Contents

Abbreviations and symbols

Roman symbols

F_t	traction force [N]
F_r	force of rolling resistance [N]
F_ω	air dynamic force [N]
F_g	grading resistance [N]
F_i	force of vehicle inertia [N]
F_{bs}	force of brake system [N]
F_{am}	traction force in acceleration mode [N]
F_{cm}	traction force in constant mode [N]
f_r	rolling resistance coefficients
T_{am}	motor torque in acceleration mode [Nm]
T_{cm}	motor torque in constant mode [Nm]
T_c	cardan shaft torque [Nm]
T	rate motor torque [Nm]
T_L	torque of load [Nm]
T_H	maximum torque [Nm]
T_S	starting torque [Nm]
t_a	time acceleration [s]
$\mathrm{m_v}$	mass of vehicle [kg]
g	acceleration of gravity [m/s^2]
$\mathrm{A_f}$	vehicle frontal area [m^2]
$\mathrm{C_D}$	aerodynamic drag coefficient

dv/dt	acceleration [m/s^2]
i_g	gear ratio of transmission
i_0	gear ratio of the final drive
r_d	radius of the drive wheels [m]
d	vehicle performance factor
v_b	base speed of motion [m/s]
v_f	maximum speed of motion [m/s]
v	speed of vehicle [m/s].
u_g	gear ratio
j	deceleration of a vehicle [m/s^2]
J_X	external mass moment of inertia [kgm^2]
J_M	mass moment of inertia of motor [kgm^2]
P	power of motor [kW]
P_L	load power for acceleration [kW]
P_e	engine power [kW]
P_{pps-c}	charge power of power storage [kW]
P_{pps-d}	discharge power of power storage [kW]
$P_{b-rated}$	rated power of energy storage [kW]
P_{b-max}	maximum power of battery [kW]
I_b	rated current of energy storage [A]
I_m	relative value of magnetization current
I_s	stator current [A]
X_R	relative value of rotor inductance
X_S	relative value of stator inductance

R_R	relative value of rotor resistance
R_S	relative value of stator resistance
N_b	number of cells
n	speed [rpm]
n_m	speed of the cardan shaft [rpm]
U_{sph}	line-to-line voltage star connected [V]
U_b	rated voltage of energy storage [V]
m	number of phases, mass [kg]
p	number of pole pairs
f	frequency [Hz]
$\cos\varphi$	power factor
D_r	outer diameter of the rotor [m]
D_{se}	stator diameter [m]
l'	effective core length [m]
Q_s	number of stator slots
Q_r	number of rotor slots
z_{Qs}	number of conductors in a slot
B_δ	air-gap flux density [T]
h_{PM}	height of the permanent magnets [m]

Greek symbols

α	grade [°]
ρ_a	air density [kg/m^3]
δ	air gap [m], mass factor

δ_l	load angle [rad]
φ	friction coefficient
γ	coefficient of braking
η	efficiency of motor
η_t	efficiency between the motor and driven wheels
η_{te}	efficiency of engine
Ω_c	angular speed of the cardan of vehicle [1/s]
Ω_w	angular velocity of the shaft wheel [1/s]

Abbreviations

AC	Alternating current
DC	Direct current
HSD	Hybrid Synergy Drive
CVT	Continuously Variable Transmission
ICE	Internal combustion engine
ECE	Economic commission for Europe
EUDC	Extra Urban Driving Cycle
PPS	Peak Power Source
SOC	State of Charge
HEV	Hybrid electric vehicle
PHEV	Plug-in Hybrid electric vehicle
IM	Induction motor
PMSM	Permanent magnet synchronous motor
PWM	Pulse width modulation

PI	Proportional–integral controller
HC	Hybrid controller
FEW	Field weakening controller
CC	Current controller

1. INTRODUCTION

According to experts the most of near future development of vehicle systems will take place in hybrid systems. The theory of the creation of electric or hybrid drives for vehicles is still in the stage of development, especially, the collaboration of all main elements and the distribution of the flow of power to minimize fuel consumption and harmful emissions into the atmosphere are not yet fully studied.

Automobile manufacturing and vehicle operation are currently one of the main sources of air pollution and a major consumer of energy and natural resources. On a vehicle the cost of fuel per unit of transport work for all types of ground vehicles is the highest. In Europe, fuel spent for vehicles is more than 30 % of all petroleum products and in the U.S. up to 50%. Emission standards are set for different categories of vehicles, depending on the weight and type of car. Environmental requirements for vehicles are being made more rigorous.

There are many ways to improve the environmental and economic performance, the major ones:

- Improve burning processes of internal combustion engines;
- Improvement of the neutralization of exhaust gases;
- Application of alternative fuels;
- Using hybrid power systems;
- Using non-conventional engine units.

At this time, almost all of major automobile companies have sent their efforts on creating vehicles with hybrid power systems. Some success in this area has been achieved: General motors, Ford Motor, Daimler Chrysler, Toyota Motor, Mitsubishi motor, Subaru, Honda, Nissan Motor, Suzuki Motor, Volkswagen AG, BMW AG, Mercedes and Volvo have development projects for hybrid vehicles.

Hybrid vehicles are as follows from their name, somewhere between a car and an electro-mobile. Attitudes towards hybrid vehicle have changed at the end of the latest century. As a result of the energy crisis and environmental problems many countries have considered the program of energy conservation and environmental protection. An analysis of possible ways to improve fuel efficiency showed that a substantial fuel savings can make use in full electric traction.

In the thesis I have reviewed the ideology of designing a parallel hybrid system for a vehicle, including electric traction that is driven by the engine. The main aim is to design and calculate an asynchronous motor and a permanent magnet synchronous motor for a hybrid system, minimizing the mass, losses and the overall dimensions of systems.

Those who are creating new designs and advanced electric vehicles with hybrid system will inevitably impact with the choice of traction motors for vehicles.

Solving the motor design problem with simple models or modifications is very difficult, as most of motors have good performance only in a relatively narrow band. Vehicles require motors which will be capable of working at a wide operating range. In addition to working in a wide speed range maintaining constant high torque, they should also be reliable, lightweight and durable.

In terms of the above, e.g. direct current motors do not meet one of the most important requirements - durability: the brushes and collector parts are subject to rapid wear. Many companies which have started research in the field of electric vehicles, almost always started research work in the field of AC electric motors: asynchronous motors or synchronous motors with permanent magnets.

For example, to minimize the weight and size of a traction motor with permanent magnet excitation, the number of poles of the rotor should be at least six, and the permanent magnets should be of the best present day materials: rare earth materials.

2. DESCRIPTION OF HYBRID SYSTEM FOR STREET VEHICLES

The first hybrid self-propelled vehicles appeared in the beginning of the 19th century. In contrast to the classic vehicle of our time, «hybrid» vehicles of that time were driven by the force of water vapor pressure, and the maximum speed of the system on wheels did not exceed 15 km/h. The first «car», where electricity was used as the driving force was designed by the Scotsman Robert Anderson in 1839 year.

After 50 years, the evolution of hybrid cars was mostly affected by two people: a native of Belgium, Piper Henry, who in 1905 patented a hybrid scheme for the vehicle, using the electric motor together with a gasoline engine, and the German Ferdinand Porsche. Improving his development, Porsche surprised the world as first in the history by introducing of a four-wheel drive hybrid vehicle. It may be noted that during the First World War, Porsche, not having higher education, continued to develop vehicle hybrids, for which work he was soon awarded the rank of professor of the Technical University of Vienna.

Of course, to produce complicated hybrid cars was expensive at the time, and so over time, cheaper classic cars with the help of the conveyor revolution of Henry Ford replaced the innovative engineering design.

The rapid growth of oil and petrol prices in 1970 had forced the developers and consumers to revert to the already nearly forgotten dreams of designers to create cost-effective and universal vehicles. In 1992, the press service of Toyota Company unveiled on the company's serious intentions to develop the most economical vehicles with low pollution. In 1997 the first hybrid car - Toyota Prius - was introduced on the Japanese market. The main reason for the start of production of the hybrid vehicle was the market demand for such vehicles and the constant increase in demands for greener vehicles. In the *Appendix 1* have attachment the history of motion from basic vehicle to electrical vehicle.

A combined power facility with an internal combustion engine is the most effective way to achieve high levels of vehicle in the near future. A hybrid car provides at the same time the ability to provide greater operating distance and to maintain the existing refuelling infrastructure. An electrical drive system is used as a motor-generator connected to the crankshaft of the engine. The engine is switched off during all, even brief stops and started only on demand after vehicle movement has started again.

In a hybrid system the engine turns a generator which supplies energy to the electric motor. Electrical motor allows the engine to work without a sharp acceleration of loads, in the most favourable conditions. Virtually all modern hybrids have an energy recovery system. The gist of it is that in braking or when driving the machine, the motor starts to spin from the wheels and operates on a generator state, in this moment the battery is charging.

Depending on the degree of hybridization the hybrids may be divided in: a mild hybrid, a full-hybrid and a plug-in hybrid, Table 1.

Table 1. Categorization of hybrid systems. Dependence on the functional capabilities of the type of vehicle

Functionality capabilities	Energy type vehicles				
	Conventional Vehicle	Muscle Hybrid	Mild hybrid	Full-hybrid	Plug-in
Shut off the engine at stop-lights and in stop-and-go traffic	+	+	+	+	+
Use regenerative braking and operate above 60 volts		+	+	+	+
Use a smaller engine than in a conventional version with the same performance			+	+	+
Drive using only on electric power				+	+
Charging the battery from home network					+
Recharge batteries from the wall plug and have a range of at least 30 km on electricity alone					+

By the principle of interaction of electric and internal combustion engine, the hybrid drives are divided into three types: *series, parallel and series-parallel systems* – Table 2.

Table 2. Comparison of hybrid systems by performance features.
(+ is excellent, ± middle, − poor)

Types	Fuel economy improvement				Driving performance
	Idling stop	Energy recovery	High-efficiency operation control	Total efficiency	Acceleration
Series	+	+	±	±	−
Parallel	±	±	−	±	±
Series-parallel	±	+	+	+	±

In the following each type of hybrid system will be considered in more details.

- **Series hybrid**

The combustion engine is used to drive a generator. Generated electricity is charging the battery and feeds the electric motor, which rotates the wheels, Figure 1. This eliminates the need of a mechanical transmission and engine clutch. To recharge the battery also regenerative braking system is used. The system has received this name because the flow of power is supplied to the driving wheels, passing a series of successive transformations. From the mechanical energy which has been produced in the combustions engine to the electrical generator, which, again, provides electricity to the motor and vice versa. Serial hybrid allows using of low power of combustions engine that constantly works in the range of maximum efficiency.

When the combustion engine is switched off, the electric battery could provide the necessary power for the movement. Therefore, they, unlike the engine, should be more powerful, which means they are more expensive. A series hybrid is the most efficient in frequent stops, braking and accelerating, and moving at low speeds. Therefore, a series hybrid is more useful in forms of urban transport

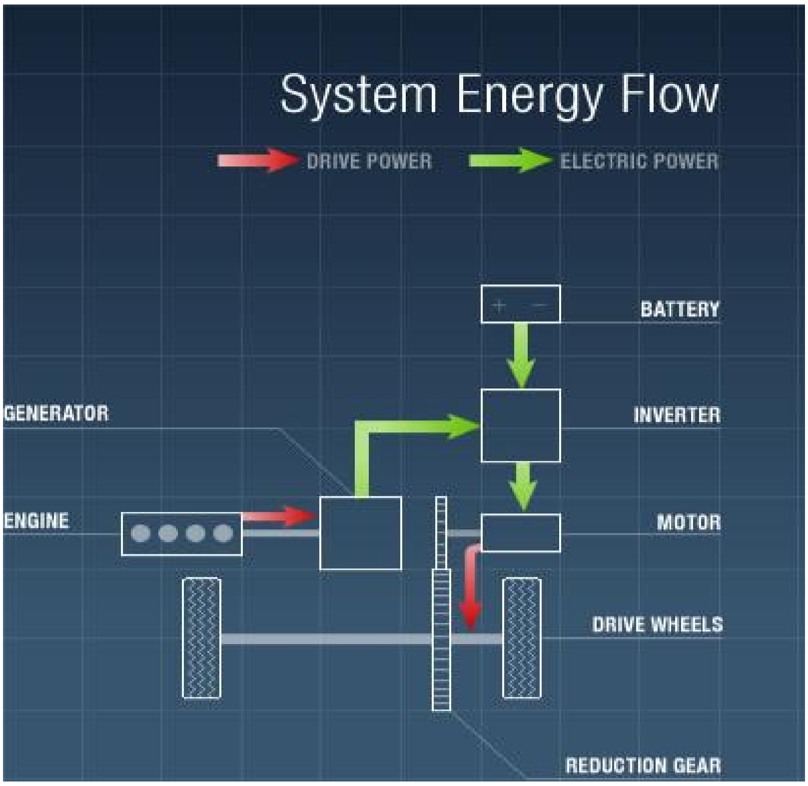

Figure 1. Series hybrid system [1]. Two electrical machines are needed.

