha}i_{\alpha} \) with several tenth of seconds \( T_{\alpha\alpha} \) time constant. This feature is similar to the separately excited DC motors, how its flux can be varied by the exciting current.

The torque-producing \( i_{\beta} \) current component can be calculated by the \( \beta \) components of equation (5.3):

\[
-R_i\dot{i}_\beta + (\omega_{\beta} - \omega)\dot{\psi}_r = 0, \text{ rearranging: } \dot{i}_\beta = (\omega_{\beta} - \omega)\dot{\psi}_r / R_i
\]

5-5

According to equations (5.5), similarly to the separately excited DC motors, the \( \Delta \omega = \omega - \omega_0 \) speed drop is proportional to the torque-producing current \( (i_\beta) \).

The application of the field oriented control method was difficult for a long time, because the rotor flux vector can be calculated by complicated algorithm and sufficiently high speed microelectronic devices are just recently available to solve the task. Several methods (machine model) exist to calculate \( \psi_r, \alpha, \omega \), and the \( m \) torque, depending on which quantities are the inputs of the calculations. For example, one method uses the (5.3) stator voltage equation in stationary \((\omega = 0)\) \( x-y \) coordinate system. The real and imaginary parts of equation (5.3) are:

\[
\frac{d\psi_{\alpha}}{dt} = \frac{L_{\alpha\alpha}i_{\alpha}\omega - T_{\alpha\alpha}\dot{\psi}_{\alpha}}{\tau_{\alpha}}
\]

\[
\frac{d\psi_{\beta}}{dt} = \frac{L_{\alpha\beta}i_{\alpha}\omega - T_{\alpha\beta}\dot{\psi}_{\beta}}{\tau_{\alpha}}
\]

5-6

Fig.5.3 represents the machine model that uses the 5.6 equations and the measured values of \( i_\alpha, i_\beta, i_\gamma \) phase currents and \( \omega \) rotor speed.

Figure 5-3.: Speed based machine model.

1.1. Normal and field-weakening mode

1.1.1. Maximal utilization of the rotor flux

Similarly to the separately excited DC motors, high dynamic drive system can be achieved by field oriented controlled induction motor, if a function similar to Fig.4.6.a is defined for the rotor flux \( \psi_r \) amplitude. The \( \omega \leq \omega_0 \) speed range is the normal mode without field-weakening, with nominal rotor flux. The \( \omega > \omega_0 \) range is the field-weakening mode, where the flux decreases hyperbolically with the speed. The \( \omega_0 = 2\pi f_s \) is the nominal synchronous speed that can be reached by nominal flux and nominal voltage, for the induction machine it is: \( \omega_0 \)
≈ω. Since more voltage is not available, the flux shall be decreased for further speed increase. Therefore the field-weakening range is for the extension of the speed range that has an important role at vehicle drives. Fig.5.4.a represents the current vector ranges that ensure the maximal utilization of the rotor flux (Capital letters stand for the fundamental amplitudes.)

There are two different control ranges (I and II). The ω≤ω (I.) range is the constant rotor flux mode: \( \psi_r=\Psi_{r_n} \), \( I_\alpha=I_{\alpha_n}=\frac{\psi_{r_n}}{L_m} \), the \( M \) torque is proportional to the \( I_\beta \) current component. \( I_{\alpha_{\max}} \) defines the maximum torque. The ω>ω (II.) range is the field-weakening range. If the inverter output voltage is limited to the maximum transient induced nominal voltage of the motor (nominal value: \( \omega \Psi_{r_n} = U_n \)), then the speed can only be increased above \( \omega \), if the rotor flux and the current decrease with the ratio of \( \psi_r=(\omega/\omega)\Psi_{r_n} \) and \( I_{\alpha}(\omega/\omega)I_{\alpha_n} \) (minimal value: \( I_{\alpha_{\min}}=\frac{(\omega/\omega_{\max})I_{\alpha_n}}{\omega} \)). The torque that can be reached by \( I_{\alpha_{\max}} \) current decreases hyperbolically (Fig.5.4.b). At regenerative brake mode the control ranges are mirrored to the horizontal axis, with the difference that generally at braking mode smaller current maximum is allowed than in motor mode.

1.1.2. Energy-efficient rotor flux control

The previously described nominal rotor flux mode is sometimes replaced with energy-efficient rotor flux control at \( \omega<\omega \) speed range. It means that if the load is smaller than the nominal current (\( I_s < I_{\alpha_n} \)), the flux is decreased (with \( I_\alpha \) component) proportionally to \( I_s \) current, so that the torque angle remains nearly constant (\( \vartheta = \vartheta_{\text{opt}} \)). The iron losses can be decreased by the described method, on the other hand the dynamic behaviour of the drive deteriorates. The not a significant energy saving is only justified, if long-term, low-load cruising mode is expected in the vehicle trip. Fig.5.5 presents the energy-efficient control ranges.

Summary of the advantages of the field oriented controlled induction motor drives:

1. The motor flux can be continuously controlled by the \( i_s \) flux-producing current component.
2. The motor torque can be continuously controlled by the \( i_\beta \) torque-producing current component in the whole speed range, even at standstill. The pull-out torque (specific to induction machines) does not exist.

3. The motor speed range can be safely extended by the application of the field-weakening range to \( \omega \sim 2\omega_m \) value, considering that at \( \sim 2\omega_m \) speed the loadability of the motor decreases, e.g. at \( I_n \) current the developable torque is: \( M \leq M_n/2 \).

4. The \( M-\omega \) mechanical characteristic curves of the field oriented controlled induction motor are similar to the curves of the separately excited DC motor (Fig.4.6.b), and possesses similar boundary characteristics.

**Inverter solutions of field oriented induction motor drives**

Those inverters can be applied for the field-oriented control that can achieve the control purposes of the field oriented control. Basically the induction motor drive can be produced with two types of inverters:

1. with voltage-source inverter and
2. with current-source inverter.

There was a long-term debate about the advantages and disadvantages of the two solutions. Nowadays, however, almost only the voltage source inverter solutions are widespread; therefore the current source inverter solutions are briefly mentioned only.

**2. Voltage source inverter fed induction motor driven vehicles**

The main feature of the voltage source inverter supply is that the inverter supplying DC voltage is nearly constant, relatively high capacitance capacitor energy storage is built in, to filter the transient load change. To achieve the field oriented control, the switching elements of the inverter constrain voltage to the motor terminals with pulse width modulation control. The higher the switching frequency of the pulse width modulation, the faster and more punctual the achievable field oriented current vector control.

The circuit diagram of the two level voltage source inverter can be seen in Fig.5.6. This is the most commonly used, well-known circuit for supplying three-phase induction motors.

Figure 5-6.: Two level voltage source inverter supply, a.) circuit diagram, b.) simplified diagram, c.) voltage vectors.

Generally the T1…T6 switching elements are IGBT voltage controlled transistors, as in the previous figure, but at high power vehicles the GTO gate-turn-off thyristors are commonly used in voltage source inverters. Thee phase control is applied for the voltage source inverter, each motor phase terminal is connected to the positive or negative bar. If three-phase control is used the number of the switching states, achievable by the pulse width modulation, is \( k=8 \), the number of the different voltage vectors (\( \bar{u}=(2/3)(u_a+\bar{u}_b+\bar{a}u_c) \)) can be switched to the motors is seven as can be seen in Fig.5.6.c. The \( \bar{u}(7)=0 \) state is identical with the \( \bar{u}(8)=0 \) state, at \( \bar{u}(7) \) all the three phase terminals are connected to the positive bar while at \( \bar{u}(8) \) all the three phase terminals are connected to the negative bar.
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Fig. 5.6.b presents a simplified diagram, can be frequently found in circuit diagrams of rail vehicles, where each “box” contains one branch of the two level voltage source inverter. Each box has three terminals (+, - and ~), and contains one branch (in a dashed box in Fig.5.6.a).

The circuit diagram of the three level voltage source inverter with GTOs can be seen in Fig.5.7. It is commonly used at high power vehicles.

![Diagram](image)

Figure 5-7.: Three level voltage source inverter supply, a.) circuit diagram, b.) simplified diagram, c.) voltage vectors.

At three level inverter, the number of the switching states is $k=27$, but the number of the different voltage vectors can be switched to the motors is only 19, including the 0 vector, as can be seen on Fig.5.7.c. The magnitude of the maximal voltage vector is $(2/3)u_e$. The larger number of the switchable voltage vectors involve that smoother voltage control can be achieved by the three level inverter even if the allowed switching frequency for the high power semiconductor elements is more limited.

The simplified diagrams are also applied for three level inverter circuits that can be found in Fig.5.7.b, where each “box” contains one branch of the three level voltage source inverter. Each box has four terminals (+, -, 0 and ~), and contains one branch (in a dashed box in Fig.5.7.a).

There can be several practical solutions of field oriented controlled, induction motor driven vehicle drive. Fig.5.8. represents one possible solution with space-vector pulse width modulation controlled voltage source inverter and general machine model. The figure presents a simplified block diagram of a vehicle drive, suitable for speed control.

![Diagram](image)

Figure 5-8.: Block diagram of a voltage source inverter fed, field oriented controlled vehicle drive

The speed control shall always be complemented with torque limitation to achieve favorable acceleration and deceleration features for passengers. The field oriented control is divided to two main channels: the flux control (lower channel, related to $\alpha$ component), and torque control (upper channel, related to $\beta$ component). The reference signal of the rotor flux magnitude ($\psi_r\alpha$) is determined depending on the speed range, according to the field-weakening strategies, that were mentioned in chapter 5.1.1. There are vehicles, where the speed control can be switched to direct torque control, i.e. the $m_s$ reference signal can be set directly. The trolley and electric car are such vehicles, where the direct torque setting imitates the function of the accelerator pedal.
In the followings some specific vehicle controls are presented.

2.1. **Voltage source inverter fed induction motor trolley-bus drive**

Fig. 5.9. presents the main circuit diagram of the induction motor drive. The motor is supplied by a two level voltage source inverter. For the control and calculating the rotor flux an encoder – mounted on the motor shaft - is required.

The voltage source inverter is connected to the overhead line with a pole through a charging-circuit and a network protecting circuit. The charging-circuit limits the switching-on transient current of $C$ smoothing capacitor until it reaches the normal charge state. The network protecting circuit is a diode bridge rectifier circuit, its two diodes are by-passed with two IGBT elements. The diode bridge protects the main circuit against reversed polarity, which can be occurred at intersections for a short time. However the diode bridge does not allow the possibility of the regenerative braking. The two IGBT elements allow the regenerative brake at normal overhead line polarity with reverse current.

Figure 5-9.: Circuit diagram of voltage source inverter fed trolley drive

The voltage source inverter fed trolley-bus drive has field oriented control, suitable for the motor mode and braking mode control. The resistive brake only operates if the network is not suitable to consume the regenerative energy.

The trolley operates with torque control, the torque reference signal is defined by the accelerator pedal position.

2.2. **Induction motor drive system of the Combino tram**
Figure 5-10.: Schematic circuit diagram of the Combino tram, and a motor bogie.

Fig.5.10 presents the schematic circuit diagram of two motors that belong to one bogie, and a picture of a motor bogie. According to the picture two motors in a motor bogie drives two wheels one behind the other, because of the low-floor design. Two motors are connected parallel to one inverter. The structure of the main circuit is similar to the circuit of the trolley, can be seen in Fig.5.9, only the network protecting circuit is missing. The reversed polarity of the supplying voltage cannot happen in trams.

2.3. Voltage source inverter fed network-friendly energy-efficient railway vehicle drives

Nowadays, most of the new locomotives are energy-efficient and network-friendly, that manifests itself in three ways:

1. capable for regenerative electric braking,
2. connected to the network with network-friendly line-side converter,
3. they have energy-efficient motor torque control.

The Siemens 1047 (Taurus) is a good example for an energy-efficient, network-friendly, dual-voltage locomotive connected to AC voltage. Fig.5.11 presents the main circuit diagram of the electric locomotive drive. The figure shows the drive system of one bogie. The 6400kW, dual-voltage locomotive has secondary number of turn switch, can be switched to 15kV 16 2/3Hz or 25kV 50Hz supplying system and it is connected to the network with a 4qS converter. The role of the 4qS network-friendly converter is detailed in Chapter 3.3.5, the circuit diagram with IGBT switching elements can be found in Fig.3.4. On the other hand the 4qS converters and the motor-side inverters of the locomotive, presented in Fig.11, are implemented by GTO turn-off thyristors. Shifting the PWM control of the three parallel 4qS converters can be applied for the reduction of the network current harmonics. The network current phase angle can be set, its optimal value is accessible (cosφ=±1).

Figure 5-11.: Main circuit diagram of a Siemens 1047 dual-voltage, universal locomotive.
There are two ways for tuning the filter smoothing the DC-link voltage, to 33Hz or 100Hz, depending on the frequency of the overhead line voltage (16 2/3Hz or 50Hz). The single-phase supply is the origin of the double frequency pulsating input power that shall be filtered.

The E186D/A/PL type Bombardier locomotive is an example for a quad-voltage locomotive. Fig.5.12 presents the circuit applied at AC voltage overhead line. The circuit of the locomotive is the same at 15kV, 16 2/3Hz and 25kV, 50Hz overhead line voltage.

Figure 5-12.: Circuit diagram of a E186D/A/PL type locomotive at 16 2/3Hz and 50Hz supply

The figure presents the drive of one bogie. For simplifying the figure, the built-in switches for the two AC voltages (15/25kV) and the charging circuits cannot be seen. On the other hand the brake resistor circuit and the supplying system of the auxiliaries are in the figure. The permissible range of the DC-link voltage is 2,1...2,8kV, the nominal (and maximum) voltage of the motors is 2183V. Fig.5.13 presents the circuit applied at 3kV DC voltage overhead line.

Figure 5-13.: Circuit diagram of a E186D/A/PL type locomotive at 3kV DC supply.

The two parallel connected converters - providing the 4qS function previously - now operate as a DC/DC step-down converter, since the permissible range of motor-side inverters DC-link voltage is lower than 3000V. The brake circuit is on the input line-side. This and the auxiliaries converter shall be designed for 3000V.

Figure 5-14.: Circuit diagram of a E186D/A/PL type locomotive at 1,5kV DC supply.
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Fig. 5.12 presents the circuit of the same locomotive applied at 1500V DC voltage overhead line. The two parallel connected converters - providing the 4qS function previously - now operate as a DC/DC step-up converter. The brake circuit is connected to the DC-link. The secondary coil of the input transformer operates as a smoothing choke.

3. Current source inverter fed induction motor driven vehicle

The current source inverter fed vehicles are less frequently used than the voltage source inverter fed vehicles. The main feature of the current source inverter is that the DC link contains a high inductance smoothing choke, instead of a smoothing capacitor. The line side converter – can produce continuous positive and negative DC voltage – generates controlled \( i \), DC current. The three phase current source inverter switches this DC current cyclically altering to two appropriate phase of the motor. At thyristor current source inverter the number of the switching states is six, electrically the conducting states replace each other with 60° (Fig. 5.15.b.). Heavy duty commutating capacitors are required for switching between the conducting states.

The field oriented control of the induction motor is achieved through that the current conducting periods are timed to the rotor flux position. While the current vector direction can take six discrete directions, the field orientation can be fulfilled only on average in one 60° period. This causes that the motor torque ripples with electric 60° periods. Fig. 5.15.a represents the schematic main circuit diagram of the thyristor current source inverter and induction motor driven BDVmot multiple unit’s drive system of one bogie.

![Schematic diagram of current source inverter driven vehicle](image)

Figure 5-15.: Current source inverter driven multiple unit, a.) schematic main circuit diagram, b.) switchable current vectors.

The line side converter is an economical version of a double bridge circuit. To avoid the former mentioned torque ripples in this vehicle such \( i \), DC current control is applied that compensates the torque ripples with varying the current vector magnitude in a 60° period at low frequency control (at low vehicle speed).

Besides the thyristor current control inverter, e.g. IGBT current source inverters also exist that consist of commutating elements. Besides the six current vector presented in Fig. 5.15.b, the \( \tilde{i}=0 \) vector can be switched with this current source inverter. The six current vectors and the 0 vector can be varied by PWM pulse width modulation with multiple frequency compared to the thyristor current source inverters, i.e the field orientation can be “smoothly” achieved. Commutating capacitors are not required; despite this a three phase capacitor bank should be connected to the motor terminals, the motor current can close through this bank at \( \tilde{i}=0 \) vector switching state.