- **Parallel hybrid**

Here, the driving wheels are driven by a combustion engine and an electric motor. The electrical machine in this hybrid is reversible, and can be operated in a generator state. The benefit of the parallel hybrid is that only one electric machine is needed. For a smooth parallel operation, computer controller is used. There is still a need for a normal transmission and the engine has to work also in non efficient transient states. The torque which comes from the two sources is divided on the depending on the traffic conditions: in the transient state in support of combustion engine connects the electric motor, as in the traditional state, and under braking, it is working as generator, and charging the battery. In a parallel hybrid for most of the time the combustion engine is working and the electric motor is used as assistance. Therefore, parallel hybrids can use a smaller battery, compared to a series hybrid system. Because the engine is directly connected to the wheels, the power loss is much less than in the serial hybrid. The disadvantage of the parallel hybrid is that, the reversible parallel hybrid machine can not simultaneously drive the wheels and charge the battery. Parallel hybrids are effective on highways and less effective in the city. However, in some cases the internal combustion engine is disconnected and the vehicle may operate on electric drive only. In *Appendix 2* attachment the configurations designing of parallel hybrid vehicle.

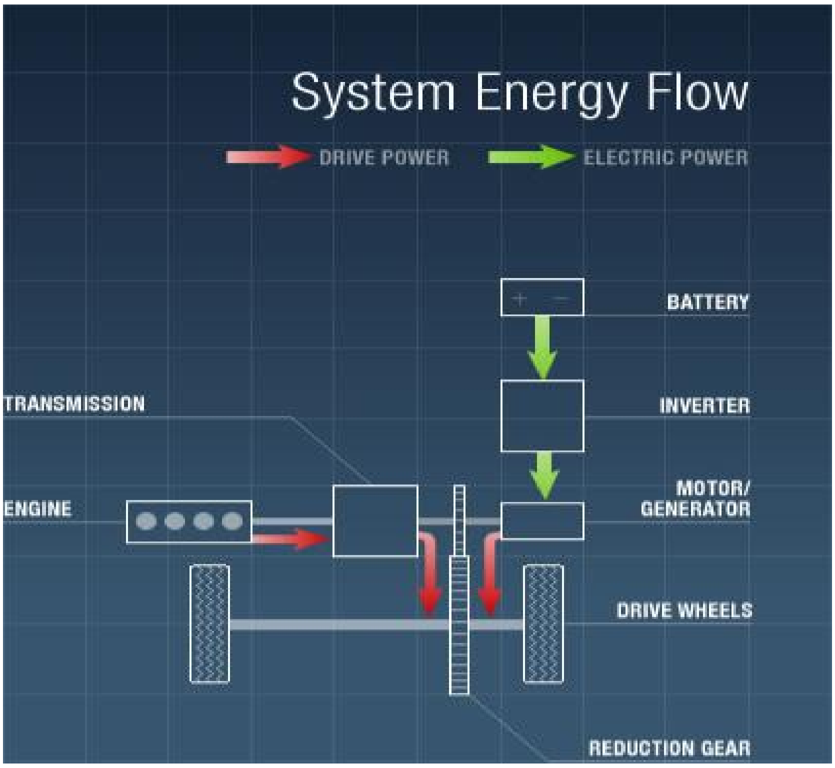

Figure 2. Parallel hybrid system [1]. Only one electrical machine is needed.

- **Series-parallel circuit.**

Toyota used its own way in the creation of hybrids. Designed by Japanese engineers, system Hybrid Synergy Drive (HSD) combines a parallel and serial hybrid system. In the parallel hybrid system Toyota added a generator and a power divider. As a result, the hybrid becomes a series hybrid: a vehicle moves and is moving at low speeds only on electric traction. At high speeds and under speed conditions at a constant speed, the combustion engine is connected. At high loads of the electric motor further fuelled by a rechargeable battery, the hybrid operates as a parallel one. In consequence of a separate generator the electric motor is used to drive the wheels and in the regenerative braking. A planetary gear reproduces the power of the engine to the wheels and the rest on the generator, which feeds an electric motor or charges the battery. The computer system constantly controls the flow of power from the two energy sources for optimal operation under all driving conditions. In this type of hybrid for most of the time working electrical motor and combustion engine is used only in the most efficient state.

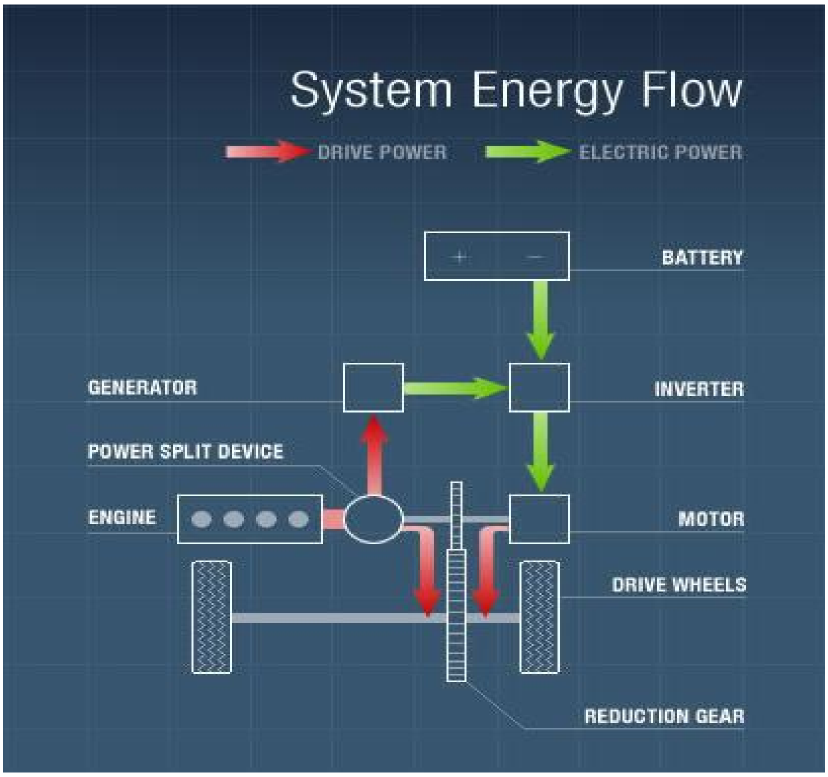

Figure 3. Series-parallel hybrid with two electric machines. [1]

The HSD system is installed on the Toyota Prius, Camry, off roadster Lexus RX400h, Toyota Highlander Hybrid, Harrier Hybrid; Sports Sedan Lexus GS 450h and Lexus LS 600h. The know-how of Toyota companies has been acquired also by Nissan and Ford and used in the production of Ford Escape Hybrid and Nissan Altima Hybrid.

2.1. The main devises of the parallel hybrid system

In my thesis, I will consider a parallel hybrid system, which consists of the following components – Figure 4.

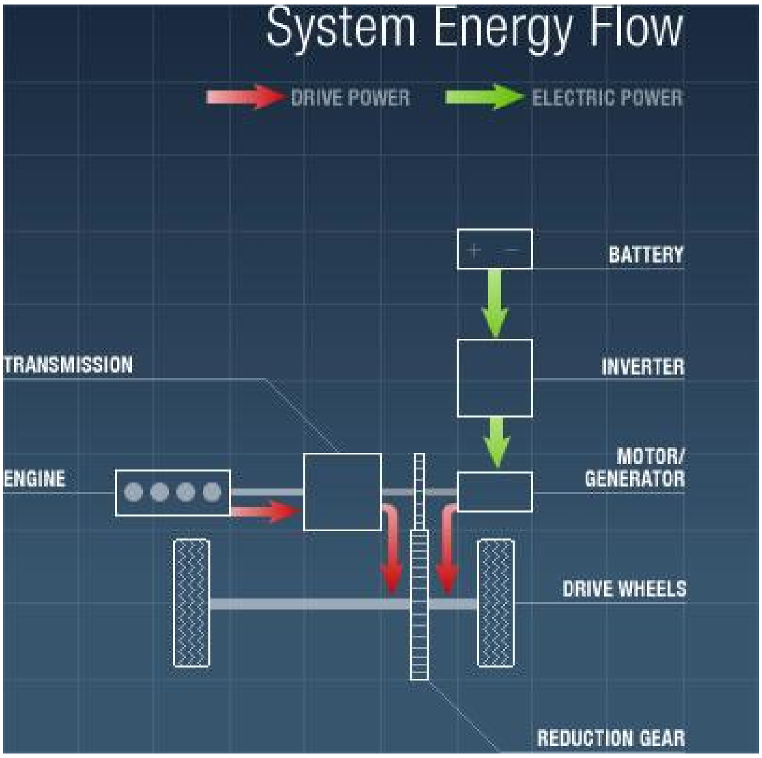

Figure 4. Parallel hybrid system [1]

- Combustion engine

- Transmission

Most hybrid vehicles are equipped with a V-belt variable-speed device – CVT. The abbreviation stands for the following – Continuously Variable Transmission, which can be translated as the transmission with smoothly vary the number of transmission.

In CVT planetary gears and connecting their elements are replaced by two variable diameter pulley of segmented steel belt. One of the pulleys is a leading, which has driving by engine. Other is driven, which is the drive wheel. CVT can choose the transfer of an infinite number of them in accordance with traffic conditions and state, selected by the driver. [2]

- Electrical motor / Generator

The electric motor provides a power increase in the engine, ensuring smooth starts and acceleration. In addition, when the regenerative braking system is activated, the electric motor converts kinetic energy in electric energy, which is stored in batteries.

An electric motor for a hybrid system must correspond in the following characteristics: compact, lightweight, high torque, high-performance, ability to work in different climatic conditions.

- Energy Centre

Hybrid Energy Centre is a system that creates and manages the stock of electrical energy which has been stored in a high-tech battery. The process of production and management of electric energy is integrated in the battery. The key components of the energy centres are:

• Battery

To ensure the electric energy and electric systems, hybrid vehicle propulsion system uses a high-performance battery.

• The control unit and power semiconductor switching device.

Control unit and power semiconductor switching device used to control the flow of energy between the generator, the battery and the electric motor. While the generator and electric devices are AC devices, the battery is a DC device. The output voltage of the battery does not match the output of the generator, and the input voltage the electric motor. Therefore, power electronic devices perform the conversion of the voltage of electrical energy in accordance with the needs of the system.

• Regenerative braking system

When the vehicle is braking the electric motor operates as a generator, to slow down the motion of the car. The produced electricity is stored in the batteries.

In traditional systems the kinetic energy, is converted into heat during braking and is lost completely. In contrast, the hybrid system is particularly effective when driving in urban environments, where acceleration and braking alternate.

The control of regenerative braking - to optimize the amount of stored energy braking system, electronically controlled, makes a decision about when to use hydraulic brakes, and when - regenerative braking. The system tries to use regenerative braking as much as possible to maximize the conservation of energy.

• Inverter

Inverter is a device that converts direct current from the battery into alternating current for the motor. When converting direct current into alternating current, it can be used to power the electric motor. In the hybrid propulsion system a high-voltage circuit is used in converting the DC into alternating current.

2.2. Advantages of hybrid system

• Economical operation

Economical operation is the main advantage of hybrids. To achieve this, it is necessary to find a balance that is to equilibrate all the technical indicators of the machine, simultaneously saving all the useful parameters of conventional cars: the power, speed, ability to rapid acceleration, and many other very important characteristics, inherent in a modern vehicle. Moreover, the ability to store energy, including not to waste away the kinetic energy of motion during braking and to charge the batteries, in addition to the main apparent advantages.

• **Environmental cleanliness**

Reducing the consumption of carbon fuels has an immediate impact on the environment. Full stop of the engines of cars on the street of cities, especially in traffic jams, has a primary role.

• Good handling characteristics

At present there is no need to install the engine from the calculation of peak load operation. At a time when you need a sharp increase in the traction load, the work includes both the electric motor and the combustion engine. This allows saving on the installation of the less powerful engine, which is operating in a more advantageous state than a large one. Such a uniform redistribution and accumulation of power, followed by the rapid use, allows using of hybrid vehicles in the installation of the sports class. Despite the fact that electric motors have a sufficiently strong torque in terms of weight and dimensions of the engine, compared to other engines, designers usually are not capable of reducing the size of electric motors.

2.3. Disadvantages of hybrid system.

• **High complexity**

Hybrid vehicles are more complex and more expensive than conventional vehicles with internal combustion engines. Batteries have a small range of operating temperatures. In addition, they are expensive to repair.

• **Disposal of batteries**

Hybrid cars, like electric ones, must have a recycling process for used batteries. Effect of emitted batteries on the environment is hazardous for the environment.

• **The high cost of some models**

Of course the complexity and "unconventionality" of hybrid models will result in an increase of prices of cars.

3. ANALYSIS OF THE BASIC DATA

In a parallel hybrid system, the electric motor-generator is used not only for rapid start-ups of the internal combustion engine, but also for the creation of extra moving power during acceleration.

ICE has high fuel efficiency and low emissions in a limited range of operation, hence it is advisable to select the power only after the machine has already minimum base speed. Motor-generator allows smoothing vibration which has created by the engine torque and increasing the transmission resource. At the same time, the problem of board electrical power, typically large for modern vehicles can be solved.

In a parallel hybrid, it is also possible to recover kinetic energy during vehicle braking. This energy could be returned to the battery and used in starting the engine and acceleration. The rational balance of power sources in a parallel hybrid system depends on the operating state and is controlled with embedded software.

As a consequence of greater efficiency of mechanical transmission and large energy losses in double-conversion, it would be advisable to use the ICE and the kinematic scheme of modern vehicle. However, in real driving conditions there are always climbs and descents, turns to the braking, changing speed and direction of wind loads, and need for overtaking. The resistance of motion is changed, causing the need to change the operation mode of transmission and engine. This is accompanied by increased fuel consumption (according to some estimates up to 30%).

Urban traffic cycles normalize acceleration, speed, movement time and the average frequency of stops. Knowing the specific parameters of the machine, one can determine the optimum ratio for the consumption of fuel combustion engine and electric power. Average power in urban cycle is 1/5 – 1/3 of the power required for dynamic acceleration at maximum torque.

Consequently, the greatest saving is achieved when a hybrid vehicle is used in an urban cycle. In accordance to experimental data, the fuel consumption in an urban cycle of a hybrid vehicle is reduced by 25 – 30%, and in some cases - up to 50 %.

- **Urban cycle**

The ECE 15 urban cycle was develop and made available for urban traffic conditions. It is characterized by low vehicle speed, low engine load and low exhaust emissions. This cycle is consisting of 3 stages of testing, Figure 5.

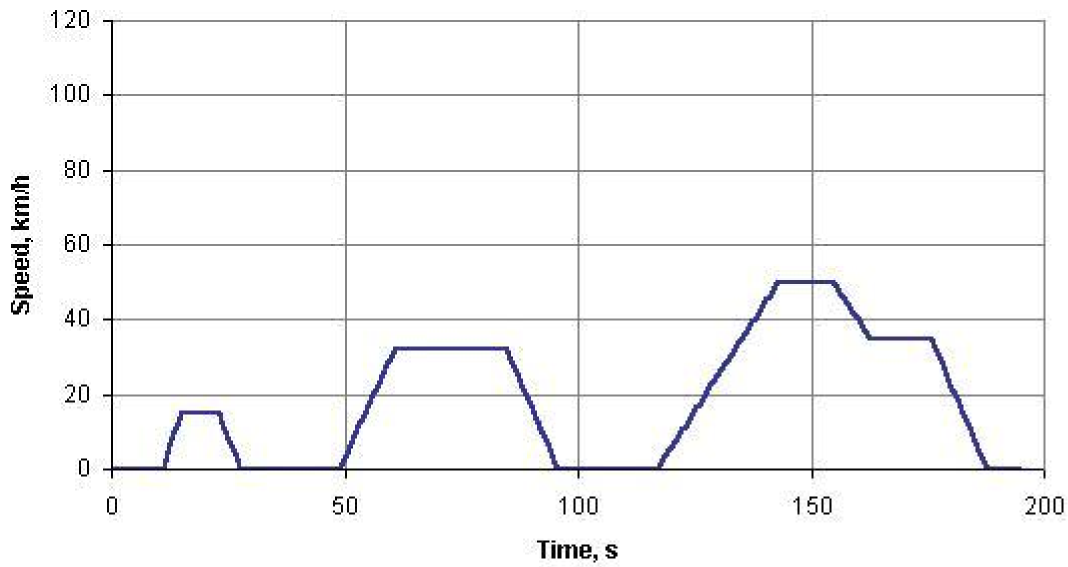

Figure 5. ECE 15 Cycle. [3]

- **Extra Urban Driving Cycle**

In extra-urban cycle as fourth state of vehicle operation was added. It consists of urban driving, more aggressive with a higher speed. The maximum speed of EUDC is 120 km/h, Figure 6.

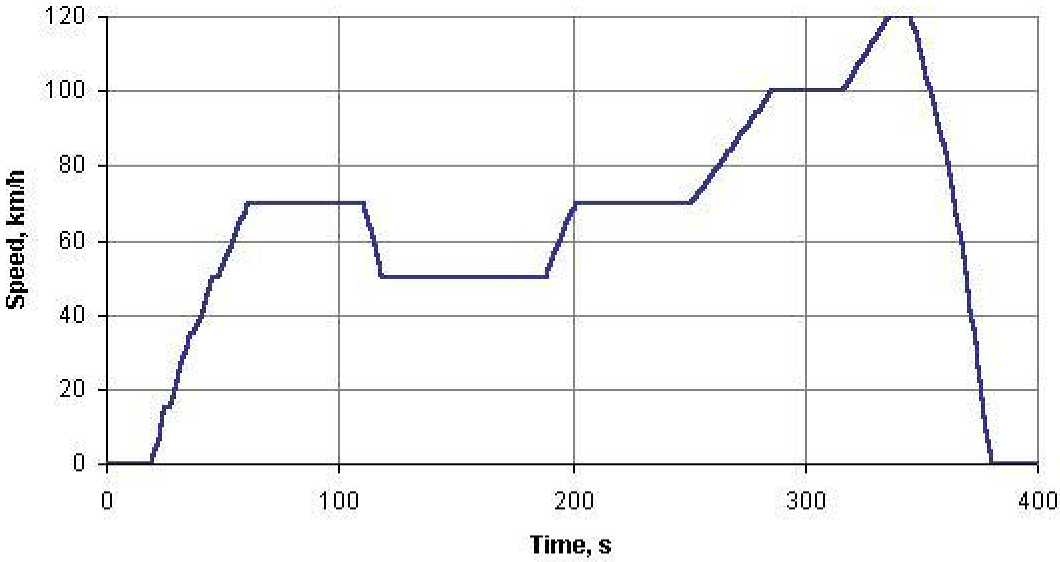

Figure 6. EUDC Cycle [3]

An alternative EUDC cycle for low-powered vehicles has been also defined with a maximum speed limited to 90 km/h, Figure 7.

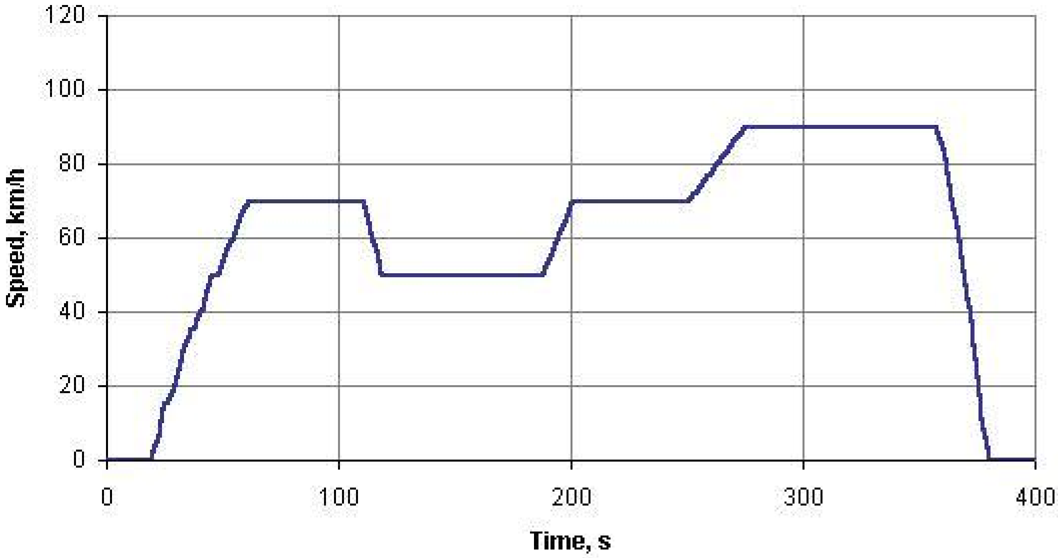

Figure 7. EUDC Cycle for Low Power Vehicles [3]

3.1. Calculation of basic parameters for design of electrical machine.

In the beginning of calculations of motors, it is necessary to determine the major forces acting on the vehicle, during acceleration and at constant motion. The Figure 8 shows the acting forces on the vehicle in the motion. [4]

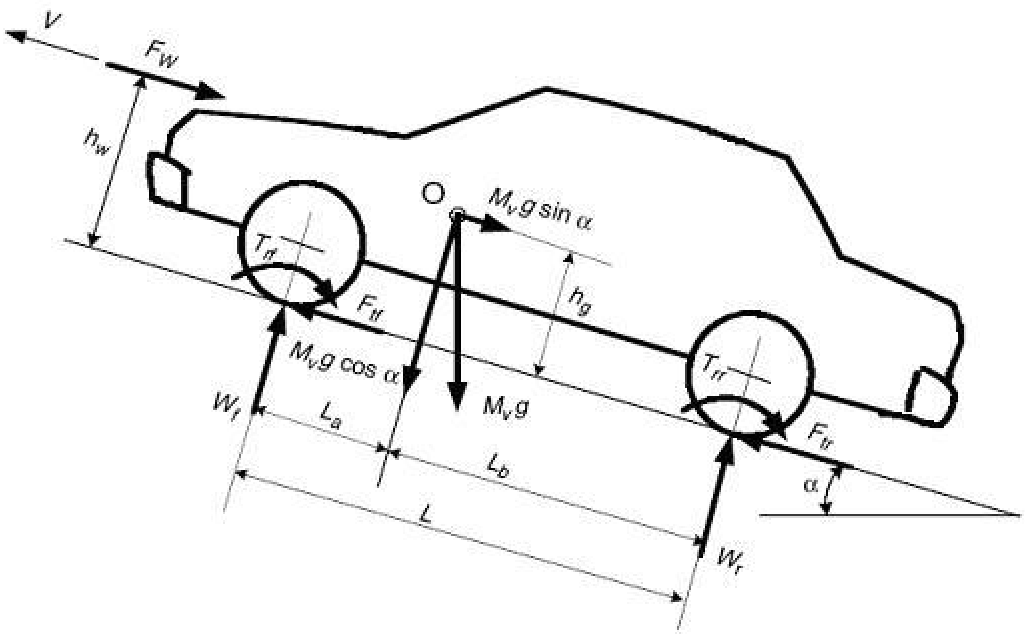

Figure 8. Acting forces on the vehicle in motion. (Mehrdad E. 2004, p. 22)

Traction force – F_t, is a force that operates in the area between driven wheels and road surface.