4. Linear induction motor driven vehicles (LIM)

Some of the modern high-speed vehicles are driven by linear induction motor (LIM). The principles of the linear and the rotating induction motors are the same, and the field oriented control can be applied as well. The rotating magnet field is equivalent to the moving (running) field at the linear version. The construction differences between the rotating and linear motors:

1. at the linear motor, the squirrel cage rotor is replaced by a more or less well conductive solid rail or a tape,
2. instead of the circular stator coil, there are plane unfolded phase coils at the linear motor and the coils have beginnings and ends,

3. the linear induction motors are produced with much larger air gap than the rotation motors.

Some of the listed construction differences only modify the regular parameters of the induction motors. Nevertheless the phenomenon of the so called end effect causes starker differences. The generation of the secondary current in the solid rail – that replaces the squirrel cage rotor - is delaying at the entrance therefore the effective length is reduced, and at the exits it ends with a delay, that causes additional loss.

At linear motor the primary part with active coil is equivalent to the stator of the conventional motor, while the squirrel cage rotor is equivalent to the solid rail or tape shape passive secondary part. Basically there are two possible solutions of the linear induction motor driven vehicles:

1. short primary part linear motor drive, when the active coil of the motor is on the vehicle with the inverter supply and the control, and the secondary part is a solid rail or tape installed along the whole track,

2. long primary part linear motor drive, when the active coil of the motor is installed on the track with the inverter supply, and the secondary part is on the vehicle.

Generally the A./ solution is designed for vehicles running on conventional rail track on wheels. The secondary part can be the rail (rail head motor that has an additional function beside the conventional locomotive drive) and it can be horizontally or vertically placed solid rail or tape. Fig.5.16. presents the schematic diagram of the construction.

![Schematic diagram of short primary part linear motor drive.](image)

Figure 5-16.: Schematic diagram of short primary part linear motor drive.

The resultant current excitation vector of the three phase coil is in a hurry to the inducted „rotor flux” of the track-rail with \(d=\vartheta(\tau_p/180^\circ)\) displacement distance that is equivalent to the \(\vartheta\) torque angle.

The B./ solution is applied at high-speed magnetic levitate vehicles, where the installation of the track is expensive. This solution has a great advantage: the inverter supply is performed outside the vehicle, the high power electric energy transmission would cause difficulties. The levitation distance of the electro-dynamically levitated vehicles can reach 10-20 cm, the linear induction motor must operate with such long air gap.

(The literature used for this chapter: [25]...[31])
Chapter 7. Synchronous motor driven electric vehicles

The synchronous motor is known for a long time ago, but only in the recent decades has provided an opportunity to apply it in intelligent drive systems as in vehicle drive systems. The breakthrough has been reached by high quality permanent magnet rotor motors and inverter fed current vector control synchronized to the rotor flux. This control is similar to the field oriented control of the induction motors, but it can be easily applied, because the rotor flux of the permanent magnet synchronous motor is approximately constant. Complicated calculations and machine model are not required, the rotor flux vector position can be definitely determined in every time instant by measuring the rotor angle.

The synchronous motor drive - provided with current vector control synchronized to the rotor flux - has at least as good dynamical properties as the field oriented controlled induction motor drive system. However the permanent magnet synchronous motor is much more sensitive, expensive and can be produced with smaller power than the induction motor. The expansion of the synchronous motor power can be reached only with separately electromagnetic excitation.

There are two possible solutions for the air gap flux density spatial distribution of the permanent magnet synchronous motor. Accordingly sinusoidal and rectangular field machines can be distinguished. The optimal (joint) current vector control of the two motor types is different. For traction the sinusoidal field permanent magnet rotor motor drive system is favorable, which speed range can be increased by field weakening mode. The rectangular field permanent magnet rotor motor drive system is applied only in low power electric vehicles, e.g. in cars.

1. Current vector controlled sinusoidal field synchronous motor drive

The rotor pole flux vector is the main parameter for the current control of the sinusoidal field permanent magnet synchronous drives that is defined according to Fig.6.1.a in x-y stationary coordinate system:

\[ \dot{\Psi}_p = \Psi_p \omega \hat{i} \]

The magnitude of \( \Psi_p \) is approximately constant, and its direction can be identified with the rotor phase angle (\( \alpha \)).

The synchronous motor drive control is based on the vector current control fixed to the direction of the pole flux. The main purpose of this control can be represented with Park vectors in d-q coordinate system at normal mode, c) in field weakening mode.

The synchronous motor drive control is based on the vector current control fixed to the direction of the pole flux. The main purpose of this control can be represented with Park vectors in d-q coordinate system, fixed to \( \Psi_p \) pole flux (Fig.6.1.b and c).

The torque of the current controlled permanent magnet synchronous machine is defined by the \( i_q \) current component and the \( \theta_p \) torque angle, because the torque can be calculated as follows (\( p^* \) is the number of the pole pairs):

\[ m = \frac{3}{2} p^* \left| \dot{\Psi}_p \right| i_q \sin \theta_p = \frac{3}{2} p^* \Psi_p i_q \]
Minimal stator current belongs to a given torque if the \( d \) component of the current is zero \( (i_d=0) \), i.e. the torque angle is \( \vartheta_d=90^\circ \), that can be seen in Fig.6.1.b. This is the energy efficient “normal mode” of the motor that possess the optimal torque transmission condition. Positive torque can be created with \( \vartheta_d>0 \) negative can be created with \( \vartheta_d<0 \) torque angle.

The field weakening mode differs from the optimal, and it is fulfilled in \( \vartheta_d>90^\circ \) and \( \vartheta_d<-90^\circ \) range as in Fig.6.1.c. The torque transmission deteriorates in field weakening mode, but the motor speed range can be expanded, that is important at traction.

**Negotiation of the sinusoidal field permanent magnet rotor synchronous motor**

For the negotiation of the cylindrical rotor sinusoidal field permanent magnet motor, the most adequate and simplest equivalent circuits can be seen on Fig.6.2 (\( L_s \) synchronous inductance). Fig.6.2.a is valid for fluxes.

![Equivalent circuits of cylindrical rotor synchronous motor](image)

**Voltage equation:**

\[
\ddot{u} = R\dot{I} + L_d \frac{\dot{q}}{dt} + j\omega \psi_p
\]

**Flux equation:**

\[
\dot{\psi} = L_d \dot{q} + \psi_p
\]

### 1.1. Normal and field weakening mode of the sinusoidal field synchronous drive

Fig.6.3. presents the current vector and the \( M-\omega \) boundary characteristics of the current controlled permanent magnet synchronous motor, where three mode ranges can be distinguished.

![Control ranges of sinusoidal field synchronous servo drive](image)

**Energy efficient, normal mode**
In Fig.6.3 the normal mode is represented by the I marked range. The main characteristic is that the torque angle is \( J_p = \pm 90^\circ \), and \( i_d = 0 \). A given torque can be produced by minimal current, i.e. minimal copper loss, and in this case a given current can be produced maximum torque. The \( M_{\text{max}} \) torque is determined by \( I_{q_{\text{max}}} = I_{\text{max}} \), by considering the short-term permitted \( I_{\text{max}} / I_n \) current overload. The energy efficient normal mode is sustainable until the voltage required for the control is \( U \leq U_{\text{max}} \), where generally \( U_{\text{max}} \approx U_n \). The dashed line shows the reachable speed range in this mode. The reachable maximum no-load speed is: \( \omega_{\text{n}} \).

**Field weakening range**

So the dashed line represents the speed that can be reached by the motor with \( J_p = \pm 90^\circ \) torque angle and maximum (nominal) voltage. While more voltage is not available, field weakening must be applied to further increase the speed. The field weakening concerns for the stator flux and does not perform the demagnetization of the rotor permanent magnets. According to Fig.6.4.b the \( \hat{\Psi}_p \) stator flux \( \hat{\Psi}_1 \) magnitude can be reduced by the \( d \) current component. The vector diagrams are concerning for fundamental values, it is represented by index 1.

**Figure 6-4.:** Vector diagrams of sinusoidal field synchronous drive, a.) for normal mode, b.) for field weakening mode.

Fig.6.4 a and b figures are concerning for an operating point with same speed and same torque (\( I_{1q} \) is equal). Based on the comparison of the two figures, the previous statement is turned out that more resultant current vector is required in field weakening mode than in normal mode for producing the same torque. On the other hand for the same speed with field weakening – by applying \( I_{1d} \) current component with opposite direction to \( \hat{\Psi}_p \) – smaller \( U_{a'} \) voltage magnitude would be required. Consequently if the \( U_{a'} \) voltage magnitude would reach the maximum (nominal) voltage, the speed would be increased with \( U_{\text{max}} / U_{a'} \) ratio. The speed increasing rate is approximately \( 2...2,5\omega_{\text{n}} \), depending on the motor parameters, and can be characterized with II and III ranges of Fig.6.3. In II range the torque is limited by \( I_{\text{max}} \) current component, as a consequence of the overcurrent protection of the resultant current vector magnitude \( I_{\text{max}} \) (in Fig.6.3.a the cycle arc with \( I_{\text{max}} \)). In III range the magnitude of the reachable torque is determined by the limitation of the field weakening component (\( i_d \)).

Fig.6.4 also presents a disadvantage of the permanent magnet synchronous motor vehicle drive. Compared to the nominal speed, the field weakening mode allows the significant increasing of the speed. If the electric control is interrupted at such a high speed, the \( U_p = \omega_p \Psi_p > U_{\text{max}} \) voltage can get out to the synchronous motor terminals that can cause inverter failure. It should be definitely avoided.

**Inverter solutions for synchronous motor drives**

Such inverters can be applied for sinusoidal field synchronous motor drive control that can fulfill the previously described current vector control. Principally there are two types of synchronous motor drives:

1. voltage source inverter fed synchronous motor drive,
2. current source inverter fed synchronous motor drive.

Nowadays almost the voltage source inverter solutions are used. The current source inverter fed synchronous motor drives were used for traction in the past by some manufacturers therefore these are briefly discussed.

**1.2. Voltage source inverter fed sinusoidal field synchronous motor driven vehicles**
Fig.6.5 presents a possible construction for voltage source inverter fed sinusoidal field synchronous motor driven vehicle.

Figure 6-5.: Voltage source inverter fed sinusoidal field synchronous motor drive.

In normal mode the prescribed value for the current d component is: \( i_{d_{\text{ref}}} = 0 \) that changes only if the motor voltage reaches the maximum value. In this case the field weakening mode starts. The reference signal of the current q component \( (i_{q_{\text{ref}}}) \) is defined by required tractive force (torque) or the output of the vehicle speed controller, according which control method was selected. The cross compensation (dashed line) is implemented to eliminate the cross-effect of the \( d-q \) components.

### 1.3. Current source inverter fed sinusoidal field synchronous motor driven vehicles

The development of the thyristor technique allowed to build high power voltage source inverter fed synchronous motor driven vehicles. It can be realized only by excitation current controlled, separately excited, slip-ring synchronous motor. Fig.6.6 presents an example, was used at the French Railways.

Figure 6-6.: Current source inverter fed sinusoidal field synchronous motor drive.

This construction is similar to the current source inverter fed drive system that can be seen in Fig.5.15. The current of the DC link is controlled by the line-side converter and the \( L \) inductance is smoothing it. There is a great difference in the operation of the motor-side thyristor bridge. At current source inverter fed synchronous motor the motor-side thyristor bridge operates with natural commutation, commutating capacitor is not required for the commutation. The operation is similar to the network commutation current converters, but the role of the three phase network is fulfilled by stator of the synchronous machine. The synchronous machine is over-excitable through the slip-rings that create the possibility for the natural commutation. Similarly to the current source inverter fed induction motor drive (Fig.5.15.) electrically the conducting states replace each other with 60° that causes torque ripples at both solutions. According to the locomotive in Fig.6.6 the torque ripples can be reduced by two stator coils shifted with 30° to each other. The auxiliary thyristors of the DC link is required for low speed operation, when the inducted voltage – that is proportional to speed - is not large enough for the natural commutation, and the current conduction states should be varied.

Over the years the voltage source inverters suitable for pulse width modulation control and the field oriented controlled induction motor drives obscured the importance of the current source inverter fed synchronous motor drives.
2. Rectangular field synchronous motor driven vehicles

The rectangular field synchronous motor drives are usually applied in low power, wheel hub motor driven vehicles. The common name of this drives is commutatorless or brushless DC drive (BLDC). The name “refers to” a mature DC machine construction, the permanent magnetic excitation is on the rotor, the winding is on the stator, the mechanical commutator is substituted by electrical commutation. At the rotor, the flux density distribution of the permanent magnetic excitation has a rectangular shape. Generally the stator has a three phase winding, but five phase vehicle motor also exists. Fig.6.7 represents a construction of a three phase drive.

![Figure 6-7. a: Three phase rectangular field synchronous drive, construction](image)

![Figure 6-7. b: Three phase rectangular field synchronous drive, phase current fitting.](image)

The main element of the circuit is a voltage source inverter that is similar to Fig.5.6, but the control method is different. To reach smooth torque proportional to the $i_a$, DC current, such current should be switched to the phases, which shape and phase position should be synchronized to the rotor position. The best current shape selection depends on the spatial distribution of the rotor flux density and the flux linkage considering the three phase coils that is represented by $K_a$, $K_b$, $K_c$ torque factors. The origin of the name is from the calculation of the machine torque: $m = K_a i_a + K_b i_b + K_c i_c$. Fig.6.7b shows the $K_a$, $K_b$, $K_c$ torque factors of the most common three phase machine construction and the machine current shape. The $K_a$, $K_b$, $K_c$ torque factor amplitude is $K_n = k N D\ell B_{max}$ (N: number of turns, $D$, $\ell$: machine dimensions, $B_{max}$: maximum flux density of the rectangular field, $k$: machine constant), the amplitude of $i_a$, $i_b$, and $i_c$ currents are equal to the $i$, DC current. The hatched areas in the torque time function represent the participation of the $a$-phase in the torque development. For reversing the torque direction the control of the phase current should be shifted by $\alpha = 180^\circ$. The control mainly consists of two phase conduction states succession, the three phase conduction is only during changes. The conduction states are cyclically altering with $60^\circ$ appointed by the inverter controller with $v_a$, $v_b$, $v_c$ electronic switches. The rectangular field synchronous machine drive is simple and it has a great dynamical behavior, but it has a disadvantage: the field weakening (shifted synchronized) mode does not provide smooth torque and the speed range can be only slightly expanded.

3. Linear synchronous motor (LSM) driven vehicles

Most of the modern high-speed vehicles are driven by linear synchronous motor (LSM). The operating principle of the linear synchronous motor is the same as the rotating synchronous motor and the control method - described in chapter 6.1.1. – can be also applied.

The plane unfolded stator coils of the linear motor are equivalent to the stator of the common synchronous machine, while the linear structure - consist of alternating polarity magnets placed an even distance - is
equivalent to the permanent magnet rotor. The magnets can be permanent magnets or excited electro magnets. Basically there are two types of the linear synchronous motor vehicle drives:

1. linear motor drive with short stator coil, when the active coil of the motor is on the vehicle with the inverter supply and the control, and the alternating polarity magnets are installed along the whole track,
2. linear motor drive with long stator coil, when the motor coils are embedded in the track, the inverter supply and the control is performed outside the vehicle, only the magnets are on the vehicle.

From these types the B./ solution is preferable at high speed, magnetic levitated vehicles especially in those solutions, where the magnets - built in the vehicle - are also for levitating the vehicle. Although the installation of the track is expensive, this solution has a great advantage: the inverter supply is performed outside the vehicle; the high power electric energy transmission to the moving vehicle would cause difficulties.

The linear motor drive of the Transrapid vehicle is an example for the B./ type solution. The specialty of the Transrapid solution is that the magnets for the traction are the same with the levitating (holder) magnets, therefore these cannot be permanent magnets. The excitation current of the holder magnets are not constant because of the levitation distance control (presented in chapter 7) consequently the flux of the magnets is not constant. At synchronous motor, the alternation of the pole flux appears as a disturbing signal in the traction force control.

Fig.6.8 presents the linear motor drive structure of the Transrapid vehicle. The winding is embedded in the bottom of the track; the levitating magnets are mounted on arms and reach under the track. The holder magnets are a series of electro magnets which are mounted a row in τ pole pitch with alternating N-S-N-S magnetic poles. The figure also represents the winding of the linear generator for the power supply of the auxiliaries.