The traction force is a result of motor rotation and transferring the torque through transmission to the driving wheels. While the vehicle is in motion, the resistance tries to stop its movement. The resistance usually includes: tire rolling resistance, aerodynamic and up-hill resistance. Let us view these forces in detail.

- **Rolling resistance**

The rolling resistance is friction between of vehicle tire and road. Friction in bearings and the gearing system also plays some part. The rolling resistance is approximately constant, are depends on vehicle speed. (Mehrdad E. 2004, p 24)

$$F_r = f_r \cdot m_v \cdot g \cdot \cos \alpha = 0.012 \cdot 2000 \cdot 9.81 \cdot 0.992 = 233 \text{ [N]} \qquad (3.1)$$

Where, F_r – the force of rolling resistance, N; f_r – rolling resistance coefficients, 0.012; m_v – mass of example vehicle, 2000 kg; g – acceleration of gravity, 9.81m/s^2; α – grade, 7 degrees.

- **Aerodynamic drag**.

When the vehicle is in motion at a speed exceeding the speed of a pedestrian, the resistance of air has a noticeable influence. Calculating the force of the aerodynamic drag may be done using the following empirical formula. (Mehrdad E. 2004, p.25)

$$F_\omega = ½ \cdot \rho_a \cdot A_f \cdot C_D \cdot v^2 = ½ \cdot 1.29 \cdot 2 \cdot 0.5 \cdot 13.8^2 = 122 \text{ [N]} \qquad (3.2)$$

Where, ρ_a – air density, 1.29 kg/m^3; A_f – vehicle frontal area, 2 m^2; C_D – is the aerodynamic drag coefficient that characterizes the shape of the vehicle, 0.5; v – speed of vehicle, 13.8 m/s.

- **Grading resistance**

When the vehicle is in motion upwards or downwards on a slope, the weight is creating a force that is directed to the bottom, as it was shown in the Figure 8. This force is creating a resistance force to the motion vehicle, or helps. This effect is called the grading resistance. (Mehrdad E. 2004, p. 25)

$$F_g = m_v \cdot g \cdot \sin\alpha = 2000 \cdot 9.8 \cdot 0.121 = 2371\text{[N]} \qquad (3.3)$$

Where, m_v – the mass of vehicle, 2000 kg.

Consequently, the total traction force which is acting on the vehicle will equal the sum of all resistance forces acting on it in motion. (Mehrdad E. 2004, p. 110)

$$F_t = m_v \cdot g \cdot f_r \cdot \cos a + \frac{1}{2} \cdot \rho_a \cdot C_D \cdot A_f \cdot v^2 + m_v \cdot \delta \cdot \frac{dv}{dt} \qquad (3.4)$$

Where, δ – is called the mass factor; dv/dt – acceleration, m/s^2.

3.2. Acceleration mode of vehicle.

The performance of acceleration mode for a vehicle is usually described by the maximum cruising speed, grade of acceleration and the power of traction motors. In this work, we have envisaged a maximum speed of the vehicle on electric the traction should be 50 km/h. Further calculations will be made for this speed.

The traction force, which is created by the traction motor and transferred on the drive wheel through transmission, may be expressed as: (Mehrdad E. 2004, p. 104)

$$F_{\mathrm{am}} = \frac{T_{\mathrm{am}} \cdot i_{\mathrm{g}} \cdot i_0}{r_{\mathrm{d}}} \tag{3.5}$$

Where, F_{am} – is the traction force in acceleration mode, N; T_{am} – is the motor torque in acceleration mode, Nm; i_{g} – is the gear ratio of transmission; i_0 – is the gear ratio of the final drive; η_{t} – is the efficiency of the whole driveline from the motor to the driven wheels; r_{d} – is the radius of the drive wheels, m.

This equation explains, that the vehicle gathers the maximum speed when the traction force represented by the right side of the equation, equals the sum of resistance forces on the left side of the equation. Therefore, we can rewrite the equation as follows:

$$F_{\mathrm{am}} = m_{\mathrm{v}} \cdot g \cdot f_{\mathrm{r}} \cdot \cos a + \frac{1}{2} \cdot \rho_{\mathrm{a}} \cdot C_{\mathrm{D}} \cdot A_{\mathrm{f}} \cdot v^2 + m_{\mathrm{v}} \cdot \delta \cdot \frac{\mathrm{d}v}{\mathrm{d}t} \tag{3.6}$$

$$F_{\mathrm{am}} = 2000 \cdot 9.8 \cdot 0.013 \cdot 0.992 + \frac{1}{2} \cdot 1.29 \cdot 0.3 \cdot 13.8^2 + 2000 \cdot 1.07 \cdot 1.15 = 2716[\mathrm{N}]$$

After calculation of traction force, can be find the torque in according to impact of traction force. Equated the right side of equation (3.5) and right side of equation (3.6), we can find the output torque required to motor for acceleration vehicle to 50 km/h.

$$T_{\mathrm{am}} = \frac{F_{\mathrm{am}} \cdot r_{\mathrm{d}}}{i_{\mathrm{g}} \cdot i_0 \cdot \eta_{\mathrm{t}}} = \frac{2716 \cdot 0.27}{1 \cdot 27/17 \cdot 0.95} = 478[\mathrm{Nm}] \tag{3.7}$$

Where, T_{am} – the motor torque in acceleration mode, Nm; F_{am} – the traction force in acceleration mode, 2716 N; i_{g} – the gear ratio of transmission, 1; i_0 – the gear ratio of final drive, 27/17; η_t – the efficiency of the whole driveline from the motor to the driven wheels, 0.95; r_d – the radius of the drive wheels, 0.27 m.

The approximate motor power, from the dynamic equation varies both on F_{am} and v and is expressed as: (Mehrdad E. 2004, p 108)

$$P_{am} = F_{am} \cdot v = T_{am} \cdot \frac{2 \cdot \pi \cdot n_{am}}{60} = 2716 \cdot 13.8 = 38[\mathrm{kW}] \tag{3.8}$$

Knowing the power and torque on the out-put motor shaft, can be determine the speed of shaft of traction motor, corresponding speed 50 km/h. [4]

$$n_{am} = \frac{P_{am} \cdot 60}{2 \cdot \pi \cdot T_{am}} = \frac{38 \cdot 10^3 \cdot 60}{2 \cdot 3.14 \cdot 478} = 775[\mathrm{rpm}] \tag{3.9}$$

The grade ability is usually defined as the grade angle that the vehicle can get over at a certain constant speed, for instance, the grade at a speed of 50 km/h.

$$\sin\alpha = \frac{d - f_r\sqrt{1-d^2+f_r^2}}{1+f_r^2} = \frac{0.16-0.012\sqrt{1-0.16^2+0.012^2}}{1+0.012^2} = 0.148 \tag{3.10}$$

Where, $d = (F_t - F_w)/m_v \cdot g$ - vehicle performance factor; f_r – rolling resistance coefficient.

The acceleration performance of a vehicle is usually described by acceleration time and distance needed from zero to a maximum speed. In this case, the considering possibility of accelerating vehicle from 0 to 50 km/h.

$$t_a = \int_0^{v_b} \frac{m_v \cdot \delta}{P_t / v_b - m_v \cdot g \cdot f_r - (1/2) \cdot \rho_a \cdot C_D \cdot A_f \cdot v^2} dv + \int_{v_b}^{v_f} \frac{m_v \cdot \delta}{P_t / v - m_v \cdot g \cdot f_r - (1/2) \cdot \rho_a \cdot C_D \cdot A_f \cdot v^2} dv$$

Where, v_b – is the base speed of motion, 13.8 m/s; v_f – is the maximum speed of motion, 16.6 m/s; δ – is the mass factor, 1.075; m_v – is the mass of vehicle, 2000 kg; P_t – is the power of motor which is transferring torque to the drive wheel trough the transmission; ρ_a – is the air density, 1.29 kg/m^3; A_f – is the vehicle frontal area, 2 m^2; C_D – is the aerodynamic drag coefficient that characterizes the shape of the vehicle, 0.5;

Using the different equation for preliminary definition power of traction force, which is transmitted from traction motor on the wheels shaft and we know from our requirement, that available time for acceleration is 12 second.

$$P_t = \frac{\delta \cdot m_v}{2 \cdot t_a} \cdot (v_f^{\,2} + v_b^{\,2}) = \frac{1.075 \cdot 2000}{2 \cdot 12} \cdot (16.6^2 + 13.8^2) = 45[\text{kW}] \qquad (3.11)$$

Substitute a preliminary value of the traction power to the equation (3.10)

$$t_a = \int_0^{13.8} \frac{2000 \cdot 1.075}{45 \cdot 10^3 / v - 2000 \cdot 9.8 \cdot 0.012 - (1/2) \cdot 1.29 \cdot 0.5 \cdot 2 \cdot v^2} dv + \int_{13.8}^{16.6} \frac{2000 \cdot 1.075}{45 \cdot 10^3 / v - 2000 \cdot 9.8 \cdot 0.012 - (1/2) \cdot 1.29 \cdot 0.5 \cdot 2 \cdot v^2} dv = 12[\text{sec}]$$

The first part of the equation corresponds to the area where the speed of the vehicle below the basic and second part of the equation corresponds to the area where the speed of the vehicle, more than the basic speed.

The full power of traction motor, necessary for acceleration vehicle from 0 to 50 km/h at 12 seconds can be expressed through the following expression

$$P_t = \frac{\delta \cdot m_v}{2 \cdot t_a} (v_f^{\,2} + v_b^{\,2}) + \frac{2}{3} \cdot m_v \cdot g \cdot f_r \cdot v_f + \frac{1}{5} \cdot \rho_a \cdot C_D \cdot A_f \cdot v_f^{\,3} \qquad (3.13)$$

$$P_t = \frac{1.075 \cdot 2000}{2 \cdot 12} (16.6^2 + 13.8^2) + \frac{2}{3} \cdot 2000 \cdot 9.8 \cdot 0.013 \cdot 16.6 + \frac{1}{5} \cdot 1.29 \cdot 0.5 \cdot 2 \cdot 16.6^3 = 45.5[\text{kW}]$$

3.3. The mode of constant motion of vehicle

The vehicle performance of constant motion is usually described by a constant speed, traction torque and speed of shaft under the selected rate.

The traction force, which has created by traction motor and transferring on the drive wheel through transmission, in the constant motion of vehicle could be expressed as

$$F_{\mathrm{cm}} = m_{\mathrm{v}} \cdot g \cdot f_{\mathrm{r}} \cdot \cos\alpha + \frac{1}{2} \cdot \rho_{\mathrm{a}} \cdot C_{\mathrm{D}} \cdot A_{\mathrm{f}} \cdot v^2 \tag{3.14}$$

$$F_{\mathrm{cm}} = 2000 \cdot 9.8 \cdot 0.013 \cdot 0.992 + \frac{1}{2} \cdot 1.29 \cdot 0.3 \cdot 13.8^2 = 375[\mathrm{N}]$$

After calculation of tractions force, needed to the wheels for movement. Equated right side of equation (3.14) and the right side of equation (3.5), we can find the output torque which a required to constant motion - 50 km / h.

$$T_{\mathrm{cm}} = \frac{F_{\mathrm{cm}} \cdot r_{\mathrm{d}}}{i_{\mathrm{g}} \cdot i_0 \cdot \eta_{\mathrm{t}}} = \frac{375 \cdot 0.27}{1 \cdot 27/17 \cdot 0.95} = 67[\mathrm{Nm}] \tag{3.15}$$

Where, F_{cm} – the traction force in constant motion, N; T_{cm} – the motor torque, Nm; i_g – the gear ratio of transmission; i_0 – the gear ratio of final drive; η_t – the efficiency of the whole driveline from the motor to the driven wheels; r_d – radius of the drive wheels, m.

The approximation of power traction can be expressed through traction force, which should need to constant motion.

$$P_{\mathrm{cm}} = F_{\mathrm{cm}} \cdot v = T_{\mathrm{cm}} \cdot \frac{2 \cdot \pi \cdot n_{\mathrm{cm}}}{60} = 375 \cdot 13.8 = 5.1[\mathrm{kW}] \tag{3.16}$$

Where, P_{cm} – the power of motor in constant motion, kW.

3.4. Deceleration energy of a vehicle.

The letter j is for value of deceleration of a vehicle. This value for deceleration mode on a horizontal good road when the braking force of vehicle is used in maximum could be calculated through the equation. [5]

$$j = \varphi \cdot g \tag{3.17}$$

Where, φ – is a friction coefficient for wheels and road; g – is an acceleration of gravity force. From the equation above it can be assumed that the deceleration has a constant value which is depends only on the friction coefficient.

Brake system of vehicle is able to ensure the deceleration value about 8–9 m/s^2 when there is a need to use emergency braking. Such a deceleration is dangerous. Hard braking is permissible only in exceptional cases. The electric motor will not be capable of achieving such a deceleration. The safest application of deceleration is about 1–5 m/s^2. [5]

The torque acting on the wheels shaft of a vehicle during deceleration calculated through the equation below:

$$T_{\text{d}} = r \cdot (F_{\text{i}} - F_{\text{r}} - F_{\omega} - F_{\text{bs}}) \tag{3.18}$$

Where, F_{ω} – the air dynamic force; F_{i} - the force of vehicle inertia; F_{r} - the resistance force of rolling motion; F_{bs} - the force of brake system; r – the radius of wheel.

The force of the vehicle inertia is equal:

$$F_{\text{i}} = m_{\text{v}} \cdot j \cdot \sigma_{\text{rev}} \tag{3.19}$$

Where, σ_{rev} – the coefficient taking into account rotating parts of vehicle; it can be found from the equation: $\sigma_{\text{rev}} = 1.05 + 0.05 \cdot u_g{}^2$; u_{g} – gear ratio. Assume the car deceleration when the combustion engine in uncoupled so the gear ration is not taken in account. [6]

The force of the brake system. Could be found through of empirical equation which is defines the relative deceleration force of vehicle:

$$\gamma = \frac{4 \cdot F_{\text{bs}}}{m_{\text{v}} \cdot g} \tag{3.20}$$

Where, γ is a constant value taking into account demands making for sage braking of a vehicle; F_{bs} – the force of braking system; m_{v} – the mass of vehicle. The relative deceleration force must be less than 0.59 for passenger vehicle and 0.51 for trucks. [7]

$$F_{\text{bs}} = \frac{0.59 \cdot m_{\text{v}} \cdot g}{4} = \frac{0.59 \cdot 2000 \cdot 9.8}{4} = 2891[\text{N}] \tag{3.21}$$

Then, can be calculate the acting torque on the cardan shaft of vehicle, during the deceleration mode. Transmission ratio between cardan shaft and wheels can be taken in account and equal 17/27. Thereby, the torque acting on the cardan is:

$$T_c = \mathrm{T}_d \cdot \frac{17}{27} = r \cdot \left(m_v \cdot j \cdot \sigma_{rev} - f_r \cdot m_v \cdot g \cdot \cos\alpha - C_D \cdot A_f \cdot \rho \cdot \frac{v^2}{2} - F_{bs} \right) \cdot \frac{17}{27} \qquad (3.22)$$

The power, which can be return to the storage system from regenerative braking by electrical machine, could be found through the following equation:

$$P_r = T_c \cdot \Omega_c \qquad (3.23)$$

Where, Ω_c – is an angular speed of the cardan shaft of vehicle.

The angular speed of cardan shaft changes during deceleration period. Assume the deceleration starts from the 50 km/h to 0, and deceleration time is 10 seconds. The value of deceleration is equal 1.6 m/s. Power which can be recuperated to the storage during deceleration of vehicle is presenting in the *Appendix 3.*

4. SELECTION MOTOR FOR PARALLEL HYBRID VEHICLE

In order to choose the motor, it is necessary to calculate the maximum rotation speed of cardan. Where, the speed of cardan shaft is one of the main criteria to selecting an electrical motor. Consider a calculation that the maximum speed of the vehicle, when the internal combustion engine can produce power for is 150 km/h.

$$\Omega_{\mathrm{w}} = \frac{v_{\mathrm{w}}}{r_{\mathrm{w}}} = \frac{41.6}{0.27} = 154[\mathrm{s}^{-1}] \tag{4.1}$$

Where Ω_{w} – angular velocity of the shaft wheel, 1/s; v_{w} – speed of the car, 41.6 m/s; r_{w} – the radius of the wheels, 0.27 m.

The transmission ratio between the wheel and the cardan shaft is 27/17. The angular velocity of the cardan shaft can be expressed as:

$$\Omega_{\mathrm{c}} = \Omega_{\mathrm{w}} \cdot \frac{27}{17} = 154 \cdot \frac{27}{17} = 244[\mathrm{s}^{-1}] \tag{4.2}$$

Then, we get the speed of the cardan shaft.

$$n_{\mathrm{m}} = \frac{30 \cdot \Omega_{\mathrm{c}}}{\pi} = \frac{30 \cdot 244}{3.14} = 2331[\mathrm{rpm}] \tag{4.3}$$

Thereby, after calculation, it may be concluded that the motor speed will be limited by the cardan speed and can not exceed – 2331 rpm. According to the acceleration mode, it was found that the maximum torque is 478 Nm and speed 775 rpm which are needed to accelerate the vehicle to 50 km/h at 12 seconds. The torque for constant motion is only 68 Nm. Traction motor is designed to operate at steady state, the regime S1.

After the calculation are power, torque, and speed of output shaft, it is necessary to determine the size and types of motor. The basis of calculation was chosen as a system with a parallel installation of an electric motor between the internal combustion engine and transmission, Figure 9.

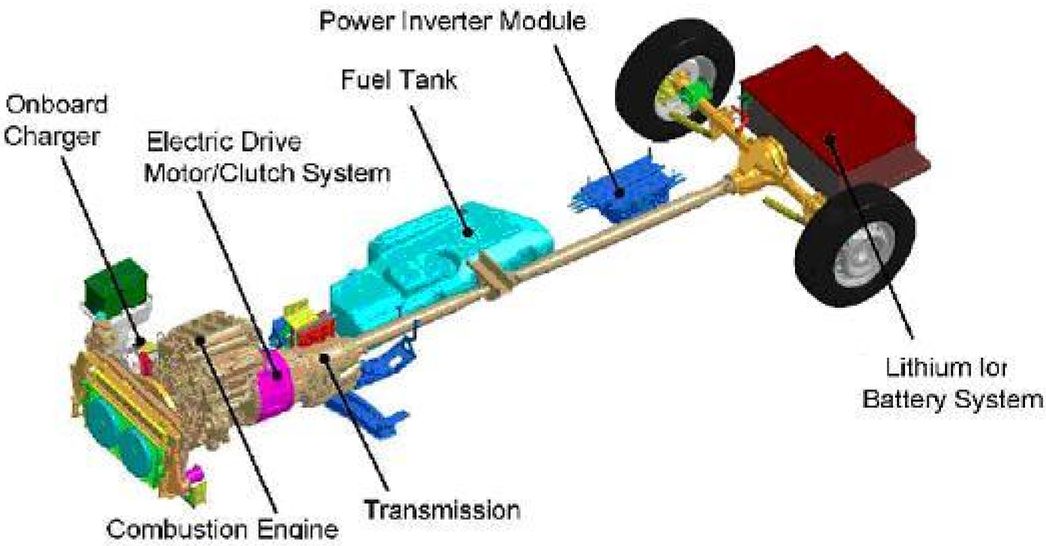

Figure 9. Parallel hybrid with pretransmission single-shaft torque. [8]

In the design of electromechanical devices in the first place it is necessary to evaluate the practicability of requirements, as well as to understand what factors limit the achievable value of an indicator and choose the best option for this system. May be noted that optimization of the motor is multicriteria. Moreover, optimization of the geometric dimensions occurs on the set of Pareto: improvement of one indicator is possible due to the deterioration of another one.

In the vehicle is advisably to use the optimized electric motors with not high mass and size. The geometry of pole pitch these engines is optimizing for specific indicators – relations electromagnetic torque for the size or power. The weight optimized engine is depending on the applied magnetic and conducting material, as well as allowable losses and the air gap.

Initial data in the design provide the required power, speed of output shafts, and the dimensions of electric traction, depending on the selected kinematic diagram. For a given structural constraints and materials used, usually to choose the optimum geometry of the active part, including the number of poles.

In the first step of pre-project evaluation is determines the possibility using with out gear implementation of electric traction. For that end, are using the power, time and speed we could find optimize dimensions. Then, according to the specified dimensions, accounting the maximum number of motor poles is realized when the diameter of stator the constant.

This analysis examines the machines with power *P* = 35; 45; 65 kW, with the speed of rotation *n* = 1000; 1500 rpm. Advisable to use these speeds in mind that rotational speed of cardan shaft with acceleration and continuously motion does not exceed 1000 rpm. From this could be excluding to use of gears in the selected kinematic diagram.

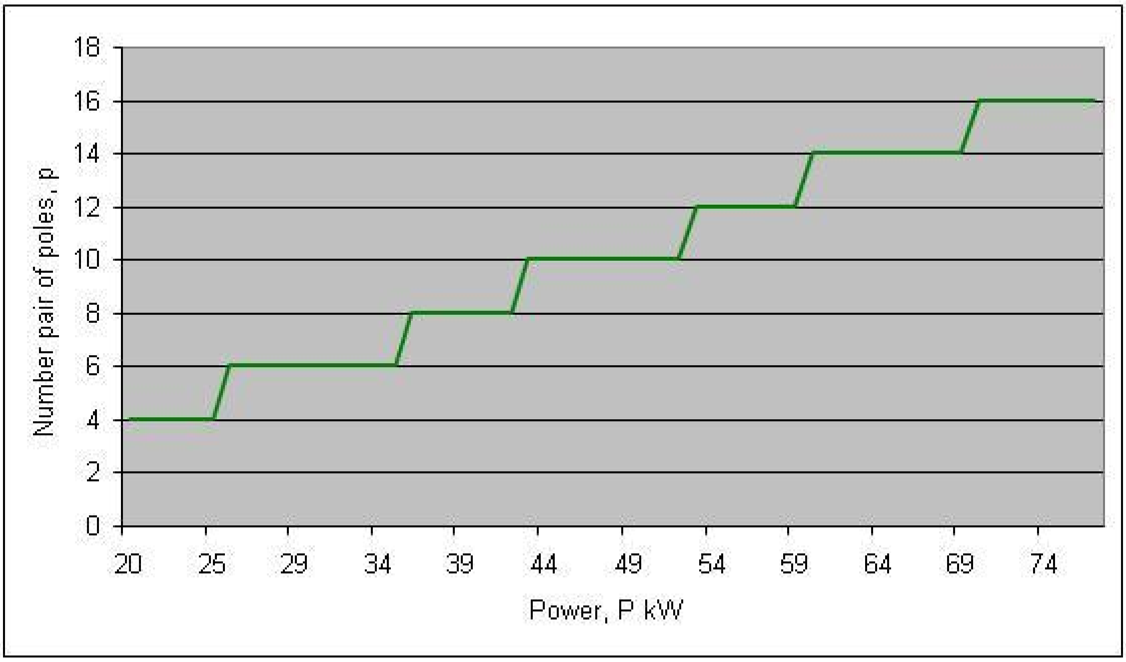

Figure 9. Dependence of number poles for the permissible power of traction motor. [9]

In the quality of evaluation criterion have chosen tractive motor was selected the following ratios: diameter and length, time and speed of the motor, and the influence of the number of pair of poles on them. In the analysis of the proposals to research motor at two types: asynchronous machine and permanent magnet synchronous machine.