The three phase winding is installed in the track iron core slots, every third slot belongs to the same phase, which is equivalent to the holder magnets – installed in the vehicle - τ pole pitch, that is shifted electrically with 180°. The a, b, c phase coils follow each other with 2-2 slot shift, that is equivalent to 120° shift in electrical angle. Differently from the common rotating machine, the winding is concentrated (one phase, one slot) and wave winding. The winding of each phase is threaded in every third slot with alternating, back and forth current direction (Fig.6.8.b and c.). The phase winding is single-turn, cable-like with insulated casing, and it consists of three parallel threads to reduce the skin effect.

The stator winding of the three phase linear motor drive is distributed to segments along the track, therefore only those segments should be supplied where the train is running, the whole track does not need to be supplied. The length of the sectors is different; it varies between 300…2080m. The selection of the length is depending on the energy demand of the given segment, e.g by acceleration or uphill the energy demand increases, and therefore it has a shorter segment. The current supply of each segment is performed by cabling installed under the track.

The tractive force control of the linear synchronous vehicle drive should be achieved with the similar principles that of the rotating synchronous motor drives torque control, that were described in chapter 6.1, by considering that the pole flux field is moving in the direction of the movement referred to the stator winding. To reach optimal tractive force development, the stator winding current time function should be synchronized to this motion, so that resultant stator field – generated by the three phase current - would run together with the pole field and shift ratio would be optimal. The normal motor mode – shown in Fig.6.1.b and 6.3 (sign l) - can be
developed if the three phase current generated moving wave stator field is leading to the holder magnet pole field with $\tau_p/2$, i.e. electrically 90°. In field weakening mode the leading should be controlled larger than $\tau_p/2$ (in accordance to Fig.6.3). For braking $-\tau_p/2$ shift, i.e. lagging must be applied. At linear motor $d=\pm\tau_p/2$ shift current wave is equivalent to the $J_f=\pm90°$ current vector control, to the optimal (energy efficient) mode as it is described in chapter 6.1.

The Fig.6.9 represents the red stator field in such time instant when the symmetry axis of the magnetic flux positive pole is getting close position to the a’ coil side. Based on the projections of the current vector in Fig.6.9.b, the required $i_a$, $i_b$, $i_c$ phase currents for a given tractive force and for this time instant can be defined. In $dt$ time interval the vehicle is moving $ds=vdt$ distance. For generating the same tractive force, the current vector should be turned with $ds(180°/\tau_p)$ electric angle, to keep the $\vartheta_e$ electric angle unchanged. The time functions of the phase current should be varied depending on the vehicle motion.

![Figure 6.9: Current control of linear synchronous motor, a.) linear, b.) vector representation.](image)

For accelerating the vehicle and increasing the traction force, the current vector magnitude should be increased, keeping the previous phase position. If the vehicle is running with constant speed, then similarly to the rotating machines the currents of the stator coils are three phase, shifted with 120° in time and symmetrical sinusoidal AC currents. If the vehicle is accelerating, then the frequency of synchronized moving wave should be increased in the stator coils. The fundamental frequency of the three phase current is $f=v/\lambda$, where $v$: vehicle speed, $\lambda=2\tau_p$ : wavelength. $f=270$Hz fundamental frequency belongs to $500$km/h speed (~$140$ms) if we calculate with $\tau_p=25.8$cm pole pitch of the magnets applied in the TR 08 type vehicle. Consequently such inverter is required for supplying the stator coils which can vary the fundamental frequency of the supplying voltage in 0-270Hz range. $(ds/dt)(180°/\tau_p)=v(\pi/\tau_p)=2\pi f$ electric angular frequency belongs to $v=ds/dt$ vehicle speed (Fig.6.9.b).

Similarly to the rotating synchronous drives, the regenerative braking of the vehicle can be reached if the displacement angle of the stator excitation wave is changed to negative (lagging instead of leading), that reverses the tractive force direction. In such cases the linear motor is operating as a generator. The braking is completed with eddy current brake can be found on the side of the vehicle at the height of the side guiding magnets.

The winding of the linear generator of the vehicle auxiliaries’ energy supply can be seen in the crown of the magnetic poles (Fig.6.8). The linear generator uses that the slots of the track iron core distort the flux density fundamental component, therefore magnetic harmonics are also generated in the air gap. The linear generator detects the change of the harmonic flux density caused by the vehicle motion, and the generated induced voltage supply the auxiliaries.

Besides the vehicle drive the described structure of the track allows the vertical levitation also. The ferromagnetic laminated iron core – the stator winding is installed into its slots - consists of parts connected tightly to each other and it is continuous along the whole track in each side. The stator winding can be discontinuous but the iron core cannot. The continuity is important because attractive force is exerted to this iron core by the levitating magnet that controls the vertical position of the vehicle. The strength of the tractive force exerting moving wave stator field is much lower than the strength of the holder magnet. Since the locomotive is running on air cushion without friction, the tractive force demand is lower than the force required for the levitation. The levitation methods of the vehicles are presented in chapter 7.

(The literature used for this chapter: [32][38])
Chapter 8. Levitated vehicles

Speed limit of traditional trains rolling on wheels is about 350km/h. At this speed, motive force transferred on the circumference of the wheel and gripping coefficient decrease so as it cannot overcome the increased rolling resistance of the locomotive. Traditional trolley contact become uncertain at high speeds so contact wire current feeding cannot be used. So, when designing high speed vehicles, traditional solutions for energy supply and traction mode must be changed.

*Technical problems to be solved in levitated vehicles are:*

1. to create contactless motive force; to design driving systems without mechanical drive and wheels to provide traction and electric brake force
2. to create levitation force perpendicular to the rail to hold the weight of the vehicle, and to control constant levitation height, if possible
3. to control lateral movement of the levitated vehicle, to hold the vehicle on the rail during curving, at cross wind etc.
4. to stabilize vehicle movement, to damp and limit inertial forces that create bias, oscillation, pitching of the vehicle body
5. to supply electric energy without contact.

There are two main solutions for levitation: air-cushion and magnetic.

### 1. Air-cushion levitation

Air-cushion vehicles have a long history. First efforts were in 1960s in France, where the so-called “Aerotrain” air-cushion train was developed with gas turbine drive and it reached 300 km/h. Experiments to develop air-cushion systems went in two directions: upper pressure and lower pressure systems.

In case of upper pressure systems high-pressure air layer to hold and support the vehicle is provided by streamed air directed to the path drawn in from above. Levitation force is provided by pressure force and overpressure of air. Two designs of several solutions can be seen in Figure 7.1.a.

[Figure 7-1.: Air-cushion levitated systems, a.) upper pressure, b.) lower pressure systems]

At lower pressure systems force needed for levitation is provided by vacuum; air is drawn from space above the vehicle so it is lifted by suction effect (Figure 7.1.b). It can be seen that this solution also solves the problem of side guiding. At upper pressure systems, side guiding has to be solved separately.

Gas turbines, turbo jets or linear turbines are used to drive air-cushion vehicles. Disadvantages of air-cushion vehicles are high required power and high noise, low total efficiency and several technical problems, for example moving in tunnels, steering and creating trains. So, designers turned their attention to magnetic levitation.

### 2. Magnetic levitation
There are several magnetic levitation solutions for basic levitation tasks, such as supporting, side guiding and stabilizing the vehicle. From these tasks supporting the vehicle is the most important, it often determines the traction system.

Developments are aimed at elaborating combined levitation and traction systems that are optimal for the whole vehicle. One element should provide several functions with energy saving operation, if possible.

Magnetic levitation force can be developed with three solutions: with permanent magnets, and with electromagnetic or electrodynamic principles.

**Permanent magnet solution** (MDS magnetodynamic suspension) is based on repulsive force between two magnets with the same polarity mounted on the vehicle and the rail. Levitation distance is automatic, it cannot be controlled.

**Electromagnetic levitation** (EMS) system is based on the interaction between controlled excited electromagnets on the vehicle and iron rail or body mounted along the rail. Attractive force between the magnet and the iron provides levitation and side guide of vehicle. As the basic effect is attractive, levitation is similar to contactless suspension. Levitation distance has to be controlled with excitation of electromagnets. If excitation control works then vehicle can be levitated in every speed region (including standing) without any auxiliary mechanical support. Critical disadvantage of electromagnetic levitation is that levitation distance is very small, about 10-15 mm, so very precise and expensive rail system is required.

**Electrodynamic levitation** (EDS) system is based on the interaction between strong magnetic field generated on the vehicle and the magnetic field appearing in special shape conductive loops (short-circuited coils) generated with motional induction. Magnetic field on the vehicle is generated by permanent magnets, electromagnets or (for example in the Japanese system) by concentrated superconducting magnets. As vehicle moves, the moving magnetic field induces current in conductive loops along the rail. Loops are connected so that their effects are suppressed in normal levitated operation of the vehicle, i.e. magnetic field moving with the vehicle generates minimal resultant current in the loops. If levitation height or side position of the vehicle changes for some reason, this generates counteraction in the short-circuited loops so vehicle recovers its stable original position, the system is self-controlled. Disadvantage of electrodynamic levitation is that it only works above velocity limit $v > v_{\text{min}}$, where $v_{\text{min}}=100-150\text{km/h}$. Below this limit, vehicle has to be lowered to wheels running on the rail. Contrary, advantage of EDS is that levitation distance can be 10...20 cm.

### 2.1. Electromagnetic levitation

Electromagnetic levitation (EMS Electromagnetic Suspension) system is based on the magnetic attraction between controlled excitation electromagnets placed on the vehicle and iron body placed along the rail. With this solution, both holding of vehicle weight and side guide can be fulfilled. Vertical levitation (or holding) force appears as holding magnet creates attractive force to the laminated or tape shape iron body placed at the bottom of the rail, and pulls the vehicle upwards (Figure 7.2.a). Vehicle acts like a suspended train where rail is realized with iron body. The task of the carrying system is to hold the vehicle at almost constant and stable distance and prevent contact of vehicle and rail.

The most well-known electromagnetic suspended system with linear synchronous motor drive is Transrapid, its construction scheme is shown in Figure 7.2.b.

![Diagram](image)

Figure 7-2. EMS levitated vehicle, a.) vertical levitation, b.) construction of Transrapid

As can be seen in the figure, vehicle is realized with arms reaching below the rail on both sides. There are two magnet groups on both arms distributed along the vehicle evenly. One magnet group provides vertical
Levitated vehicles

Suspension and the other provides side guidance. Magnets acting in vertical direction and mounted on the lower part of the arms have two functions: partly provide suspension, partly act as moving part of the linear synchronous motor. The operation of linear synchronous motor is described in chapter 6.3. “Supporting” magnets has to be realized with alternating polarity, because of their linear synchronous motor functionality, as can be seen in Figure 6.8.

Two side magnet rows, that can be seen in Figure 7.2., control the side (horizontal) position of the vehicle, it is important during curving and cross-wind. Side guide is realized similarly to supporting system so there are magnetically conductive iron rails (tapes) on the side of the main rail, opposite to the magnets.

Magnetic system for suspension (support) and side guide holds the vehicle in levitating position. Levitation distance has to be controlled with excitation control of the electromagnets. otherwise instability problems may arise. (If levitation distance increases, attractive force decreases, so distance increases more. If distance decreases, attractive force increases more.)

The scheme of the control of levitation distance can be seen in Figure 7.3.

![Figure 7.3. Control of levitation (suspension) distance]

Excitation current of the magnets is controlled. Every magnet has an airgap sensor and separate control. Excitation of every magnet is controlled so that levitation distance is almost constant. (There are 46 suspension or holder magnets in vehicle TR 08.)

Optimal levitation distance is 10 mm for type TR 08, deviation allowed is ±2 mm. If the train is laying on the rail (because levitation magnets are off) then distance is 160 mm. Side guide magnets has the same distance control.

Vehicle is able to move only if it is levitating. Effects happening when levitation force disappears:

1. If holding levitation magnet is switched off totally then levitation force disappears. The arms holding the magnets (Figure 7.2.a) are formed so that the train slips with a “landing skid” on the narrow metal stripes mounted on the surface of the rail. Under normal operation, this contact happens only when vehicle stands.

2. If some holding magnets malfunction during travel then holding force can be balanced with increasing the excitation of the remaining magnets. This is done automatically with separate distance (airgap) control if magnetic field of the holder magnets can be increased with excitation control.

Critical characteristic of electromagnetic levitation is that it works with very small, approx. 10-15 mm, levitation distance so it requires very precise and expensive rail construction. Power required for levitation magnets is similar to the power required for air conditioning inside the train. Vehicle has linear motor drive and can provide motion force along the full length of the vehicle. Force is not limited by sliding risk.

Auxiliary power supply of levitated vehicle type TR 08 is realized with linear generator and moving transformer, as it is described in chapter 3.4. Linear generator consumes a part of motive power so increases the tractive resistance of the vehicle. This can be seen on the tractive resistance characteristic of Transrapid type Tr 08 (see Figure 7.4.). In the figure, the biggest component is windage depending on the head surface, and the side resistance (due to side effects) and the force resulting from the linear generator are added. There is no rolling resistance. Brake force of the linear generator against movement depends on the load current of the linear generator. The figure is for maximal load.
As can be seen in the figure, linear generator can be loaded with maximal current till about 140 km/h, while its voltage increases with velocity. At about 140 km/h, generator reaches its maximal power, after that its load has to be limited hyperbolically.

Voltage of linear generator is proportional to the velocity of the vehicle. It cannot be used at low speed, around stations. Moving transformer for auxiliary supply, described in section 3.4., was developed to solve this.

### 2.2. Electrodynamic levitation

Electrodynamic levitation (EDS) system is based on the inductive magnetic interaction between strong magnetic field generated on the vehicle and the magnetic field appearing in special shape conductive loops placed along the rail. Magnetic field can be generated with electromagnets or superconducting magnets (in case of Japanese vehicles series ML), or permanent magnets (for example in Inductrack system). Winding along the rail can be realized with simple short-circuited conductive loops, 8-shape, or figural 8-shape short-circuited coils.

The biggest advantage of EDS system is that levitation is inherently stable, no feedbacked position control is required. A small deviation of the levitation distance returns the vehicle to its original position, because of the counteraction developed in the short-circuited loops.

An important disadvantage of EDS system is that at low speed (\(v<100\ldots150\text{km/h}\)) current induced in the short-circuited loops is not high enough to create the required lifting force that can counteract the weight of the vehicle. Vehicle must be lowered to wheels in this case, until it reaches speed where levitation force is enough to hold the vehicle. As the vehicle must be able to stop everywhere, the whole rail must be constructed so that it must be capable of operating at both low and high speeds.

An example for an *EDS electrodynamic levitation system based on superconducting magnets* is the vehicle series type ML (magnetic levitation) developed in Japan. Development of technical solutions in the vehicles can be investigated from 1974. Important stages in the development are shown in Figure 7.5.

---

During first attempts, levitation, side guide and traction functions were separated (Figure 7.5.a). Separate superconducting magnets were used for levitation and side guide. In novel solutions, the number of superconducting magnets was reduced, and they use combined winding system as shown in Figure 7.5.b and c. Development in the placement of superconducting magnets can also be seen in Figure 7.6.
Levitated vehicles

Figure 7-6. Placement of SCM superconducting magnets on the vehicle, a.) distributed evenly, b.) partly concentrated, c.) placed at the ends of the train.

The most novel solution, combined placement of superconducting magnets at the ends of the waggon in bogies can be seen in Figure 7.6.c. This arrangement helps placing the superconducting magnets far away from the passengers.

There are two main streams in the development of superconducting magnets, LTS (low temperature below 4.2K) and HTS (high temperature above 20K) superconductors. The structure of an LTS superconducting magnet unit can be seen in Figure 7.7.

Figure 7-7. LTS superconducting magnet built in Japanese ML (Maglev)

Superconducting magnets can create about 700kAturn excitation. Unit shown above consists of four magnets placed at about 1-2m distance and with alternating polarity. Superconducting magnet can hold its few tesla flux density with a small decreasing, about 0.44% per day.

Shape and distribution of winding elements along the rail is a result of an optimization design process, just as the selection of superconducting magnet system, which is a long development work.

Zero-flux levitation structure is shown in Figure 7.8 with the usual coordinate system. x axis is in the direction of the vehicle speed, z axis is the direction of the vertical levitation and y axis is in side guide direction.