In practice, the size of the active part of machine is often constant. In according with common data would like estimate the motor with number of pair of poles *p* = 4, 6, 8, 10. The Figure 9, based on the results of researching of traction motor in the Moscow Sate of Road-Transport University, was drafted the recommendation for choosing the number of pair of poles for chosen power of the traction motor. In the *Appendix 4* is preliminary calculation of traction motor with constant an outer diameter of the stator 219 mm.

Due to preliminary calculations, we have the opportunity to evaluate and conclude with further selection of the optimized motor in according to our requirements.

• With increasing the numbers of poles *p*, are decreasing the length of the motor – *l'* [m] and increasing an outer diameter of the rotor – D_r [m]

• With increasing the numbers of poles *p*, are increasing the frequency of supply network – *f* [Hz], and increasing the torque – *T* [Nm]

• When increasing the speed of the motor – *n* [rpm], are decreasing the length of motor – *l'* [m], and decreasing the torque – *T* [Nm]

Based on the preliminary calculation, would like to choose the optimality asynchronous machine and permanent magnets synchronous machine in according for requirement of kinematic diagram. *Appendix 4*

Asynchronous Machine

Table 3. Basic parameters of preliminary design of asynchronous machine.

P	U_{phase}	n	p	f	l'	D_r	D_{se}	T	T_H / T_N
kW	V	rpm		Hz	m			Nm	
35	166	1500	6	150	0.52	0.135	0.219	222	2.5

Knowing the parameters of an asynchronous motor, could be done the test in accordance with requirements to accelerate from 0 to 50 km/h for 12 seconds. For accomplish this, will be used the standard equations the electromechanical drive of the vehicle. [10]

- *External moment of inertia on the motor shaft*

$$J_X = 91.2 \cdot m_v \cdot \left(\frac{v}{n}\right)^2 = 91.2 \cdot 2000 \cdot \left(\frac{13.8}{1500}\right)^2 = 16[\text{kgm}^2] \qquad (4.4)$$

m_v – the mass of vehicle, kg; v – the speed of vehicle, m/s; n – the speed of output shaft of motor, rpm.

- *Maximum torque*

$$T_{\mathrm{H}} = 2.5 \cdot T = 2.5 \cdot 222 = 555[\mathrm{Nm}] \tag{4.5}$$

T_{H} – the maximum torque, Nm; 2.5 – the ration of maximum torque and rated torque; T – the rated torque, Nm.

- *The torque of load in acceleration*

$$T_{\mathrm{L}} = \frac{F_{\mathrm{am}} \cdot v \cdot 9.55}{n} = \frac{2716 \cdot 13.8 \cdot 9.55}{1500} = 242[\mathrm{Nm}] \tag{4.6}$$

T_{L} – the torque of load, Nm; v – the speed of vehicle, m/s; n – the rated speed of motor, rpm.

- *Acceleration time from 0 to 50 km/h*

$$t_{\mathrm{a}} = \frac{\left(J_{\mathrm{M}} + \frac{J\mathrm{x}}{\eta} \right)}{9.55 \cdot (T_{\mathrm{H}} - T_{\mathrm{L}})} = \frac{\left(\frac{16}{0.95} \right) \cdot 1500}{9.55 \cdot (555 - 242)} = 9[\mathrm{sec}] \tag{4.7}$$

J_{X} – the mass moment of inertia of motor, kgm^2. Where J_{M} is far less the $J_{\mathrm{X},}$ and we could neglect this value; J_{M} – the external mass moment of inertia, kgm^2;

Permanent Magnet Synchronous Machine

Table. 4. Basic parameters of preliminary design of permanent magnet synchronous machine.

P	U_{phase}	n	p	f	l'	D_{r}	D_{se}	T	$T_{\mathrm{H}} / T_{\mathrm{N}}$
kW	V	rpm		Hz	m			Nm	
35	166	1500	6	150	0.28	0.135	0.248	227	2.5

Knowing the parameters of an permanent magnet synchronous machine, could be done the test in accordance with our requirements to accelerate from 0 to 50 km/h for 12 seconds. For accomplish this, will be used the standard equations the electromechanical drive of the vehicle. [10]

- *External moment of inertia on the motor shaft*

$$J_{\mathrm{X}} = 91.2 \cdot m_{\mathrm{v}} \cdot \left(\frac{v}{n} \right)^2 = 91.2 \cdot 2000 \cdot \left(\frac{13.8}{1500} \right)^2 = 16[\mathrm{kgm}^2] \tag{4.8}$$

m_{v} – the mass of vehicle, kg; v – the speed of vehicle, m/s; n – the speed of output shaft of motor, rpm.

- *Maximuml torque*

$$T_{\mathrm{H}} = 2.5 \cdot T = 2.5 \cdot 227 = 567[\mathrm{Nm}] \tag{4.9}$$

T_{H} – the maximum torque, Nm; 2.5 – the ration of maximum torque and rated torque; T – the rated torque, Nm.

- *The torque of load in acceleration*

$$T_{\mathrm{L}} = \frac{F_{\mathrm{am}} \cdot v \cdot 9.55}{n} = \frac{2716 \cdot 13.8 \cdot 9.55}{1500} = 242[\mathrm{Nm}] \tag{4.10}$$

T_{L} – the torque of load, Nm; v – the speed of vehicle, m/s; n – the rated speed of motor, rpm.

Acceleration time from 0 to 50 km/h,

$$t_{\mathrm{a}} = \frac{\left(J_{\mathrm{M}} + \frac{J\mathrm{x}}{\eta} \right)}{9.55 \cdot (T_{\mathrm{H}} - T_{\mathrm{L}})} = \frac{\left(\frac{16}{0.95} \right) \cdot 1500}{9.55 \cdot (567 - 227)} = 8[\mathrm{sec}] \tag{4.11}$$

J_{M} – the mass moment of inertia of motor, kgm^2. Where J_{M} is far less the $J_{\mathrm{X},}$ and we could neglect this value; J_{X} – the external mass moment of inertia, kgm^2.

5. CALCULATION AND SELECTION OF ENERGY STORAGE

5.1. Calculation of energy storage

When a vehicle operates in a stop-and-go motion mode, the power must be transferred to and from the traction motor very often. However, the energy source in this state is discharging quickly. In this case, maintaining the battery in a state of charge (SOC) is necessary for the performance of the vehicle. Let us view the different variants of motion and according to the charge or discharge of battery depending from the vehicle state.

Motion of vehicle with an electric motor: In this case, the car is moving using the traction power from the electric motor and energy is taken from the battery. In this mode, the internal combustion engine is switched off or is at idle. Engine, electrical machinery and discharged power source can be written: (Mehrdad E. 2004, p. 263)

$$P_{\mathrm{e}} = 0$$

$$P_{\mathrm{m}} = \frac{P_{\mathrm{L}}}{\eta_{\mathrm{t}}} = \frac{38 \cdot 10^3}{0.95} = 40[\mathrm{kW}]$$
$$P_{\mathrm{pps\text{-}d}} = \frac{P_{\mathrm{m}}}{\eta} = \frac{40 \cdot 10^3}{0.87} = 47[\mathrm{kW}] \qquad (5.1)$$

Where, P_{L} – the load power for acceleration; η_{t} – the efficiency between traction motor and driving wheels; P_{m} – the motor power; $P_{\mathrm{ss\text{-}d}}$ – discharge power of power source; η – efficiency of motor.

The hybrid work of engine and traction motor: In this case, the engine combustion operation is set on the acceleration state by controlling the engine to produce power P_{e}. The remaining power demand is supplied by the traction motor. The motor power output and PPS discharge power are expressed as (Mehrdad E. 2004, p. 264)

$$P_{\mathrm{m}} = \frac{P_{\mathrm{L}} - P_{\mathrm{e}} \cdot \eta_{\mathrm{te}}}{\eta_{\mathrm{t}}} = \frac{38 \cdot 10^3 - 39 \cdot 10^3 \cdot 0.9}{0.95} = 3.1[\mathrm{kW}] \qquad (5.2)$$

$$P_{\text{pps-d}} = \frac{P_{\text{m}}}{\eta} = \frac{3.1}{0.87} = 3.5[\text{kW}]$$

Where the combustion engine power is defined as

$$P_{\text{e}} = \frac{v}{1000 \cdot \eta_{\text{te}}} \cdot \left(m_{\text{v}} \cdot g \cdot f_{\text{r}} + \frac{1}{2} \cdot \rho_{\text{a}} C_{\text{D}} \cdot A_{\text{f}} \cdot v^2 + m_{\text{v}} \cdot g \cdot i \right) \tag{5.3}$$

$$P_{\text{e}} = \frac{13.8}{1000 \cdot 0.9} \cdot \left(2000 \cdot 9.8 \cdot 0.012 + \frac{1}{2} \cdot 1.29 \cdot 0.5 \cdot 2 \cdot 13.8^2 + 2000 \cdot 9.8 \cdot 0.111 \right) = 39[\text{kW}]$$

Peaking Power Source charge mode: Let us consider the case when the vehicle is moving by the combustion engine at constant speed of 50 km/h. Then the electric motor operates in the generator mode and transfers the received energy to the battery. (Mehrdad E. 2004, p. 264)

$$P_{\text{m}} = \left(P_{\text{e}} - \frac{P_{\text{L}}}{\eta_{\text{te}}} \right) \cdot \eta_{\text{t}} \cdot \eta = \left(39 \cdot 10^3 - \frac{5.1 \cdot 10^3}{0.9} \right) \cdot 0.95 \cdot 0.87 = 27[\text{kW}] \tag{5.4}$$

$$P_{\text{pps-c}} = P_{\text{m}} = 27[\text{kW}]$$

Where, $P_{\text{pps-c}}$ – charge power of power source

The regenerative braking for motion with constant deceleration: When the demanded braking power is less than the maximum regenerative braking power the electric motor can work as a generator and produce braking power which is transferring for charging a power source. The motor power output and $P_{\text{pps-c}}$ charge power are (Mehrdad E. 2004, p. 264)

- Acceleration mode:

$$P_{\text{m}} = P_{\text{L}} \cdot \eta_{\text{t}} \cdot \eta = 38 \cdot 10^3 \cdot 0.95 \cdot 0.87 = 31[\text{kW}]$$
$$P_{\text{pps-c}} = P_{\text{m}} = 31[\text{kW}] \tag{5.5}$$

Where, $P_{\text{pps-c}}$ – charge power of power source

- Motion of the vehicle with constant speed:

$$P_{\text{m}} = P_{\text{L}} \cdot \eta_{\text{t}} \cdot \eta = 5.1 \cdot 10^3 \cdot 0.95 \cdot 0.87 = 4.3[\text{kW}] \tag{5.6}$$

$$P_{\text{pps-c}} = P_{\text{m}} = 4.34[\text{kW}]$$

Where, $P_{\text{pps-c}}$ – charge power of power source

5.2. Selection of energy storage

Energy storage is fundamental to electric, hybrid electric and plug-in hybrid electric vehicle operation, and it has proven instrumental to achieving efficient operation of fuel cell vehicles. The prospects for large-scale introduction of these vehicles and realization of their near-zero emission benefits are tied to the availability of energy storage systems that provide high performance.