Figure 7-8. Winding with 8-shape loops, a.) at one side of the rail, b.) cross-connected left and right loops

Winding is realized with connected 8-shape loops placed next to each other running along both sides of the rail, as can be seen in Figure 7.5.b. Zero-flux levitation is based on the fact that magnetic field moving with the vehicles induces voltage with the same direction in the upper and lower loops which partly suppress each other because of the 8-shape connection. Current from the resultant voltage create magnetic fields with opposite
direction in the upper and lower loops. The system is self-controlling, i.e. minimal remaining current is flowing (zero-flux). Remaining current is set by the force required to hold the weight of the vehicle, and how much decreasing between the superconducting magnet and the cross of the loop is required. Derivative function of levitation force $F_z$ by levitation distance is $dF_z/dz$, the coefficient of rigidity, which describes with how much dynamics the system goes back to equilibrium, if it deviates for any reason. Vertical levitation height, i.e. position of the vehicle, is determined by the geometrical position and side height of the loops.

To side guide the vehicle, loops on opposite sides of the rail, shown in Figure 7.8.a, are cross-connected as shown in Figure 7.8.b. Superconducting magnets on the opposite sides of the vehicle has opposite polarity.

Levitation operation can be indicated with N-S (north-south) polarity of the magnetic fields of the loops (Figure 7.9):

![Figure 7-9. Forces developed during levitation](image)

For vertical levitation, the polarity of magnetic fields of lower loops is the same as the polarity of the superconducting magnets (placed on the vehicle) so repulsive (lifting) force is developed. The polarity of the upper loops is opposite to the polarity of the superconducting magnets so attractive force is developed which also lifts the vehicle. If the vehicle deviates from its lateral central position then the currents flowing in the left and right loops become different. Cross-connection eliminates this difference so it creates force which helps to pull back the vehicle to the centre.

Winding system inside the rail is shown in Figure 7.10.

![Figure 7-10. a: Structure of the rail, photo](image)

![Figure 7-10. b: Structure of the rail, placement of levitation, side guide and traction coils](image)

Levitation coils cross-connected to 8-shape pairs, according to Figure 7.8, are indicated with red colour. Winding for traction linear motor is indicated with blue. In the figure, two-layer three-phase winding is shown but one-layer solution is also possible. In case of one-layer winding, it can be integrated with four levitation coils.

**Driving system of EDS levitated Japanese vehicle series signed ML** is similar to linear synchronous motor drive described in chapter 6.3. Difference is required because of the superconducting magnets, comparing to Transrapid, as an example there. Superconducting magnets used in EDS levitation create high flux density and have larger geometric dimensions so only some of them is used in one waggon, as can be seen in Figure 7.6.c. Magnetic poles are opposite next to each other, and have a distance of $\tau_p$ polar pitch, similar to Figure 6.8. Instead, superconducting magnet groups are placed to a distance integer multiple of $2\tau_p$. Tractive force is local, concentrated at places where superconducting magnet groups are, similarly to trains with bogies. Opposite to this, tractive force is distributed along the whole body of Transrapid. Because of the geometry of
superconducting magnets, pole pitch of the magnets is in the range of about \( \tau_p \approx 2m \), opposite to pole pitch \( \tau_p \approx 25.8cm \) at Transrapid. Because of larger pole pitch, frequency of the fundamental harmonic of the three-phase current feeding the linear motor can be much (ten times) less than for Transrapid. As \( f = \frac{v}{\lambda} \), wavelength is \( \lambda = 2\tau_p \), at the same vehicle speeds \( v = 500km/h \) (~140m/s), maximal frequency \( f \approx 35Hz \) is enough for feeding.

*Normal operation brake* in EDS levitated vehicle MLU002 is solved with regenerative brake, linear synchronous motor recuperates energy into the supply network through the inverter and the DC link circuit. For the case if supply fails, an alternative brake system must be used, which can be resistance, frictional or aerodynamic brake. Resistance brake transforms kinetic energy to heat on a brake resistance connected to the DC link circuit of the inverter. Resistance brake is effective over a certain velocity. At lower speed, below 350km/h, frictional brake can be used in addition to resistance brake. However, if speed is higher than 350km/h, mechanical frictional brake cannot be used, even if resistance brake fails. At higher speeds, aerodynamic running resistance (windage) can be used to brake, securely and effectively, even if both electric and mechanic brake fails.

*To increase windage*, by hydraulically opening brake plates on the front sides of the vehicle and each waggon, frontal area of the vehicle can be increased. These brake can be operated during levitation or running on wheels, too. Instability and oscillation does not appear, and increasing the surface affects in about one second. Tests proved that braking is secure even if one of the plates (e.g. side plate) does not open or plates do not open at the same time, for example on the front and the rear wagons.

(References used in this section are: [39]...[44])
Chapter 9. Drives of electric and hybrid-electric cars

One special group of electric vehicles is electric cars, which were aimed to give an alternative against internal combustion engines from the beginning, but the competition is unbalanced. The biggest advantages of internal combustion engines are their high energy density fuel (diesel oil, petrol, PB-gas) which is available in big amount, the possibility to use additional power (sometimes too high), and the simplicity of refilling. Nowadays it became obvious that we cannot postpone actions to lower pollution in big cities, replace oil, and increase use of renewable energy sources. To decrease pollution, one of the most important steps to take is to replace internal combustion engines with electric or hybrid-electric drives.

Development of electric solutions can be found in every vehicle types, from mopeds through passenger cars and trucks, till city buses. Nowadays, the direction of the development is that electric solutions should reach the same or almost the same running and comfort behaviors as regular for internal combustion solutions. Earlier developments were aimed to build lightweight, small, low-power, less comfort mini electric cars (LEV, SULEV Light, Superlight Electric Vehicle). These cars were planned to be used for short-length urban transport, shopping and going to work. One special category is vehicles for parks, environmental places and closed places, where pollution is prohibited so only vehicles with pure electric drive and energy storage are permitted.

Advantages of electric drives vs. internal combustion engines

Most of the drives are electric in everyday life activities and industry. Only one area exists where electric drive did not win, and this area is road transport. Break-through is not easy in this filed although electric drives have several advantages here also.

Advantages from environmental and energetics viewpoints:

1. There is no pollution during operation;
2. Less noise generated;
3. Efficiency of energy conversion is much higher.
4. In case of electric drive, during stops in urban traffic, which happens often, energy consumption can be minimal. No energy is needed for no-load (compare with the no-load running consumption).
5. Energy regenerating braking can be solved; kinetic energy during slowing down can be used for electric energy generation. With regeneration, 20...30 % energy saving can be reached because of frequent acceleration and deceleration in urban traffic.

Advantages from vehicle design viewpoint:

1. Properties and characteristics of electric drives can be varied freely with electronic devices, they can be fitted to user demands in every respect.
2. Torque-speed limit characteristics of almost all kinds of electric drives can be set to meet the ideal characteristics of traction. There is no need for gearshift between the electric motor and wheels. In contrast, internal combustion drives have to use variable mechanical gears, because their torque-speed characteristics are different than traction characteristics.
3. Multi-motors or axle-box motors can be used. Common control of multi motors has no technical problem.
4. With using several, low power motors the design is easier, especially for low board vehicles.
5. Axle-box motor drive can be implemented only with electric drive.
6. With multi-motors energy regeneration is easier, electric and traditional mechanical (hydraulic or pneumatic) brake can be combined for more wheels.
7. Possible to use per-wheel controls to prevent spinning-off and slippage.
From this summary we see that electric drive can be an ideal solution for urban and public road transport with respect to environmental and energetics aspects. The bottleneck to re-build vehicles to electric ones is the problem of energy storage on board. Development directions of electric cars are also restricted by electric energy supply.

Main development directions of electric drive vehicles:

Electric cars, literally, are the first three ones in the list above. The main characteristic of electric cars is that they have no internal combustion engines, drive is strictly electric. Pure electric car is where energy generation, charging and storing are also electric and pollution of the vehicle is zero. Vehicles having fuel cells use electric storage too to store electric energy but refilling is not electric, pollution is not zero, stack gas appears depending on the fuel (hydrogen, methanol). Section 8.1 deals with electric cars.

Contrarily, in hybrid-electric vehicles internal combustion engines and one or more electric motors can be found. Pollution is decreased with this hybrid solution but is does not become zero. Drive of the wheels is purely electric or combined with internal combustion drive. In these vehicles batteries or ultra-capacitors are used to store electric energy temporarily, but the main energy source is fuel stored in tank. In PHEV vehicles electric network charge is also used for refilling energy. Fuel consumption and pollution is determined by the internal combustion engine. One of the main design aim of hybrid cars is to decrease consumption and pollution while improve running behaviours. Nowadays new terms like full, middle and mild hybrid cars are used, which gives the ratio between total power and electric power used for traction. Section 8.2 deals with hybrid cars.

1. Electric cars

In electric cars, purely electric drive is used, for which electric energy source and supply network is needed on-board. We can distinguish three groups based on the type of the energy source:

Electric motor drive has to be chosen and designed so that its M-ω characteristic is suitable for traction needs and no gearshift (variable mechanical gear) is needed. Mechanical characteristic of an electric drive for a given F-v traction characteristic can be seen in Figure 2.5. Design and selection is introduced in Section 2.3. Estimation of F-v traction force can be based in Figure 1.4, where minimal specific traction demand is summarized for urban vehicles.

Almost every types of electric drives introduced in Section 2.4 can be used in electric cars. The following four tables demonstrate this. In Table 8.1 and 8.2, data of cars with batteries realized as specific products and prototypes are described. Data of fuel cell electric cars are summarized in Table 8.3 and 8.4 (Source: M. H. Westbrook: The Electric Car. UK University Press, Cambridge. 2005.)

Third rows of the tables show the drive type used in the cars:

1. Separately excited DC drive (described in Section 4.1.5) is used more and more rarely. Usual structure of this drive is introduced in Section 4.2.5, one of the possible electric circuitries can be seen in Figure 4.19. Formerly, multistep switch controlled series excited DC drive was also used for electric car drives. Switches were used to change series resistance like vehicles described in Section 4.2.1, or terminal voltage was changed by varying serial and parallel connections of battery cells.

2. Voltage source inverter-fed 3-phase induction (AC induction) motor drive with field-oriented control is used often, described in Section 5.2.

3. Permanent magnet (PM) sinusoidal field synchronous motor drive with voltage source inverter is often used in electric cars, introduced in Section 6.1.2.

4. Brushless DC drive with voltage source inverter is used for lower-power electric cars, especially for wheel hub motors, described in Section 6.2. Three- and five-phase types of this drive are developed and applied by several manufacturers.

5. Pilot cars with SRM switched reluctance motor drive exist but are not described here.

Table 8-1. Technical data of electric cars with batteries (till February 2001).
## Drives of electric and hybrid-electric cars

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Citroen</th>
<th>Daihatsu</th>
<th>Ford</th>
<th>GM</th>
<th>Honda</th>
<th>Nissan</th>
<th>Nissan</th>
<th>Peugeot</th>
<th>Renault</th>
<th>Toyota</th>
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<tbody>
<tr>
<td>Model name</td>
<td>AX/Saxo Electrique</td>
<td>Hijet EV</td>
<td>EV1</td>
<td>EV Plus</td>
<td>Hypermini</td>
<td>Altra EV 106 Electric</td>
<td>Clio</td>
<td>RAV4</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>PM Synchron</td>
<td>3-phase induction</td>
<td>PM Synchron</td>
<td>PM Synchron</td>
<td>Separately excited DC</td>
<td>AC Induction</td>
<td>PM Synchron</td>
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<td>NiMH</td>
<td>NiMH</td>
<td>Li-ion</td>
<td>Li-ion</td>
<td>NiCd</td>
<td>NiCd</td>
<td>NiMH</td>
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<td>102</td>
<td>49</td>
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<td>62</td>
<td>20</td>
<td>22</td>
<td>50</td>
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<tr>
<td>Voltage (V)</td>
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<td>345</td>
<td>120</td>
<td>114</td>
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<tr>
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<td>32</td>
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<td>11,4</td>
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<td>Conductive</td>
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<td>Conductive</td>
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<tr>
<td>Top speed (km/h)</td>
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<td>129</td>
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<td>100</td>
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### Drives of electric and hybrid-electric cars

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<th>Daimler</th>
<th>Fiat</th>
<th>Ford</th>
<th>GM</th>
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<td>e-KA</td>
<td>Impuls 3</td>
<td>Rapan</td>
<td>Roadster -EV</td>
<td>Libero</td>
<td>E-com</td>
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<td>3-phase induction</td>
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<td>Separately excited DC</td>
<td>AC induction</td>
<td>PM Synchron</td>
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<td>Charge time</td>
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<td>8 (80% in 4h)</td>
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Table 8-2. Technical data of electric cars with batteries (till February 2001, cont.).
### Drives of electric and hybrid-electric cars

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<tr>
<th>Manufacturer</th>
<th>Daimler Chrysler</th>
<th>Daimler Chrysler</th>
<th>Ford</th>
<th>Ford</th>
<th>GM</th>
<th>GM</th>
<th>Honda</th>
<th>Mazda</th>
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<tbody>
<tr>
<td>Model name</td>
<td>NECAR 5 SUV</td>
<td>Command P2000 HFC</td>
<td>Th!nk Focus FCV</td>
<td>Opel Zafira HydroGen 1</td>
<td>FCV-V3</td>
<td>Demo-FCEV</td>
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</tr>
<tr>
<td>Drive type</td>
<td>3-phase induction</td>
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<td>3-phase induction</td>
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<td>PM synchron</td>
<td>3-phase induction</td>
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</tr>
<tr>
<td>Power source</td>
<td>Fuel-cell + methanol reformer or H storage</td>
<td>Fuel-cell + methanol reformer or battery</td>
<td>Fuel-cell + H storage</td>
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<td>Max power O/P (kW)</td>
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<td>145</td>
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<tr>
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Table 8-3. Technical data of fuelcell electric cars.

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<th>Manufacturer</th>
<th>Mitsubishi</th>
<th>Nissan</th>
<th>Peugeot/Citroen</th>
<th>Renault/Volvo Euro Project</th>
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<th>VW</th>
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</table>

Table 8-4. Technical data of fuelcell electric cars (cont.).
### Drives of electric and hybrid-electric cars

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<th>Partner</th>
<th>Fever</th>
<th>FCEV</th>
<th>Bora Hymation</th>
<th>Sharan</th>
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</thead>
<tbody>
<tr>
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<td>PM Synchron</td>
<td>Synch wound rotor</td>
<td>PM Synchron</td>
<td>3phaseinduction</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Power source</td>
<td>Fuel-cell+ reformer</td>
<td>Fuel-cell + reformer or H storage</td>
<td>Fuel-cell + H storage + NiMH battery</td>
<td>Fuel-cell + methanol reformer</td>
<td>Fuel-cell + H storage</td>
<td>Fuel-cell + reformer</td>
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</tr>
<tr>
<td>Max power O/P (kW)</td>
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<td>50</td>
<td>89</td>
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<td>Voltage (V)</td>
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<td>Top speed (km/h)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Claimed max Range (km)</td>
<td>400</td>
<td>500</td>
<td>350</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Date of production</td>
<td>2005</td>
<td>2004/5</td>
<td>2003/4</td>
<td>2003</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Battery fed electric cars called “Puli” were manufactured in Hungary, Hódmezővásárhely, with series excited DC drive, 10 pieces of 6V/240Ah lead-acid batteries, 65 km/h max speed and 60-100 km range. In contrast, Tesla-Roadster luxury car was developed in 2007, with inverter fed AC induction drive, Li-ion batteries, 130km/h max speed and 400 km range.

From the tables above, we can see that supply voltage can be varied in a wide range 114-330V, both for battery or fuel cell fed vehicles. Load current can be reduced if supply voltage is increased for a drive with certain power need. Optimal selection of voltage and current is influenced by the energy source and the type of drive. Vehicles exist where voltage used for drive is different that the voltage of the energy source, in this case DC/DC converter is needed. Such a vehicle can be seen in Table 8.4, where fuel cell voltage is 90V and drive voltage is transferred to 250V.

**Energy supply for electric cars**

Electric energy needed for electric cars is determined by the drive, mainly, but energy needed for auxiliaries can also be high.

Auxiliaries in traditional vehicles with internal combustion engines are fed by auxiliary battery with 6, 12 or 24V output voltage, directly or through a power electronic circuit. Controlled charging of this auxiliary battery is realized with a generator driven by the engine.

In contrast, generator cannot be found in electric cars. As we use the same auxiliaries, low-voltage auxiliary battery can also be found in electric vehicles. This battery must be charged by the main circuit. The typical structure of the main circuit for electric cars can be seen in Figure 8.1. The main power source can be battery, fuel cell alone or with a secondary energy storage device.
Auxiliaries used in traditional cars induce special consequences. Auxiliaries are designed so that there is no need to connect their negative pole to the battery; the negative pole is realized by the body of the car. If the DC/DC charger shown in Figure 8.1 is not isolated, then the negative pole of the main circuit will also be at body potential. There are electric cars where main voltage is divided to 50-50% and “grounding” is at the middle. In this case the circuit is asymmetric, with respect to the auxiliary battery, but voltage is reduced to \( \pm U_{\text{main}}/2 \) for electric shock protection. In modern high-power vehicles, auxiliaries with alternating current may exist, in this case DC/AC inverters are connected usually to the main circuit (see Figure 8.1).

### 1.1. Electric cars with battery

Types of batteries selected by the manufacturers may vary, as can be seen in the fourth rows of Tables 8.1 and 8.2. Energy storages used in cars were acid or lead batteries formerly. Nowadays they are used only for auxiliaries and they are closed (gel) or valve regulated lead acid (VRLA) types. There were times when a lot of electric cars were manufactured with NiCd batteries, but their usage was prohibited by the new environment protection provisions, because Cd is dangerous waste. Instead, Nickel-Metalhydrid (NiMH) type batteries were developed with almost the same parameters. Main data of these three traditional types are summarized in the first three columns of Table 8.5. Data of Lithium based batteries can be found in the fourth column for comparison. These data are getting better and better as development continues.

<table>
<thead>
<tr>
<th>Battery type</th>
<th>Lead-acid</th>
<th>Nickel-Cadmium, NiCd</th>
<th>Nickel-Metalhydrid, NiMH</th>
<th>Lithium-ion and Lithium-ion polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational temperature</td>
<td>-10…55ºC</td>
<td>-40…50ºC</td>
<td>-40…50ºC</td>
<td>-45…85 ºC</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Liquor of sulfuric acid</td>
<td>Liquor of alkali solution</td>
<td>Liquor of alkali solution</td>
<td>Organic electrolyte or polimer</td>
</tr>
<tr>
<td>Non-operative voltage</td>
<td>2,1V</td>
<td>1,35V</td>
<td>1,35V</td>
<td>3,5V</td>
</tr>
<tr>
<td>Energy-storing capacity/unit</td>
<td>30…45Wh/kg</td>
<td>40…55Wh/kg</td>
<td>50…80Wh/kg</td>
<td>100…250Wh/kg</td>
</tr>
<tr>
<td>Power/unit</td>
<td>100…200W/kg</td>
<td>180…260W/kg</td>
<td>180…250W/kg</td>
<td>300…800W/kg</td>
</tr>
<tr>
<td>Lifetime</td>
<td>300…850 cycle</td>
<td>600…1000 cycle</td>
<td>600…1000 cycle</td>
<td>500…1200 cycle</td>
</tr>
</tbody>
</table>
Batteries listed here can be operated in normal temperature which ensures their use for general purposes. They can be used without additional devices in electric cars.

A possible promising type for electric vehicles was NaNiCl₂ battery (called “Zebra”), with high efficiency and 90-100Wh/kg energy storing capacity. Its main disadvantages are its complexity and high working temperature (300-350°C).

Li-based batteries gave a breakthrough with respect to their application in vehicles, especially lithium-ion and lithium-polymer types.

Lithium-ion (Li-ion) technology is based on movement of lithium ions. During charge ions drift to the negative carbon-based electrode, while they drift to the positive metal-oxide electrode during discharge. Organic solvent with conductive additions is used as electrolyte. Li-based batteries were first developed in the 80s. They used metallic lithium and could overheat during overload which led to explosion and melt. Nowadays, batteries use several compounds or additional materials as lithium ion sources (e.g. yttrium) so lithium is bound securely. Despite of the dangers, a lot of manufacturers develop Li-ion batteries, because their electric and energy storage properties are the best. Energy storage capacity (Ah) is about twice as of NiMH batteries which come from the doubled cell voltage. (Cell voltage is ≈3,5V when fully charged). Even, discharged cell can provide about 3 V comparing to 1-1,35V for NiCd or NiMH batteries. More advantages are their relative light weight and that no crystals appear during operation.

Li-polymer battery is a promising development, too. Its main advantage is that no, or very few electrolyte is used, they use special polymer to separate anode and cathode. This fact can produce thin and flexible cells, no thick-wall container is needed to protect environment against electrolyte. But, shorter lifetime and longer charging time is expected.

These batteries can be compared by several viewpoints, like: operational temperature, energy storage capacity, specific power, lifetime, energy efficiency, production cost, robustness, maintenance.

Energy storing capacity per unit (specific energy), which is 30-170Wh/kg for present batteries, is the most important for vehicle application. This nominal value is given by the manufacturers for 25°C operational temperature and constant nominal current discharge. Energy available for real use can vary and depends on temperature, overload, deterioration etc. About 15kWh energy is needed to operate 1t mass vehicle for 100 km. This means that 300 kg of batteries with 50Wh/kg energy storing capacity would be needed but half would be enough when using 100Wh/kg energy storing capacity. So improving energy storing capacity is very important.

Power per unit (specific power) is also an important parameter. It shows how much $P=ui$ momentary dynamic electric power load the battery can bear. Based on this data and the voltage, we can estimate how much overcurrent can be permitted, how much is the allowed charging current and whether boost charging is acceptable.

Ragone-diagrams are often used to compare different battery types. The diagram shows energy storage capacity vs specific power, often comparing to other energy storages.

Battery energy storage is based on series connected battery cells. Batteries used in vehicles can be operated without additional devices, no or very little (periodical) maintenance is needed, except type NaNiCl₂ („Zebra”). The main circuit of an inverter-fed battery car can be seen in Figure 8.2.

Figure 8-2. Main circuit diagram of inverter-fed car with battery.

As shown earlier, the negative pole of the main battery or the central point is on the same potential as the car body. Charger for the low-voltage auxiliary battery is connected to the mainbattery.
Energy efficiency of the selected main battery is important for vehicles application, which describes that what percentage of the filled in energy can be taken out. The energy efficiency is:

\[ \eta_E = \frac{E_{\text{out}}}{E_{\text{in}}} = \frac{\int_{t_{\text{ch}}} u_{\text{dc}} i_{\text{dc}} dt}{\int_{t_{\text{dc}}} u_{\text{dc}} i_{\text{dc}} dt} \]

In the expression index \( ch \) index means voltage and current during charge time and \( dc \) during discharge time. Discharge value \( u_{\text{dc}} \) of output voltage \( u_{\text{main}} \) is always lower than no-load voltage in Table 9.5 \( (u_{\text{dc}} < U_{\text{no}}) \), and charging value is higher \( (u_{\text{ch}} > U_{\text{no}}) \). Main circuit voltage \( u_{\text{main}} \) depends on several factors, like current, charge and deterioration state, environmental temperature. Typical change in output voltage vs charge degree is shown in Figure 8.3.a, where the parameter is the current of the battery. The limit of discharge is set by final discharge voltage \( U_{\text{end}} \), which can be even zero for some battery types. Charging is limited by permitted maximal value \( U_{\text{max}} \).

![Figure 8-3. Characteristics of batteries, a.) voltage change vs charge degree, b.) output capacity vs overload and c.) temperature vs current.](image)

Charge degree is marked with SOC (State of Charge) value, which gives how much capacity is available to reach final discharge state comparing to the nominal capacity of the accumulator.

Nominal capacity of the battery is the amount of charge available during nominal discharge time \( t_n \) with nominal discharge current \( I_n \) at 25°C temperature, \( K_n = I_n t_n \), which is given by the well-known Ah (Ampere-hour) value. \( t_n \) nominal discharge time can vary, for vehicle batteries is it 5 hours typically, but can be 10, 20 hours, too. If the discharge current is higher than the nominal value, for example \( I/I_n = 2 \), than discharge time decreases to \( t_{dc} < (t_n/2) \) value, this means that actual output capacity decreases in case of overload. Capacity change is shown in Figure 8.3.b. The amount of output charge decreases also if the temperature of the battery is lower than 25°C, this change is shown in Figure 8.3.c.

Capacity of batteries is strictly connected to energy storage capacity, for which nominal value is \( E_n = K_n U_n = I_n t_n \), where \( U_n \) is nominal voltage measure on the poles at nominal current, which is lower than no-load voltage \( U_{\text{no}} < U_{\text{n}} \). Output voltage changes during operation, and depends on charging degree as well as load current, as can be seen in Figure 8.3.a.

Charge that can be got during time \( t_x \) with discharge current \( i_{\text{dc}} \) is \( E = \int_{t_x} u_{\text{dc}} i_{\text{dc}} dt \). The output energy for this time period is \( E = \int_{t_x} u_{\text{dc}} i_{\text{dc}} dt \).

Usable energy also depends on \( u_{\text{dc}} \) discharge voltage, but energy storing capacity depends on overload and temperature, similarly as for capacity shown in Figure 8.3.b and 8.3.c.

Current \( I_n \) of battery feeding the main circuit (its \( K_n \) nominal capacity) must be set so that it should provide the designed nominal power \( P_n = U_n I_n \). The designed power is the sum of the power required by the drive and the auxiliary devices. During design, we have to consider that the battery should provide \( I > I_n \) current because of the dynamic requirements of the vehicle drive. It could be overloaded while accelerating and could recuperate decelerating energy with regenerating braking (dashed direction in Figure 8.2). Regenerated energy can reach even 20-30% of used energy for urban vehicles. Energy saving is the highest in urban vehicles because in this
case they brake and stop often. To reduce dynamic load of batteries, an ultracapacitor can be used as additional energy storage combined with the main circuit (Section 8.1.3).

One of the main components of running cost of battery vehicles is the life-cycle of the accumulator. This means the maximal value of charge-discharge cycles that a battery can endure. This value specifies how often the whole battery set should be replaced. If the max number of charges is 1000 and the car is used and recharged every day, then the lifetime is three years.

Disadvantages of using batteries are the following:
1. Relatively low specific energy storing capacity;
2. Frequent charge required, while boost charge is hard to realise;
3. Relatively short lifetime;
4. Hard to measure the remaining available energy;
5. Used batteries have to be gathered and recycled.

Disadvantages show that the most promising application of battery vehicles is urban transport. Range available with one charge is relatively short because of the low energy storage capacity of the batteries. One more problem arises. Not only the drive but all the other equipments are electric, this means that lower comfort should be used to reduce consumption. Every comfort equipment, especially air conditioning shortens the range of the vehicle.

Because of low energy storage, the vehicle should be charged often and charging adapter and protection circuits must be used.

Several solutions exist to charge the main accumulator:
1. High capacity boost charging stations;
2. Slow charge from consumer electric network (during night);
3. Slow charge at work parking lots;
4. Special parking lots with high-frequency power transmission;
5. With solar cell built onto the vehicle (additional charging with solar cell);
6. With additional treadle operation generator built into the vehicle.

From the list above we can see that there are two main charging methods: fast (boost) and slow. Slow charging is better for increasing lifetime. Boost charging means heavy stress for batteries. In this case additional slow charge cycles are also preferred. From this we can conclude that the connection to the charging network should be available for several charging methods.

Boost charge would be optimal if recharge time could be fast (10…15 mins) enough comparing to internal combustion engines. This means a lot of problems. One big problem is that charging current must be much higher than nominal current $i > I_n$ ($t / t_n$). If nominal charging time is $t_n = 5$ hours for an accumulator, and charging time is expected to be $t = 10$ minutes then charging current should be 30 times than nominal ($t / t_n = 30$). Another problem is that high-power charging stations should be installed for boost charging. For example, 90 kW charging power is required to charge fully a 15kWh energy storing battery in 10 minutes. Besides, both the battery and the station must be secured and protected.

Opportunities to reduce boost charge power:
1. increasing charge time to an acceptable value,
2. partial boost charge to 40-50% of full capacity.
There are charging stations where boost charge is available. Shape and handling of filler head is similar to petrol ones, only the filler is connected to the electric charger with a cable. Energy required for recharge is transmitted with special high frequency transformers. Insulated energy transmission, which is important for safety, can be guaranteed with inductive coupling. The structure of a boost charger can be seen in Figure 8.4.

![Figure 8-4. Typical structure of a boost charging device.](image)

Boost charger consists of a network filter, high frequency power supply and filler head. The AC/AC converter provides one-phase, regulated, 30-70kHz frequency AC voltage and charging current control. Primary coil installed in the filler head and ferrite-core secondary coil installed in the vehicle create high-frequency coupled transformer. Secondary voltage is transformed to rectified DC with an AC/DC converter.

**During slow charge at night or in parking lot** charging current demand is similar to nominal current, $i_{ch} < (2-3)I_n$. Acceptable charging time can be 5-8 hours for night and during work time, and can be shorter for other parking lots. During night, charging should be operated with normal household electric network. The charger itself can be outside or inside the vehicle, or divided as shown in Figure 8.4. The simplest one is the charger inside the vehicle, which needs additional space and weight but can be connected conductively (with simple industrial plug) to the network. Newer developments target to create high-frequency inductive charging at parking lots. This charging method is similar to the one that can be seen in Figure 8.4 but inductive connection is realized not with a filler head. Primary coil of the transformer is flat inside the parking lot and the car should be stopped so that the coupling between the two coils be the best.

**Solar cell and treadle generator additional charging** is used in hobby vehicles. In both cases it is important that electric circuit should prevent energy consumption of the chargers. For example, solar cells should not be energy consumers when there is no light for normal operation (in dark). Additional charging electronics always include a rectifier diode which prevents that the direction of the charging current changes. In solar cell chargers electronics and control is set to give the best efficiency for the solar cell and to provide continuous current. This ensures maximal output power during different light intensity.

**Battery management** is used when batteries are connected to microcontroller based state monitoring, protection and signal electronics. The main roles of the management are:

1. to monitor temperature of the battery,
2. to monitor voltage difference between cells or cell groups, and start balancing if required,
3. to monitor charging state of the accumulator.

**Equalizing charging voltage of battery cells** can improve the charge efficiency and lifetime of batteries for both boost charge and the time after charge. If the batteries are connected in serial during operation, then charging is also made in serial, with controlling voltage and charging current of the charger. Voltage is not uniform on the cells, especially during boost charge. There are battery cells where voltage is lower or higher than average. This difference worsens the use of the whole system. This can be a big problem during boost charge, because some cells can be over-charged while others are underfed. Capacity of the system decreases because of the underfed cells and lifetime shortens because of the over-charge. There are special control systems to provide voltage equalization. In Figure 8.5.a., voltage higher than acceptable is decreased with shunt circuits. Current on the shunt means loss in the system.
Drives of electric and hybrid-electric cars

Figure 8-5. Voltage equalizing of batteries a./ with shunt circuits, b./ chain connection. c./ Operational circuit diagram for chain connection.

Figure 8.5.b shows an almost loss-less solution. In the chain, $EQ$ circuits compare voltages on two neighbor cells. If voltages are different, then they control the difference of the charging currents. This idea can be seen in Figure 8.5.c. If $u_1 > u_2$, then transistor $T1$ opens and $i_1 < i_2$. In this circuit only the current difference causes loss on resistance $R_{EQ}$. Potential divider consists of two resistances $R$, and provides reference signal.

It is important to calculate the charging state of the main battery in electric vehicles, just like to measure the level of petrol in petrol-driven cars. We have to know how much the „remaining“ energy is in the accumulator, what range can be reached without recharge. Momentary available energy is measured by a relative available energy referred to the nominal capacity of the battery in the literature. This value is called SOC (State of Charge), in percent.

There are several methods to calculate charge state:

1. measuring consumed charge ($\int i \, dt$) and comparing it with calculated capacity coming from the characteristics of the battery,
2. measuring consumed energy ($\int u \cdot i \, dt$) and comparing it with calculated energy storage capacity coming from the characteristics of the battery,
3. capacity calculated from voltage measurement, calculated from the response to dynamic (rectangle shape) load change,
4. capacity calculated from impedance measurement, calculated from the response to superposed sinus voltage signals.

All of the methods require a lot of calculations, and we have to take into account the temperature and lifetime state of the battery.

Instead of a battery, ultracapacitor (super-capacitor) can also be used.

Ultracapacitor is a new and important product nowadays. It is a special capacitor which can take and provide extra high power.