For full HEV's, battery capacities need to be several times larger than the minimum energy required for vehicle electric power because energy must be delivered at high power that reduces available energy. Also, on occasionson the battery must provide energy repeatedly within relatively short periods during which insufficient battery charge is restored by the engine and regenerative braking. (Fritz R. et al. 2007, p. 21)

For PHEV's, the required battery capacities are substantially larageer than for full HEVs, actual capacity will be detemined by the specified rated electric power. During normal PHEV operation the battery is being discharged continuously until its state of charge has drop down to a predetermined level. When that level is reached, the PHEV control system switches vehicle and battery operation to the charge-sustaining mode. PHEV batteries must meet peak power requirements even at the lowest SOC. (Fritz R. et al. 2007, p. 21)

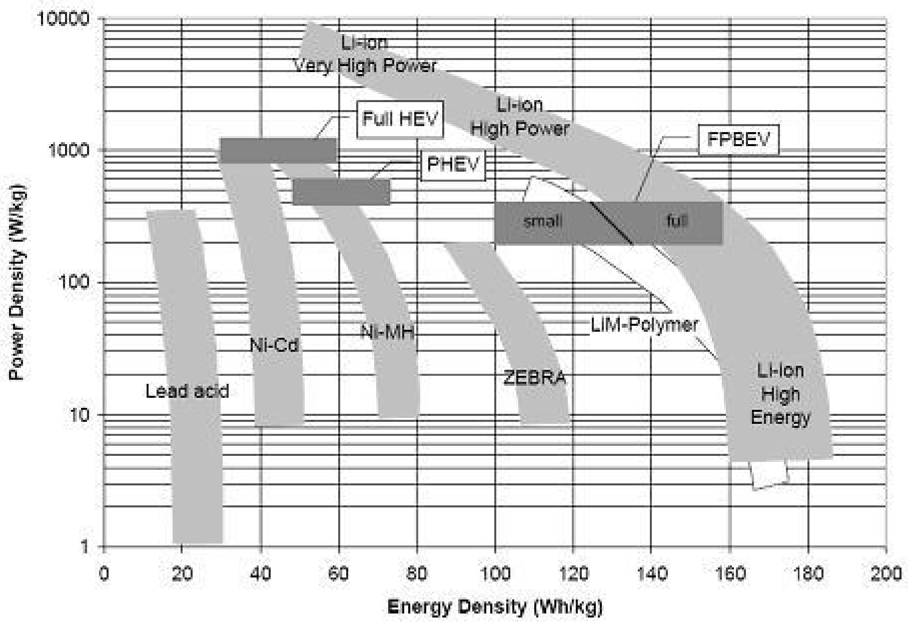

Figure 11. Potential of Battery Technologies for HEV, PHEV and EV Applications
(Fritz R. et al. 2007, p. 25)

The primary functions and capabilities provided by the storage systems of electric vehicles and the main types of hybrid electric vehicles are summarized in Table 4. With increasing vehicle functional capabilities the vehicle energy storage system needs to deliver increasing amounts of electric power and energy. These increases are determined almost entirely by the vehicles incremental capabilities Table 4, as shown in recent analyses of mid-size HEV architectures and PHEV designs. The energy storage system of fuel cell hybrid electric vehicles provides additional functions but the performance requirements are geneally similar of full HEV's.

Table 4. Vehicle Functional Capabilities Provided by Energy Storage.
(Fritz R. et al. 2007, p. 20)

Vehicle Type	Functional Capabilities
Micro HEV	Automatic start and stop plus regenerative braking
Mild HEV	Micro HEV capabilities plus power assist to vehicle IC engine
Full HEV	Mild HEV capabilities plus electric launch
Plug-in HEV	Full HEV capabilities plus electric range with grid-charged electricity
FPBEV	Exclusively electric propulsion power and energy (grid-charged)

Figure 11, has showed the approximate ranges of energy and power densities required for the batteries of the various advanced-technology vehicles, Table 5. It also includes the general relationship between power and energy densities for the battery types used or being considered for automotive. In *Appendix 5* have attachment the current situation are using different types of batteries in different HEV and analysis market of battery-companies for HEV and PHEV.

Table 5. Vehicle Energy Storage System Performance Requirements.
(Fritz R. et al. 2007, p. 21)

EDV Type	Weight	Peak Power	Power Density	ES Capacity	Energy Density
	kg	kW	W/kg	kWh	Wh/kg
Full HEV	50	40 – 60	800 – 1200	1.5 – 3	30 – 60
Plug-in HEV	120	50 ; 65	540; 400	6 ; 12	50 ; 75
FPBEV	250	50 ; 100	200; 400	25 ; 40	100 ; 160

Li-ion batteries have the following important characteristics for application to vehicles:

- Their energy efficiency and charging/discharging efficiency are high.

- A high single-cell voltage, three times that of Ni-MH batteries and twice that of lead-acid batteries. That means the number of cells in a battery can be relatively small advantageous with regard to numbers of parts and connections between terminals.

- Charging and discharging reactions produce relatively little heat, so a simple cooling system is adequate and operation is possible in wide range of ambient temperatures

In the parallel hybrid drive system, the battery is used mainly for engine assistance when the vehicle starts moving and accelerates, continuously moving and for recovery of braking energy when the vehicle decelerates. In our case we have seen the possibilities acceleration without supply of combustion engine. From After analysing different battery companies, I have made a conclusion to favour Hymotion company's battery. Consequently, I have chosen the Hymotion L5 Plug-in Conversion Module, which has a high specific energy of and at the same time has a good balance of weight and capacity, was adopted for the parallel hybrid drive system. The structure of battery is shown in Figure 12, and the battery's specifications are shown in Table 6. [12]

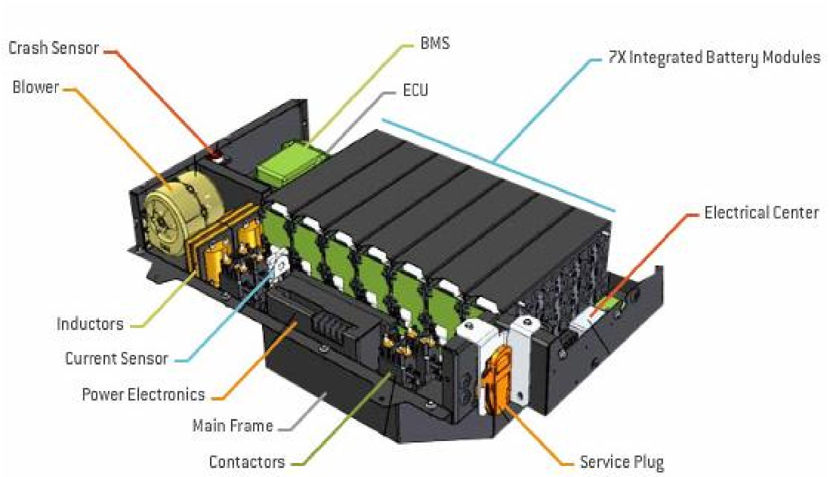

Figure 12. The structure of Hymotion L5 Plug-in Conversion Module

Hymotion increases the electric capability of the hybrid platform by supplementing the vehicle's factory battery. The Hymotion module's greater stored energy capacity allows using electric drive more often and for longer distances.

Batteries modules are based on the Nanophosphate lithium ion batteries that deliver higher levels of power, safety, and life than conventional lithium ion batteries.

The Hymotion L5 Plug-in Conversion Module is based on the Nanophosphate and battery that uses regular 120 V grid power to recharge, providing the user with ~ 10 kWh of rechargeable energy storage at full capacity.

Table 6. The battery's specifications.

Hymotion L5 Lithium-Ion battery				
$P_{b\text{-}max}$ for 30 sec. at 50% SOC	$P_{b\text{-}rated}$	I_b	U_b	N_b
kW	kW	A	V	Number of cells
61	10	41	194 – 288	72

HEV have attracted tremendous attention during the latest years. Increasing environmental concern and a steady increase in fuel prices are key factors for the growing interest in the HEV.

6. DESIGNING OF SELECTED MOTORS

6.1. Design an asynchronous motors

Asynchronous machine technology is a mature technology with great research and development activities. Development in digital signal processor and advanced vector control algorithm allow controlling an induction machine without special maintenance requirements [13]. Asynchronous machines are used widely in the industry because of their low cost, safety and reliability. Asynchronous machines are used in electric and hybrid electric vehicle applications because they are compact, low-cost, operate over in different speed range, and are capable of operating at high speeds. The size of the induction machine is smaller than DC machine in the same power rating. There are two types of asynchronous machines: squirrel cage and phase-wound rotor. In squirrel cage machines, the rotor winding consists of short-circuited copper or aluminum bars. In phase-wound rotor asynchronous machines, the rotor windings are brought to the outside with the help of slip rings so that the rotor resistance can be varied by adding external resistance. Squirrel cage asynchronous machines are of huge interest for industries as well as for EV's and HEV's. Instantaneous high power and high torque capability of asynchronous machine have made an attractive for the propulsion system of EV and HEV.

According to the aim of the thesis an asynchronous machine has been designed. During the calculation was made an analysis and drafted recommendations for the design of traction motors for EV and HEV's. In calculation the traction motors with small geometric dimensions, one could recommend to choose the number of stator slots Q_s = 24, 30, 36, 42, 54 and the number of rotor slots, respectively, Q_r = 16, 22, 26, 32, 44. Electrical machines of low power generally have $Q_r < Q_s$, this is due to a number of technological reasons, as well as with the increase the number of rotor slot Q_r, the rotor current is reduced and in the machine of small power the cross section of winding bar becomes smaller.

In larger electrical machines typically $Q_r > Q_s$, to limit excessive currents in the rotor winding bar and increase the uniformity of equal distribution of conductors in the slot.

The air gap should be selected on the basis of magnetization current. Typically, the value of magnetization current of asynchronous motor in relative unit is in the range of $I_m = 0.2 – 0.3$, only low-power machine can reach the value $I_m = 0.5 – 0.6$. Magnetization current is inversely proportional to the air gap. In the design of asynchronous machine should be using $\delta = 0.5 – 1$ mm. This will ensure acceptable to receive the optimal value of magnetization current. With respect to the active resistance of stator and rotor, here is necessary modeling of geometric size, number of poles and the number of slots at stator and rotor. The determining factor is the relative value of design resistance $R_S \approx R_R = 0.02 – 0.05$, reactance $X_S \approx X_R = 0.08 – 0.2$.

Typically, in such electrical machine the number of poles of $p \leq 8$, since an increase in the number of poles more than $p = 6$, the values of reactance and resistance increase dramatically, thus resulting in reduction of efficiency of the electrical machine and value of starting torque. The power and speed have played a direct role in the designing.

At the bottom are basic data of design an asynchronous motor, Table 7 and *Appendix* 6 shows the basic characteristics of the asynchronous machine.

Table 7. Basic data of design an asynchronous machine.