Usually, energy stored in a capacitor $C$ charged to voltage $U$ can be calculated as $W=CU^2/2$. The capacity of the capacitor is $C=\varepsilon_\varepsilon_0 A/\delta$, where $\varepsilon_\varepsilon$ is relative permittivity of the dielectric, $\varepsilon_0=8,85\times10^{-12}$F/m is the permittivity of vacuum, $A$ is area of capacitor plates, $\delta$ is thickness of dielectric. Traditional capacitors have only about 0,1 Wh/kg relative (specific) energy storage even for the best polyethylene dielectric.

$U$ltra $c$apacitor is a two-layer capacitor made by special electro-chemical technology where dielectric thickness $\delta$ is extremely small, sometimes in the range of $\mu$m. Because of this, very high, 500-1500F capacitors can be made with low loss and long lifetime. Relative energy storing capacity is much higher than that of the traditional capacitors, in the range of 5 Wh/kg, but much lower than the energy storing capacity of batteries (50…150Wh/kg). Voltage permitted on the poles of the ultracapacitor is low (3-5 V) so several serias-connected cells are required, similar to the batteries. The plates of ultracapacitors can be flat or scrolled. Dielectric used between the plates can be carbon-metal composite, foam carbon, activated synthetic monolithic carbon, polymer carbon film, metaloxide etc. Ultracapacitors are manufactured by several companies, like ESMA, ELIT, NESS, PowerCache, SAFT, etc.
In several applications not the energy storage capacity of the ultracapacitor is used, but its high peak-power input and output capacity, for a short time period (impulse regime). Momentary power of a capacitor is \( p = u i \), where \( u \) is voltage of the capacitor, \( i \) is charging or discharging current. Even 2.5kW/kg unit (specific) power is possible momentarily, depending on the type of the ultracapacitor. Direction of current can be charging, in this case capacitor consumes power, or discharging, when it generates power.

One of the most important application field of ultracapacitors is in electric cars. There are experiments where they are used for main energy supply, but they are used as secondary and temporary energy storage more frequently. Using it we can prevent the primary energy source from peak loads.

### 1.2. Fuel cell electric cars

The development of fuel cell electric cars is very important and several car manufacturers deal with it, as can be seen in Table 9.3. and 9.4. There is example for fuel cell bus as well.

**Comparing fuel cell and battery energy sources**

In Fuel Cell Electrical Vehicles (FCEVs) fuel cell, like battery, serves as DC energy source. Main electric circuit and vehicle drive are also similar (Figure 8.1.), only voltage \( U_{\text{max}} \) is generated by a fuel cell. But, some important points are different for fuel cells sources:

1. Fuel cell is electro-chemical converter, it cannot store electric energy.
2. Fuel cell, like internal combustion engine, works with fuel, so electric energy can be produced only if there is enough fuel and operating conditions are fulfilled.
3. Storing and refilling fuel is more complex than even for internal combustion engines because fuel used in FCEVs is hydrogen usually which is stored as high-pressure gas or liquid, or methanol reformed. Secure handling and storing of hydrogen is an important challenge nowadays.
4. Operating intensity of a fuel cell in normal operation regime changes as electric consumption changes. Fuel cells can follow the dynamic stress required for acceleration with delay in basic configuration.
5. Fuel cell energy source cannot utilize regenerated energy from braking; its current direction cannot change.
6. Because of the last two disadvantages, fuel cell energy source alone cannot be used in vehicles; it has to be extended with an energy storage device. This can be electric storage, battery or ultracapacitor (as can be seen on Table 9.3 and 9.4) or flywheel mechanical storage. Section 9.1.3. deals with these devices. Nowadays, Ovonics Company develops fuel cell combined with metalhydrid hydrogen storage which enable regeneration and eliminated delay with chemical energy storing.
7. Operation of fuel cell has to be controlled and monitored continuously; its control and auxiliaries are complicated. Starting the operation of the cell, its cooling and monitoring fuel level has to be provided separately.
8. Fuel cells are sensitive for ambient temperature when starting; there are problems when starting them below -4°C.
9. Pollution of fuel cell vehicles is not zero, even when using pure hydrogen. Besides water resulting from the burning of hydrogen, nitrogen-oxides can appear if air and not pure oxygen is used. When using methanol fuel, carbon dioxide is also appear, as secondary product.

#### 1.2.1. Fuel cell energy source for cars

Fuel cell is an environment friendly electro.chemical power source. There are several types of fuel cells:

1. AFC (Alkaline Fuel-Cell) with traditional alkaline,
2. PEMFC (Proton Exchange Membrane Fuel-Cell), with polymer membrane electrolyte,
3. MHFC (Metal Hydrid Fuel-Cell), PEMFC combined with metal-hydrid hydrogen storage,
4. PAFC (Phosphoric Acid Fuel-Cell),
5. MCFC (Molten Carbonate Fuel-Cell),
6. SOFC (Solid Oxid Fuel-Cell) with zirconium ceramic,
7. high pressure fuel cells.

From these types, PEMFC is used in vehicles, where operating temperature is about 70-80°C, operating pressure is 1-10bar. Its handling is the best for vehicle application. Theoretical and practical structure of such a cell can be seen in Figure 8.6.

![Theoretical structure of a PEM cell.](image)

![Practical structure of a PEM cell.](image)

In the cell, chemical reaction is realized with proton change while electron flow (signed as e⁻) is closed through the external circuit. Proton exchange membrane, coated with platinum or graphite, is surrounded by anode and cathode which are porous plates. Coating intensifies the chemical reaction. Yellow indicates oxygen, blue indicates hydrogen admissions. The secondary product, water, appears on the cathode.

The fuel cell energy source is built up from these flat PEM cells, connected in serial. The structure of this fuel cell is shown in Figure 8.7.

![Theoretical structure of a fuel cell energy source.](image)

In no-load operation the output voltage is \( u = U_0 \) (switch \( K \) is open, load current is zero, \( i = 0 \)). In load operation \( i > 0 \) and output voltage \( u < U_0 \). If current increases, voltage decreases non-linearly. Fuel cell energy source, like battery, is built up from several cells connected in series because the cell voltage is low, in the range of 1V. Output voltage depends on the number of the cells (N), quality of fuel feeding, operational temperature and pressure, and load current \( i \). Load current depends on the active surface of the cells and the maximal current density \( q[A/cm^2] \). Maximal current density can be in the range of 0.5…1A/cm² for a typical cell.
The changing of voltage when current or temperature changes is important for vehicle application. This depends on the quality of cells connected in series. Dependency of voltage $u_c$ on load current density $q$ is shown in Figure 8.8, based on the measurements in National Energy Laboratory.

Figure 8-8. Voltage vs load for a single PEM fuel cell.

The figure shows the output power of a PEM cell at 70°C operational temperature for different feeding modes. The two upper curves show pure hydrogen feeding, the upper one with compressed air, the lower one without air compression. The lowest curve stands for reformed hydrogen feeding which includes carbon-monoxide as well. From the figure we can conclude that voltage changes in a wide range. Voltage drop can reach 40-50% at maximal load.

Temperature dependency of output voltage for a fuel cell is indicated in Figure 8.9. The figure shows $u\cdot i$ load measurement at different load temperatures $T(°C)$ for a 5 kW PEMFC built from 75 cells connected in series.

Figure 8-9. Output voltage vs temperature for a PEM cell.

On the figure we can see that temperature dependency of output voltage is significant, it can change in the range of 43-74V caused by the load and the temperature together.

Electric power available from fuel cell is the product of its current $i$ and output voltage $u_c$, $p=u_c\cdot i$. Unit (specific) power density for the electrode surface is $u_c\cdot q$, its maximal value is 0.5…0.7W/cm² per cell. There is another indicator value for power density which is power per volume expressed in liters W/ℓ.

Technical data for measuring and comparing electric properties of fuel cells are the following:

1. no-load voltage;
2. load capacity per unit, maximal current density;
3. maximal power density;
4. recovery time of the fuel cell;
5. operational conditions (temperature and pressure);
6. operational efficiency.
Transient behavior of a fuel cell is characterized by its recovery time. In the fuel cell, the development of the electrochemical processes and the changing of the intensity of these processes cannot happen without delay. As load changes, it needs time to stabilize the processes and create a new operating point, and this time depends on the fuel feeding. Recovery time is given for the transient process where load changes from no-load to 90% of maximal load current, until the new operating point is reached. Recovery time is not the same as the time needed for starting the operation of the system.

Operational temperature is important for two things. On one hand, we have to know the minimal temperature where the fuel cell can be started, and what temperature is where chemical processes can operate with maximal efficiency, on the other, which is required for optimal operation.

Efficiency of the fuel cell: quotient of output electric energy during a given time, and heat energy from the burning of fuel for this time.

Output electric energy for time $\Delta t$ is the integral of instantaneous power:

$$W_{el} = \int_0^{\Delta t} P \, dt.$$  

8-1

If mass of fuel $\Delta m_{fu}$ is required for this output power during time $\Delta t$, and energy storing capacity for mass unit $w_{fc}[\text{Wh/kg}]$ is known, then efficiency of fuel cell is

$$\eta = \frac{\Delta W_{el}}{W_{el} \Delta m_{fu}} = \frac{1}{w_{fc}} \int_0^{\Delta t} P \, dt.$$  

8-2

Efficiency of fuel cells is relatively high comparing to other electric energy sources: 50-70%.

Energy source includes auxiliary devices, like cooler, feeder, pressure controller etc. besides the fuel cell itself (Figure 8.10.).

Figure 8-10. Fuel cell with auxiliary devices.

Efficiency of the whole fuel cell energy source is lower than the value (8.2) because fuel cell has to supply energy for auxiliary electric devices (Figure 8.10.). Output power for vehicle traction is $p_{ki} = u(i_{i_{aux}} + i_{i_{aux}}) = u_{main}(i + i_{aux})$, part of the momentary output power generated $p_{aux} = u_{i_{aux}}$, is required for auxiliary consumption, which decreases the overall efficiency. Its impact is important in low-load operation when output current $i$ is low and is comparable with auxiliary current $i_{aux}$.

Control methods for fuel feeding:

1. Type A feeding, when fuel (hydrogen) has constant pressure and flows through. Fuel cell consumes fuel as required for operation, and unnecessary, not-burned fuel is fed back to the feeding side. Output power of the fuel cell can be set by the pressure (velocity) of the air flowing in. If the amount of air increases, then hydrogen consumption and the intensity of chemical processes inside the cell also increase.

2. Type B feeding, when the amount (and pressure) of the hydrogen is controlled, pressure of the air is plentifully available. This type is similar to the feeding of petrol or gas injected internal combustion engines.
Nowadays, there are complete fuel cell energy sources for vehicle and other applications.

As an example, structure of elements of the Xcellsis product type XCS-HY-75, hydrogen fed fuel cell is shown in Figure 8.11.

Figure 8-11. Elements of type XCS-HY-75 fuel cell.

Fuel is high pressure (10bar) compressed gas hydrogen at normal ambient temperature, stored in a vessel. Feeding of fuel is type A. The device consists of modules:

1. The heart of the device is a PEMFC fuel cell which operates at 1-4 bar pressure and 70-85ºC temperature. Ambient temperature allowed during operation is 5-40ºC, during storage is 10-40ºC.

2. Air compression module compresses inlet filtered air to the required pressure before air gets into humidifier. Humidifier module waters the inlet hydrogen and air with deionized water taken from the cooling system. Both preparing processes improve the efficiency of the chemical process.

3. Pressure controller module controls fuel pressure from 10bar storage pressure to 1-4 bar operating pressure. Not used fuel is refilled. Hydrogen valve in the refilling loop opens if security or other emergency issues arise.

4. Water steam condenser module reuses part of the water resulted from fuel cell.

5. Cooling and heat exchanger module controls operating temperature of fuel cell.

6. An auxiliary voltage regulator module is also part of the system. Auxiliary battery can be operated from this DC/DC converter.

The whole system is controlled by a microcontroller. Central microprocessor unit controls information and data flow, and monitors the device. The system can be connected to external controller through this unit. The load and efficiency characteristic for a 68kW and 250V nominal voltage fuel cell can be seen in Figure 8.12.

Figure 8-12. Load and efficiency characteristic of type XCS-HY-75 fuel cell.

250 V nominal voltage can be measured on the output poles at about 270A load current. Output voltage is higher than 250V with lower load, its maximal value is 450V. Drive system must be designed to tolerate 450V without damage.
As can be seen from the efficiency characteristic in Figure 8.12., 50% efficiency (its catalog data) can be reached only in a narrow range at 20…30kW. Efficiency worsens outside this range.

The mass, volume and energy consumption of the auxiliary modules is significant comparing to the main fuel cell module. Noise of air compressor can also be high.

The size of Xcells product type XCS-HY-75 fuel cell (applicable in electric car also) is 1770x950x300mm, its recovery time is 1s. Its picture can be seen in Figure 8.13.

Figure 8-13. Type XCS-HY-75 fuel cell

**Transient behavior of a fuel cell:** It is important for every energy source devices; what pulse load it can bear and how transient processes pass off. The following oscillogram (Figure 8.14.) shows the transient behavior of a 30kW 70V purely hydrogen fed fuel cell made by Nuvera Fuel Cells Europe, which demonstrate the time functions of the typical values of the fuel cell for load step change from 50A to 550A.

Figure 8-14. Transient characteristics of Nuvera Fuel Cells.

During load change, the control system of the fuel cell changes the pressure of inlet air. Mass flow can increase with delay after increasing pressure. The new load state sets in about 1 second, while output voltage decreases to 64V from about 82V. Current of air compressor is relatively high (about 50A) comparing to the current of the fuel cell, as can be seen in the figure. Because this is the main part of the auxiliary consumption, current of fuel cell increases to about 600A during the process.

1.2.2. Application of PEMFC fuel cell in electric vehicles

The theoretical structure given in Figure 8.10 is not complete, if PEM cell is used, two problems arise:

1. Pulse type, dynamic load change during acceleration would not be fulfilled,

2. Regeneration of energy would not be fulfilled as PEM cell cannot change its current direction.

To overcome these problems, the PEM fuel cell has to be extended with temporary energy storage. This storage can be battery, ultracapacitor or flywheel mechanical energy storage. Nowadays MHFC type fuel cells are developed where fuel cell is combined with metal-hydrid hydrogen storage which realizes chemical energy storage.

In vehicles, combined energy source with battery or ultracapacitor is used most often.
a/ Fuel cell combined with battery energy storage can be seen in Figure 8.15. Battery is connected to the output of the fuel cell with a DC/DC converter. Figure also shows a possible electric circuit for this DC/DC conversion (Buck-Boost), L1-C elements have filter function. The circuit is similar if ultracapacitor is used instead of battery for secondary energy storing.

![Figure 8.15. Fuel cell combined with battery energy storage.](image)

With appropriate control we can reach that fuel cell works in optimal condition and with minimal fuel consumption during most of the normal operation, and battery takes the extra stress from pulse load change. Regeneration can be realized with combined energy source. About 40% fuel consumption saving can be reached with combined energy source and optimal load distribution, comparing to pure fuel cell feeding, taking into account the regeneration capacity of the accumulator. Economic operation in transient mode can be realized with correct control strategy.

Load distribution between the fuel cell and battery can be controlled with the DC/DC converter. Operating states of the combined energy source are:

1. steady state: \( i_{\text{load}} \approx \text{const.} \) and \( i_{\text{load}} \approx i_{\text{FC}} \).
2. during acceleration, when \( i_{\text{load}} > i_{\text{FC}} \) is required, battery can provide additional current, \( i_{\text{load}} = i_{\text{FC}} + i_{\text{down}} \).
3. purely battery operation is possible, for example during starting of the fuel cell or malfunction: \( i_{\text{load}} = i_{\text{down}} \) (\( i_{\text{FC}} = 0 \)).
4. if load is lower than average \( i_{\text{load}} < i_{\text{FC}} \), battery can be charged: \( i_{\text{FC}} = i_{\text{load}} + i_{\text{up}} \).
5. regeneration is possible during brake state of the vehicle: \( i_{\text{load}} = i_{\text{up}} \) (\( i_{\text{FC}} = 0 \)).

Battery must be designed to bear current peaks higher than average and to store the resulting required energy. As battery can be with lower nominal power than total power required, it has to be protected with SOC (State of Charge) control.

A FCEV application example is a vehicle with combined fuel cell and battery developed by Toyota (Toyota Motor Corporation, Aichi, Japan). The PEMFC cell used is 90 kW, hydrogen fed, air mass controlled, with air compression and air humidifier. Secondary energy storage is made by 6.5Ah NiMH batteries with air cooling. Drive is realized with 80kW maximal power, water cooled permanent magnet synchronous motor with current vector control introduced in Section 6.1. Motor is fed by a water cooled inverter. The circuit can be seen in Figure 8.16.

![Figure 8.16. Circuit diagram of fuel cell combined with battery energy storage.](image)
Control system of the vehicle consists of three parts: electric drive control block, load distribution controller, and fuel cell controller. Theoretical scheme of the control is shown in Figure 8.17. (On the figure, index \( B \) stands for battery, \( v \) for vehicle speed, \( \omega \) is angular velocity of the motor, \( m \) is torque of the motor.)

![Figure 8-17. Control diagram of fuel-cell combined with battery energy storage.](image)

As shown in the figure, torque of the motor (\( m_a \)) can be set in two ways. One method is direct torque signal controlled by accelerating and brake pedal, as in traditional vehicles. Another method is selectable speed controlled operation (tempomat) when motor torque is set by output signal of the speed controller.

*In continuous traction operation* required traction power \( P_{req} = m_a \omega \) can be calculated from required traction torque \( m_a > 0 \). Load distributor controls the feeding of hydrogen and air of the fuel cell and sets reference voltage \( u_v \) of voltage regulator DC/DC converter connected to the battery based on this calculation. In steady state, controlled voltage is set so that current of energy storing battery is almost zero. In this case the required power is provided by the fuel cell with \( i_{fc} \) current. Control strategy of the voltage can be seen in Figure 8.18.

![Figure 8-18. Setting output voltage level for combined energy source.](image)

If the SOC of the battery is too low, then reference voltage \( u_v \) is reduced to increase current of fuel cell until it can provide charge for battery as well as driving the vehicle.

*During acceleration, when load pulse appears*, load distributor controller increases fuel feeding and realizes “additional acceleration” control with voltage regulator (decreases \( u_v \)). Battery provides additional current and power for traction temporarily until fuel cell gets into the new operating point. Load distribution control provides protection for both fuel cell and battery.
In electric regeneration brake operation mode the torque reference signal of the motor is negative, \( m_r = -m_{\text{brake}} \). In this case the load distributor controls the operation point of the fuel cell to zero load, switches off fuel feeding and increases voltage reference signal \( u_{vr} \). Energy flow reverses with the DC/DC converter. Energy is fed back to the battery and it is charged. Energy regeneration to the fuel cell is not possible.

The inner set-up of the vehicle is shown in Figure 8.19.

![Set-up of a Toyota FCEV fuel cell car](image)

**Figure 8-19.** Set-up of a Toyota FCEV fuel cell car.

**b.** Fuel cell source combined with chemical energy storage is MHFC (Metal Hydrid Fuel-Cell) where fuel cell is extended with metal-hydride hydrogen storage. This solution is developed by Ovonic Fuel Cell Company.

Fuel cell used in MHFC for vehicle application is similar to PEMFC solid polymer-electrolyte cell but the material of the cathode and anode is different. Metal-hydrid is used instead of porous material used in anode of PEMFC and metal-oxide in the cathode. MHFC can be made by less expensive materials and can work without platina catalyst but metal-hydrid coating increases its mass and unit (specific) power is also less.

Metal-hydrid coating on the anode can store hydrogen temporarily, depending on its material and mass, and this storing is realized with atomic bond. If there is metal-hydrid stored hydrogen in the cell, then starting and operation without normal feeding can be realized. MHFC bears both advantages of fuel cell and battery. It can regenerate energy (with opposite current direction) as long as metal-hydrid can store generated hydrogen. From these comes its name “regenerative fuel cell”.

The main differences between the operation of PEMFC and MHFC fuel cells are:

1. PEM cell can provide energy only if fuel feeding is continuous and available every moment, and other operating conditions (pressure, temperature, correct feeding operation etc.) are fulfilled. Amount of feeding fuel and air can be changed only with time delay which limits the dynamic load of the electric output. Direction of output current cannot be changed.

2. MHFC cell can use stored hydrogen as long as its storing capacity is available. This provides fast response to dynamic load change without delay. It can generate electric energy without momentary external fuel feeding for a certain time period. This new construction provides energy regeneration ability, it can produce hydrogen from electric energy. If there is a regenerative electric energy on the output, i.e. the direction of the current changes, it fills its hydrogen storage, as long as its capacity is reached. Electric output power available is not so sensitive to starting and operational temperature, pressure and feeding. Output voltage decreases slowly during operational hours and its lifetime is longer than for PEM cells. Characteristic of output current vs. voltage is similar to PEM cells but lower current density is allowed for MHFC cells.

Advantages of MHFC fuel cells:

1. If the metal-hydrid hydrogen storage is full then energy source can start practically without delay.

2. It reacts fast to dynamic load change; it can reach the new operating point practically without any delay.

3. It can tolerate pulsating current load more than PEM cells.

4. The direction of the output current can be changed for a certain time period so it can provide regenerating brake operation.

### 1.3. Electric cars with multiple energy storage
Electric cars are often equipped with multiple energy storage combining the advantages of the combined solutions. We give two examples for cars with multiple energy storage devices.

**Battery car combined with ultracapacitor** utilizes the relatively high energy storing capacity of battery and higher unit power of ultracapacitor at the same time. Main energy supply is the battery of which energy storing capacity limits the range of the vehicle. Secondary energy source is ultracapacitor of which power determines the maximal current of pulse load change, i.e. the dynamics of acceleration and regenerative braking. With appropriate circuit and control, ultracapacitor can take the pulse load instead of the battery. With this, the lifetime of the battery can be extended. Energy stored in the ultracapacitor during regenerating brake can be used for traction, for example for next accelerating the vehicle. The scheme of battery combined with ultracapacitor in electric car can be seen in Figure 8.20.

![Figure 8-20. Scheme of battery combined with ultracapacitor in electric car.](image)

In the figure, continuous line indicates current direction in traction mode and dashed line shows the current direction during braking. DC/DC converter has to be able to control energy flow in both directions, often buck-boost circuit is used for that. Buck-boost conversion can distribute load between battery and ultracapacitor in all operating modes, traction or braking. This circuit enables controlled bi-directional energy flow even if the voltage of the ultracapacitor is lower than that of the battery or if it is higher. Based on the measurement data from NREL Laboratory shown in Figure 8.21., we can compare the load currents of battery systems with or without ultracapacitor, during one load cycle. (Internet: http://www.ctts.nrel.gov)

Blue line indicates battery load in case of pure NiMH battery supply (positive is the direction of charging current, negative is for discharge). Red line shows what current the ultracapacitor can take and green line indicates the moderated pulse load of the battery, comparing to the original blue line.

![Figure 8-21. Load measurements of battery combined with ultracapacitor.](image)

In an **battery combined with flywheel energy storage** device the flywheel drives a separate electric generator. The flywheel must rotate in order to supply energy. Speed-up of the flywheel can be made with external or internal energy source. External source can be at one end of the rail in case of a rail-guided vehicle, for example, where flywheel can be revved up before going back to traffic and this can provide the necessary energy. Internal source is required for cars. Rev up can be made with battery or with regeneration energy during brake. Kinetic energy store in the flywheel can be used for accelerating the car. Two flywheels rotating in opposite direction with aligned shafts have to be used in order to avoid decrab problems caused by precession effect.

**Flywheel energy storage** is a cylinder or disk shape rotating mass with very high rotational speed. Kinetic energy stored is $W = \Theta \omega^2 / 2$, where $\Theta$ is the inertial of the rotating mass, $\omega$ is the rotational speed. Because of the quadratic dependence, rotational speed should be set the highest acceptable. Mechanical strength limits the maximal rotational speed. Stored energy can be as high as 2,8kWh/kg which is similar to the specific energy of
fossil fuels. Advantage of the flywheels is that it can be converted to electric energy with higher efficiency (η~90%) than the chemical energy of traditional fuels. Disadvantage is that the flywheel has to be revved up and energy storing has loss over time. The main cause of the loss is bearing friction and windage. To reduce them, flywheels are often rotated in vacuum and electromagnetic levitating bearing is used instead of traditional bearings. According to the literature, there are flywheels with 200000 l/min (ω=20940rad/s) rotating speed where annual loss is less than 20%. Flywheels are expensive and complex solutions. The scheme of battery combined with flywheel energy storing in electric vehicle can be seen in Figure 8.22.

Figure 8-22. Battery combined with flywheel energy storing in electric vehicle.

Flywheel device is connected to the main circuit with DC/DC converter which controls bi-directional energy flow. Flywheel can store energy if it rotates. During rev up electric motor M/G operates in motor mode and gets energy from the main circuit. When providing energy, M/G operates in generator mode and its current from DC/DC converter helps to supply energy for the traction. Optional capacitance C helps absorb high current peaks.

2. Hybrid-electric cars

In Hybrid-Electric Vehicles (HEVs) there is an internal combustion engine (IC) and one or more electric motor for traction. Drive of the wheels is purely electric or combined with the internal combustion engine. The main aim of the design is to combine the advantages of internal combustion engines and electric motor drives, exploiting the advantages of electric motors and high unit (specific) energy of fossil fuels. Energy source is fuel stored in vessels, just as in traditional internal combustion cars. Accumulator, ultracapacitor or both are used to store electric energy temporarily. Pollution is characterized by the internal combustion engine.

Internal combustion engine and electric motor can interact in several ways. We distinguish several hybrid solutions: serial, parallel, simple and intelligent.

Table 9-6. Technical data of some well-known hybrid-electric cars.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Honda</th>
<th>Toyota</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model name</td>
<td>Insight</td>
<td>Prius</td>
</tr>
<tr>
<td>Hybrid type</td>
<td>simple hybrid, IMA (Int. Motor Assist)</td>
<td>Pinion gear intelligent hybrid</td>
</tr>
<tr>
<td>Type of  internal combustion motor</td>
<td>petrol motor+VTEC control</td>
<td>Atkinson-cycle petrol motor +VVT-i control</td>
</tr>
<tr>
<td>Cylinder volume</td>
<td>1ℓ</td>
<td>1,5 ℓ</td>
</tr>
<tr>
<td>Power of ICM</td>
<td>50kW (5700 f/min)</td>
<td>52kW (4500 f/min)</td>
</tr>
<tr>
<td>Torque of ICM</td>
<td>89Nm (1000 f/min)</td>
<td>111Nm (4200 f/min)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>155kW (5600 f/min)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>288Nm (4400 f/min)</td>
</tr>
</tbody>
</table>
Table 9.6 summarizes some technical data of well-known hybrid-electric car types. Besides, almost every car manufacturer develops hybrid cars. These developments show wide variety. There are cars with petrol and diesel engines, serial and parallel hybrid, synchronous or induction electric motors. New development is the PHEV (plug-in) hybrid-electric vehicle where energy refill can be made not only by fuel but electric charge, too.

### 2.1. Serial hybrid-electric cars

In a serial hybrid-electric vehicle the drive (traction) is purely electric. The internal combustion engine \( IC \) with electric machine \( ISG \) and inverter-type converter acts like a controlled electric energy source (aggregator) and is not included in the drive directly. \( ISG \) (integrated starter/generator) stands for its function; its role is to start internal combustion engine as well as to generate electricity. Starter motor used in traditional cars is not used here. \( ISG \) electric machine can be synchronous or induction type. The structure of the main circuit with voltage-source inverter fed AC drive is shown in Figure 8.23.

![Figure 8-23. Serial hybrid-electric vehicle.](image)

Electric drive connected to \( u \), DC voltage can besingle or multi.motor solution. Figure 8.23 shows a single-motor vehicle drive with motor \( EM \).

Electric power of energy converter with internal combustion engine is \( p=u \cdot i \), where \( u \) is voltage and \( i \) is current. Internal combustion motor is connected mechanically only to \( ISG \) electric machine but not to the wheels. Because of this, required power can be provided in a rotational speed range where fuel consumption, efficiency and pollution are optimal. We also have to prevent the internal combustion engine from transient load for optimal operation, is possible. If momentary current \( i \) differs from current \( i_\text{t} \), then differential current \( (i-i_\text{t}) \) must be provided by an interim energy storage which can be battery or ultracapacitor. Power required for average load is provided by the internal combustion engine, interim energy storage serves for transient momentary load so it can be designed for relatively low energy storage.

The direction of the differential current \( i_a=i-i_\text{t} \), can be charging or discharging. During acceleration, current of battery \( i_a \) is added to current \( i_\text{t} \). In contrast, current \( i \) flowing into the DC circuit in opposite direction charges interim energy storage during regeneration braking. During electric brake energy regeneration is possible only into the accumulator, the direction of current \( i_\text{t} \) cannot change because regeneration towards the internal...
Drives of electric and hybrid-electric cars

combustion engine is not possible. Reusing the regenerated energy is limited to the amount that the interim storage can store. This energy can be reused during acceleration.

Main characteristics of serial hybrid-electric systems are:

1. Advantage is that its structure is simple, drive is purely electric.
2. Energy regenerating brake can be realized depending on the size of the electric energy storage.
3. Wheel hub motors can be used (multi motor drive).
4. Optimal operation of internal combustion engine can be realized independently of the operating state of the vehicle.
5. Disadvantage is that vehicle power must be installed more times. Taking into account the efficiencies, internal combustion engine, the ISG generator and the EM electric machine must be designed to total vehicle power. The design rating of the electric energy storage depends on the vehicle type, it can be in the 0-100% power range.

2.2. Parallel hybrid-electric cars

The main characteristic of parallel hybrid-electric vehicles is that traction drive is an internal combustion engine, similarly to traditional vehicles. The additional electric drive assists in torque development, usually. Drives can be separated in some cases. There are three types of parallel hybrid solutions:

1. Selection of drive is realized with a mechanical switch and several clutches in traditional parallel hybrid vehicles.
2. In simplified hybrid vehicle, selection is realized with controlling an electric machine installed to the driven shaft.
3. Controller can select the driving motors in two-shaft parallel hybrid vehicles.

2.2.1. Traditional parallel hybrid vehicles

Traditional parallel hybrid vehicle is realized so that both internal combustion engine and electric motor can be connected mechanically to the wheels of the vehicle. Different operating modes can be selected with three clutches. Gear-box must remain because of the internal combustion engine. The structure of a traditional parallel hybrid type vehicle can be seen in Figure 8.24.

![Figure 8-24. Traditional parallel hybrid type vehicle.](image)

Drive realized with EM electric machine is fed by a battery and can serve different functions:

1. It can act as autonomous electric drive with CL0 and CL 2 clutches. This no-polluting and high efficiency mode can be used in urban traffic, as long as the battery discharges completely.
2. Starter function can be realized with clutches CL 2 and CL 1.
3. If the internal combustion engine is already working, then drive is realized with the internal combustion engine and all three clutches work. Electric machine charges the battery or helps accelerating the vehicle, if required.

Inverter feeding connected to the electric machine has to be able to operate in both power flow directions, as described above, and we have to control it according to the selected mode.

Electric drive can take part during problematic operation modes of the internal combustion, at starting or accelerating the car when high dynamic stress arises. Regenerating brake mode is also possible. Electronic control system harmonizes optimal internal combustion and electronic drive modes and continuous transition between the modes.

Main characteristics of traditional parallel hybrid-electric system are:

1. Power of electric drive can be much lower than the power of the internal combustion engine. Electric drive must be designed for required power of the urban traffic only, starting and acceleration is short and electric motor can be overloaded for this short time.

2. Power of internal combustion engine can be designed to highway traction, which is more economical, if acceleration torque is provided by the electric motor.

3. Disadvantage is that mechanical system is complex.

2.2.2. Simplified parallel hybrid vehicles

*Simplified parallel hybrid vehicle* is different than traditional internal combustion vehicles because it contains higher power, electric machine functioning as integrated *ISG* (integrated starter-generator) and higher power high-voltage accumulator. Gear-box remains. The degree of hybridization can be measured with nominal power of electric machine and internal combustion engine:

\[
\gamma = \frac{P_{el}}{P_{IC} + P_{el}}.
\]

Based on this value, we can distinguish minimal, mild, middle hybrid vehicles. If \( \gamma \) is higher, electric motor can provide more additional power for acceleration and can take more regenerated energy. IMA, „Integrated Motor Assist” is used for *ISG* electric machine drive, because of its increased assistance significance. The structure of simplified parallel hybrid type vehicle can be seen in Figure 8.25.

**Figure 8-25.** Simplified parallel hybrid type vehicle.

*ISG* electrical machine connects to the main shaft of the internal combustion engine with fix or no gears, it cannot be disconnected with a clutch so the vehicle cannot be driven with autonomous electric drive. The result of the simpler construction is that drive can be done only by the internal combustion engine. In contrast, additional torque with electric machine and brake energy regeneration can improve efficiency of the internal combustion engine and the whole vehicle significantly. Gear-shifting can be more economic and rapid with *ISG* electric machine and start-stop function in urban traffic can be realized more easily.

The best-known simplified parallel hybrid vehicle is the Honda Insight „mild-hybrid” car, but several other developments exist. Electric machine used in Honda Insight is integrated with the internal combustion engine, has the same shaft as the driving shaft, disk-shaped, multi-pole synchronous machine (BLDC brushless DC motor) with permanent magnet rotor. The sketch of the motor is shown in Figure 8.26.a.
Drives of electric and hybrid-electric cars

In Figure 8.26.b., measurements of NREL laboratory in 2001 can be seen. This figure indicates how the torque and power data of the 50kW internal combustion engine IC of the examined vehicle can be improved with a 10kW ISG integrated machine. The time period of torque boost is limited by the battery, which has 6.5Ah capacity and 144V voltage in this vehicle.

Field oriented controlled induction machine drive can also be used for ISG integrated machine.

The main characteristics of the simplified parallel hybrid vehicles are:

**2.2.3. Two-shaft, parallel hybrid vehicles divided to front and rear axle drives**

In two-shaft parallel hybrid vehicles divided to front and rear axle drives parallel operation of internal combustion engine and electric motor drive is realized on different shafts of the vehicle. In contrast with traditional parallel hybrid-electric vehicles, not torques but traction forces on wheels are summarized.

The structure of such a drive can be seen in Figure 8.27. One shaft is driven by internal combustion engine IC with electric machine EM1, similar to Figure 8.25., and the other is driven purely by the electric motor EM2. The two electric drives are connected to the same battery.

Disadvantages of simple parallel drive can be eliminated with this solution and purely electric drive can be realized on one shaft. Gear-box and clutch must remain in the internal combustion drive.

**2.3. Intelligent hybrid-electric vehicles**

Advantages of serial and parallel type drives are combined in intelligent hybrid-electric vehicles (Full-hybrids). Vehicle can be driven with purely electric, purely internal combustion or combined modes. Continuous cooperation of the two drives are set that the operating point and rotational speed of the internal combustion engine be optimal relating to fuel consumption, operation modes with high consumption and low efficiency be eliminated.

Main parts of the intelligent hybrid-electric vehicle system are:
1. internal combustion engine,
2. two (or more) electric machine with power comparable to the internal combustion engine,
3. interim electric energy storage (battery, ultracapacitor),
4. smooth, changeable rotational speed transmission controlled electrically between the main shaft of the inernal combustion engine and the driving shaft of the vehicle.

Main characteristics and control aspects of intelligent hybrid-electric vehicles are:

*The role of the electric energy storage* is to provide energy and take energy for transient loads. These roles are, that has to be taken into account during design, are:

Intelligent hybrid-electric vehicles use different technics to optimize rotational speed of internal combustion engine. Based on this, three types of intelligent hybrid-electric vehicles can be distinguished:

### 2.3.1. Intelligent hybrid-electric vehicle with planetary gear mechanical drive

*The structure of intelligent hybrid-electric vehicle planetary gear mechanical drive* can be seen in Figure 8.28.

![Planetary gear hybrid-electric vehicle](image)

Figure 8-28. Scheme of a planetary gear hybrid-electric vehicle and the wheel itself.

Main shaft of the internal combustion *IC* engine is connected mechanically to the drive consisting of three or four planetary gears. Electric machine *ISG*, which function is generator and to start and set operating point, is connected to the inner wheel called sun-wheel. Electric motor *EM* is connected to the outer, so-called ring-wheel of the drive. The electric motor is also connected to the wheels of the vehicle with fixed gear-wheels. So, rotational speed $\omega_{\text{EM}}$ of electric motor is proportional to the speed of the vehicle. Electric motor is part of the hybrid drive system, but purely electric drive is also possible with it.

*Continuous variable transmission* (CVT) can be realized with planetary gears between the rotational speed of internal combustion $\omega_{\text{IC}}$ and driving shaft $\omega_{\text{EM}}$. This provides that internal combustion engine can provide the traction power at optimal rotational speed, where efficiency (relative fuel consumption) is the best. Control of variable transmission, i.e. ratio of $\omega_{\text{IC}}$ and $\omega_{\text{EM}}$, together with setting optimal rotational speed, can be reached with controlling rotational speed $\omega_{\text{ISG}}$ of electric machine *ISG*. The equation between rotational speed of sun $i$ and ring $o$ wheels of the planetary gears wheels is:

$$\omega_{\text{ISG}} + \frac{Z_o}{Z_i} \omega_{\text{EM}} \left(1 + \frac{Z_o}{Z_i}\right) \omega_{\text{IC}} = 0$$
where \( z_o/z_i \) is the teeth ratio of outer (ring) and inner (sun) wheels. From this equitation we can calculate the rotational speed of the internal combustion engine:

\[
\omega_{IC} = \frac{z_i}{z_o} \omega_{EM} + \frac{z_i}{z_{r(z)}} \omega_{ISG}
\]

From this, we get that gear ratio \( r = \omega_{IC}/\omega_{EM} \) can be changed electrically with the \( \omega_{ISG} \) rotational speed of the generator:

\[
r = \frac{\omega_{IC}}{\omega_{EM}} = \frac{z_i}{z_o} \left( 1 + \frac{z_i}{z_{r(z)}} \omega_{ISG} \right)
\]

One of the realizations of planetary gear drive in Toyota Lexus hybrid-electric car can be seen in Figure 8.29.

Change regarding to Figure 8.28 is that machine \( EM \) is not connected to the ring wheel directly but through another planetary gear drive, where wheels are standing. Also, we can see that there is a wheel reductor between the ring wheel and the wheels of the vehicle with a fix \( r_{fix} \) ratio.

Figure 8-29. Planetary gear drive used in Toyota Lexus hybrid-electric car.

Utilization of power from internal combustion engine can be optimized electrically with a planetary gear. Power appearing on the shaft of the internal combustion engine can be separated into two components:

\[
P_{1C} = M_{IC} \omega_{IC} = M_{IC} \frac{z_i}{z_o} \omega_{EM} + M_{IC} \frac{z_i}{z_{r(z)}} \omega_{ISG} = P_M + P_{ISG}
\]

The first part of (8.6) is mechanical power \( P_M \) transferred to the wheels of the vehicle:

\[
P_M = M_{IC} \frac{z_i}{z_o} \omega_{EM} = M_{IC} \omega_{EM}
\]

If the vehicle stops \( \omega_{EM} = 0 \), then \( P_M = 0 \).

The second part of (8.6) is power \( P_{ISG} \) transmitted to the shaft of ISG machine:

\[
P_{ISG} = M_{IC} \frac{z_i}{z_{r(z)}} \omega_{ISG} = M_{ISG} \omega_{ISG}
\]

Main function of power \( P_{ISG} \) is to supply main electric circuit in generator mode. Electric motor drive \( EM \) is fed from the main circuit, supply for auxiliary devices and charge for additional energy storage (battery or
ultracapacitor) is connected here. A different operation mode is the starting of the internal combustion engine when machine ISG has to work as starting motor with consumed electric power \( P_{ISG} \).

**Torque required for traction** can also be controlled electrically with planetary gear drive. In this case torque on drive shaft is the sum of torques of internal combustion engine \( IC \) and electric machine \( EM \):

\[
M = M_M + M_{EM}
\]

8.9

Assuming that wheel drive efficiency is ideal 100%, component \( M_M \) is a torque going through the wheel drive and proportional to the torque of the internal combustion engine \( M_{IC} \), appearing in equation (8.7). Torque \( M_{EM} \) is produced by electric machine \( EM \), its value can be controlled electrically, and can be in both directions (additional acceleration or brake). The limits of \( M_{EM} \) vs. rotational speed \( \omega_{EM} \) are determined by the short-time and steady-state load limit curves of the selected controlled electric drive. In motor mode \( M_{EM} > 0 \), and this creates additional torque on the drive shaft in the same direction as torque \( M_M \), according to Figure 8.30.

![Figure 8-30. Block diagram for traction torque development.](image)

Resulting torque \( M \) creates traction force. Dynamic behavior (acceleration) of the vehicle is determined by the inertia \( \Theta_{red} \) reduced to the shaft of the electric machine and by the traction resistance of the vehicle.

Output power of electric machine \( EM \) is \( P_{EM} = \omega_{EM} M_{EM} \). There can be operation mode when \( P_{EM} > P_{ISG} \), so power taken from the main electric circuit is higher than supplied. The difference of the power is supplied by the battery. This mode can exist only for a limited time until the battery discharges completely.

**Brake operation mode of hybrid-electric vehicles**

With respect to the internal combustion engine, brake mode means reduced fuel feeding or stop similarly to no-load running, according to the motor control. Internal combustion engine provides the traditional engine brake torque in brake mode which comes from the fuel compression and mechanical friction and cannot be controlled. In engine brake \( M_{IC} \leq 0 \), so is \( M_{M} \leq 0 \).

Well-controlled energy regeneration brake can be realized with the generator mode of electric machine \( EM \), which corresponds to \( M_{EM} < 0 \) on the output shaft, decelerating the wheels. Direction of the current \( i \) in the main circuit (Figure 8.28) changes because of the regenerating brake. This mode can last only for a certain period of time until charging of battery is allowed without the risk of overcharge.

Only those wheels can be decelerated with regenerating brake which are in mechanical connection with the electric drive \( EM \), so only the (partially) electrically driven wheels. Regenerating electric brake is always extended with traditional electrohydraulic brake system for the sake of security, where controlled ABS (anti-blocking system) can be also realized. Wheels not driven by electric drive can be decelerated only with friction and with loss.

*Control diagram of intelligent hybrid-electric vehicle* can be seen in Figure 8.31.
Drives of electric and hybrid-electric cars

Figure 8-31. Control diagram of intelligent hybrid-electric vehicle.

The signal of accelerator pedal $AP$ starts three processes. On one hand, it provides reference signal to feed control of internal combustion engine, and sets torque reference signal to electric machine $EM$ on the other. And, in the same time, it initializes a control process to set optimal operational rotational speed $\omega_{IC}$ with machine $ISG$. Optimal operation point can be calculated with shorter, partially steady-state operations. Signal of brake pedal $BP$ sets reference brake torque of electric drive $EM$. When pressing brake pedal powerfully, electric brake switches to brake operation provided by traditional electrodynamic brake system, continuously and without steps.

Another control task, not indicated in Figure 8.31., is to control the current (power) $i_t$ of main electric circuit supplied by machine $ISG$, to control the charge of the DC-link energy storing battery or ultracapacitor. As an example, the SoC state of the battery in a Toyota Prius hybrid car is set to about 55% of full charge from different starting points, as indicated in Figure 8.32. (purple, red, blue lines). This measurement was taken in NREL Laboratory. With this control, we can provide enough energy for additional acceleration and prevent overcharge during brake.

Figure 8-32. Control of charge for the battery in a Toyota-Prius hybrid car

The state of the battery was examined with UDDS standard acceleration-deceleration cycles.

To realize the operation modes described above, complex control of electric drives is required. Only electric drives with intelligent rotational speed and torque control can be used. The best solutions for this purpose are inverter-fed field-oriented current vector controlled synchronous or induction motor drives.

2.3.2. Intelligent hybrid-electric vehicle with Strigear drive

*Intelligent hybrid-electric vehicle with Strigear drive* was developed with the idea of Stridberg Powertrain AB. An internal combustion engine and two electric machines are connected to a special “Strigear” propulsion unit which enables both serial and parallel hybrid operation with a traditional gear-box. The scheme of the driving system and the picture of the whole propulsion unit, with electric machines $ISG$ and $EM$ on the two sides, can be seen in Figure 8.33.
Electric machine ISG is on the same shaft as the internal combustion unit and electric machine EM connects to the output shaft through a gear-box. Disadvantage of Strigear system is that gear-box used in traditional vehicles remains, and clutch CL also remains, which is placed in between the two electric machines. Advantages of serial and parallel connected hybrid drives can be utilized with Strigear system. When selecting different operation modes, the state of clutch is important.

Operation modes available when clutch CL is open are:

1. Operation modes available when clutch CL is closed are:

   Traditional gear-box is required for the last two modes.

### 2.3.3. Intelligent hybrid-electric vehicle realized with double rotor electric machine

*Intelligent hybrid-electric vehicle realized with double rotor electric machine* is a new development of Swedish Royal Institute of Technology, KTH/EME. Its operation is similar to planetary gear driven hybrid vehicle but planetary gear is replaced with a double rotor, double fed electric motor. Figure 8.34 shows this driving system. On the right side, the picture of an experimental model can be seen.
Drives of electric and hybrid-electric cars

Figure 8-34. Structure of a hybrid-electric vehicle realized with dual-rotor electric machine.

There is electric transmission with controlled torque and rotational speed between the output (driving) shaft and the shaft of the internal combustion engine IC. Electric transmission is realized with a 4-quadrant transmission 4QT unit which is indicated with dashed lines in the figure. This unit is an electric machine consisting of two rotors and one stator.

The inner rotor (in red) has the same shaft as the internal combustion engine and is 3-phase wound. Windings are fed through slip rings by the inverter INV-1. The outer rotor (in blue) is connected mechanically to the driving shaft of the wheels directly or through a fixed mechanical gear. The outer rotor has multi-pole magnets, and it has specially arranged magnets on the inner rotor side and on the stator side also, as shown on the right side of Figure 8.34. The stator of the machine (in green) also has three-phase windings and is fed through the inverter INV-2. Both inverters are connected to the common battery storage in the DC-link.

The functions available with the 4QT double rotor machine can be understood more easily if we divide it to two machines.

Figure 8-35. Dividing 4QT double-rotor electric machine to two separated machines.

4QT can be described as two machines, as can be seen in Figure 8.35, and it can be constructed with two electric machines with permanent magnet rotors where there are magnets only one-one side of the rotors. (Magnets are on the inner part of the rotor on the left and outer part of the rotor on the right.) 4QT is implemented by current vector controlled synchronous drive for both machines, so the position of the current vector is synchronized electrically to the position of the permanent magnet rotor.

On the inner rotor (in red), a controlled rotating field with rotational speed ±Δω can be produced with current vector control by the inverter INV-1. This rotational speed Δω is added to or subtracted from the rotational speed of the internal combustion engine. Because it is a synchronous machine ωout=ωIC±Δω determines the rotational speed of the outer (blue) rotor and the resulting driving rotational speed of the vehicle. With double rotor machine, like with planetary gears, continuous changeable gear can be realized between the rotational speed of the internal combustion engine and that of the driving shaft.

Additional electric torque ±ΔM can be realized with current vector control in the 3-phase winding of the stator (in green) so the torque of the output shaft can be controlled electrically. Additional acceleration can be realized with positive torque ΔM, and brake and energy regeneration to the battery can be realized with negative torque. Torque on the driving shaft of the vehicle is the sum (with correct signs) of the torques of the internal combustion engine and electric machine, Mout=MIC±ΔM. Power required for additional acceleration ±ΔMeout is provided by inverter INV-2.
Every operating modes can be realized, like for the planetary gear solution. Internal combustion engine can provide power at optimal rotational speed. 4QT can be considered as an electric shaft between the internal combustion engine and driving shaft. Regenerating brake is also possible. Controlled starting of the internal combustion engine can be solved by current vector torque controlled inverter supply of the inner (red) rotor, for both standing and moving vehicles. Also, energy supply for the DC-link circuit can be realized with this method if it is in generator mode.

Dynamic behavior of the vehicle, like acceleration and deceleration, can be improved with 4QT. Purely electric drive is also available. State of the DC-link circuit can also be monitored easily.

Disadvantage of the solution is that slip rings are required for connecting to the inner wounded rotor. Slip ring-brush system decreases reliability of the device, requires maintenance, wears and sensible to dust.

According to Royal Institute of Technology, designation 4QT indicates that double rotor electric machine has to operate in four quadrants, it has to work with reversed rotational speed and torque.

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