№	Name	Denomination	Unit of measure
1	Power, P	35	kW
2	Speed, n	1500	rpm
3	Line-to-line voltage star connected, U_{sph}	288	V
4	Number of phases, m	3	
5	Number of pole pairs, $2p$	6	
6	Frequency, f	75	Hz
7	Power factor, $\cos\varphi$	0.86	%
8	Efficiency, η	0.90	%
9	Outer diameter of the rotor, D_r	0.135	m
10	Outer diameter of the stator, D_{se}	0.224	m
11	Effective core length, l'	0.55	m
12	Rated torque, T	190	Nm
13	Air gap, δ	0.001	m
14	Number of stator slots, Q_s	54	
15	Number of rotor slot, Q_r	44	
16	Number of conductors in a slot, z_{Qs}	5	
17	Air-gap flux density B_δ	0.80	T
18	Stator current, I_s	82.27	A
19	Maximum torque, T_H	578	Nm
20	Starting torque T_S	380	Nm
21	Starting torque per rated torque	2.5	
22	Total mass	80.7	kg

6.2. Design an permanent magnet synchronous motors.

Permanent magnet (PM) synchronous machines are extensively used in industrial, transportation, and electrical vehicles. PM machines are challenging asynchronous machines in EV and HEV's due to their high energy per unit of volume, compact size, high efficiency, and extensively speed range. The availability of rare-earth permanent magnets give rise to the development of PM machine technologies in high-performance applications [14]. The basic difference between a PM machine and other types of rotating electric machines is the form of excitation. PM machines use permanent magnets in the rotor as the field exciting circuit, which produces air-gap magnetic flux. As a result, the permanent magnets provide a loss-free excitation without any external stationary electric circuit. However, the DC bus voltage control is not as easy as in an induction machine due to the permanent source of flux. The main apprehensive about PM machines are possibility of broken magnets and demagnetization of magnets due to heating caused by eddy currents at high speeds [14].

PM machines can be classified into two categories: permanent magnet synchronous machine (PMSM) and permanent magnet brushless DC (PM BLDC) machine. In a PMSM, the stator winding is sinusoidal distributed along the stator circumference producing a sinusoidal back-emf; the stator winding of a PM BLDC is concentrated which produces a trapezoidal-shaped back-emf. Three-phase balanced supply to the stator windings of a PMSM produces a sinusoidal current linkage in the air gap.

Permanent magnets in the rotor are shaped appropriately, and a sinusoidal rotor flux linkage can be established by controlling their magnetizing directions [15]. The electromagnetic torque is generated on the shaft by the coordinate action of the stator and rotor magnetic fields.

There are three types of PMSM depending on the shape and position of the permanent magnets in the rotors: surface installation PM machine, inset PM machine and interior PM machine. The surface installation and inset PM machines are often collectively called surface mount PM synchronous machines. In the surface mounted PMSM, the magnets are easily epoxy-glued or wedge-fixed to the cylindrical rotor. An interior PMSM has its magnets inside the rotor, which is harder to construct but reduces eddy current effect on the magnets at high speed, in the *Appendix 7* have showed example of interior PMSM which is using Toyota. At the bottom are basic data of design surface mount PM synchronous machines, Table 8 and in the *Appendix* 6 have showed basic characteristic of permanent magnet synchronous machine.

Table 8. Basic data of design an permanent magnet synchronous machine.

№	Name	Denomination	Unit of measure
1	Power, P	35	kW
2	Speed, n	1500	rpm
3	Line-to-line voltage star connected, U_{sph}	288	V
4	Number of phases, m	3	m
5	Number of pole pairs, $2p$	6	p
6	Frequency, f	75	Hz
7	Power factor, $\cos\varphi$	0.97	%
8	Efficiency, η	0.94	%
9	Outer diameter of the rotor D_r	0.135	m
10	Outer diameter of the stator, D_{se}	0.250	m
11	Effective core length, l'	0.26	m
12	Rated torque, T	222	Nm
13	Air gap, δ	0.0016	m
14	Number of stator slots, Q_s	54	
15	Load angle, δ_l	27.9	degree
16	Number of conductors in a slot, z_{Qs}	11	
17	Air-gap flux density, B_δ	0.9	T
18	Stator current, I_s	77	A
19	Height of the permanent magnets, h_{PM}	5.8	mm
20	Maximum torque, T_H	500	Nm
21	Peak torque per rated torque,	2.24	Nm
22	Total mass, m	80.9	kg

6.3. Techno-economic study of chosen motors

Consider the cost of manufacturing of engines:

a) Asynchronous machine,

b) Permanent magnets synchronous machine,

Expenses which form the cost of product (works, services), are grouped according to their economic content of the following elements, Figure 13.

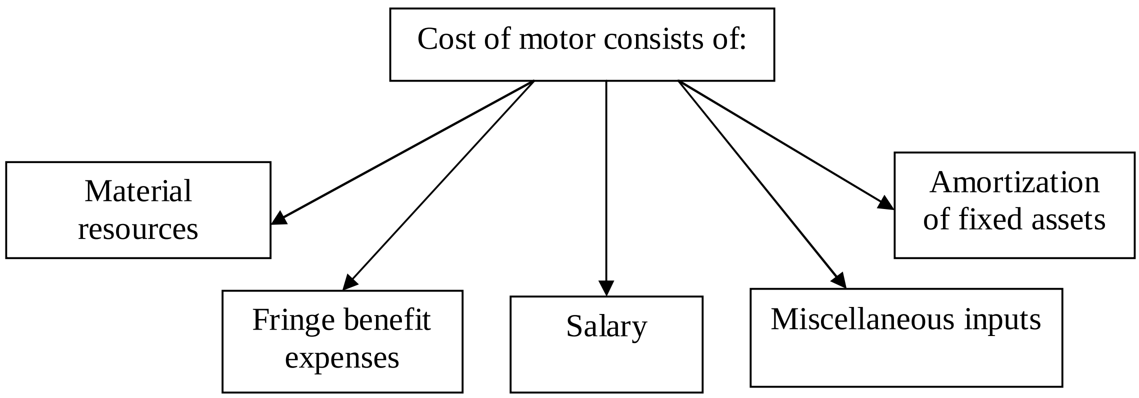

Figure 13. The prime cost affecting on the price of motor.

Material resources reflect *the cost of:*

- Acquisition of raw materials, which are part of the produced product, forming the basis of spare parts;

- The purchase of products and semi-exposed in the future assembly;

- Acquired by the fuel of all types spent on technological objectives;

- All types of energy (electrical, thermal, compressed air, cold, etc.) spent on the needs of the enterprise.

Expenditure on wages - reflect the cost of wages of production staff, including bonuses for employees productive outcomes, incentives and compensation payments.

Allocations for social requirements - reflect the mandatory contributions to the established laws of social insurance, pension funds, the State Fund for Employment and health insurance from the cost of employees to be included in production costs.

Amortization of fixed assets - reflects the amount of depreciation deductions for the full recovery of fixed assets.

In this part will be analyzed the calculations the cost of basic materials for the manufacture of two different electrical machines on the level of prices at the beginning of 2009 in Russia. From the data can be made a preliminary conclusion about the difference cost between an asynchronous – Table 9, and an permanent magnets synchronous machine – Table 10.

Table 9. Cost of basic materials of Asynchronous motor.

N	Name	Price	Amount	Total price
		€/kg	kg	Euro
1	Electrotechnical steel	16,2	45	729
2	Copper	7	20,4	142
3	Isolation	21	0,8	16,8
4	Constructional material	698	14,5	10121
5	Total value			11008

Table 10. Cost of basic materials of Permanent magnet synchronous motor.

N	Name	Price	Amount	Total price
		€/kg	kg	Euro
1	Electrotechnical steel	16,2	39,5	640
2	Copper	7	19	133
3	Isolation	21	0,5	16.8
4	Constructional material	698	14,5	10121
5	Magnet	100	4,6	460
6	Total value			11360

6.4. Comparison of IM and PMSM

Present day asynchronous motors are products of long research and development time, much longer than the corresponding time of permanent magnets motors. One of the advantages of these types of machines is that they have a lower cost, are reliable, can be obtained with different geometric dimensions, have the possibility to work at different speed ranges and have a simple drive system. Most of companies with development of hybrid vehicle have focused on the permanent magnet machines. One of the reasons is that an asynchronous motor is consuming more energy to create the magnetic field than permanent magnet motors. Thus the power factor and efficiency are decreasing.

The magnets are very sensitive to temperature and with increasing the speed of rotation giving the eddy current effect, which cause an increase in temperature, resulting in the lost magnetic properties, the maximum torque and speed of PMSM are limited by the maximum output voltage, complicated drive system, and difficulties in field weakening. In asynchronous motors, the temperature in the winding insulation can not exceed a critical value, otherwise an insulation breakdown will result. During the designing an asynchronous motor the temperature range is a fundamental design target.

After comparison of positive and negative sides of motors in this case, it is more optimal to use the PMSM. Because the PMSM is responsible for all our technical requirements; the much smaller length than asynchronous motor; the large power factor and higher efficiency; and the cost for production not much more expensive as asynchronous motor.

7. DRIVE SYSTEM

Conformity of electrical motor and power inverter in the traction drive system, is main question of reducing the cost of hybrid control unit with the required traction characteristics.

The first step in design of power converters includes choosing the class of power devices, determine the maximum DC link voltage from the energy storage and choosing inverter voltage.

In the frequency regulation of electric motors is a need to regulate the voltages, which is supplied to a machine. The ways to regulate the output voltage in semiconductor converter are divided: amplitude, phase and pulse-width modulation (PWM).

Most of systems of HEV's use the PWM. The main advantages of PWM are: the high speed voltage regulation; high efficiency and small size of a possible smoothing filter. The disadvantages of PWM are remarkable switching losses and extra losses in the electrical machine due to switching harmonics.

Principle of rational choice the power converter taking into account the static analysis of traction motor is obvious. The large electromagnetic torque develops at the current limitation in the machine winding. Therefore, advisable to realize the maximum torque with minimum current supply, that could allow to minimizing at current consumption of machine from the power converter. In the maximum speed of rotation, it is appropriate to use maximize voltage. As a result, the installed capacity of power converter will be minimal.

Should remind, that mode of rotating motors with maximum torque and maximum speed rotation are different. In the first case, the consumption of current is a maximum, but the required voltage is less, because the slip significantly less then critical range. The second - on the contrary, the voltage is maximum, but the required current is not minimized. Area of realize the torque of traction motor, taking into account the current limitation and voltage is showing in Figure 13.

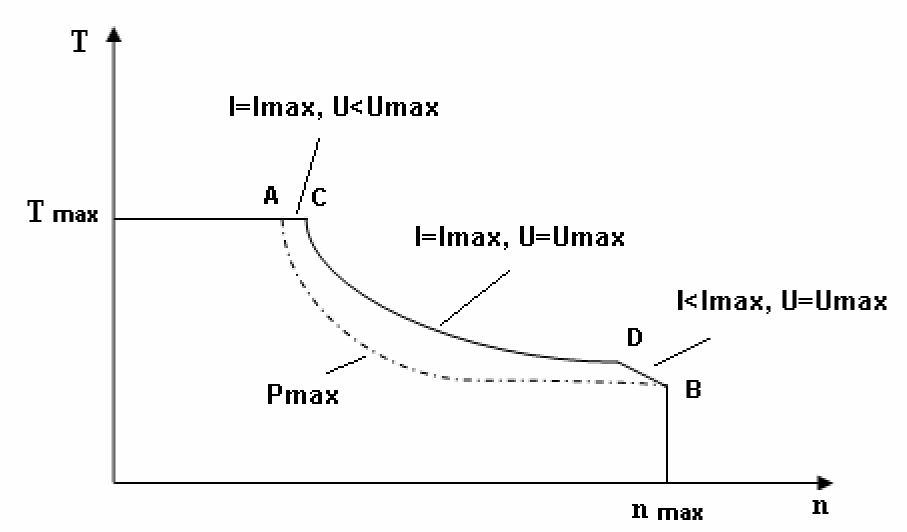

Figure 13. Area of realized torque of a traction motor

The maximum torque T_{max} is realized up to the frequency of rotor rotation, which is showed in the AC-area in the figure. Then, the maximum torque in the maximum speed rotation can be realized by current. In the DB-area of medium speed rotation the output power remains constant as the speed increases.

In pre-project optimization of the geometric dimensions of asynchronous traction motor I did not consider the choice range of voltage and currents. This is due to the fact, that the optimization of motors is typically characterized by a sufficiently large number of pole pairs. This allows the application of sequential/parallel connection of poles windings, making any desired current and voltage motor and adapting with the characteristics of power converter modules. One of the additional points is to increase the number of turns in the winding and connection windings in a star or triangle.

For operation in the system motor – converter, in most cases are using the Flux Current Control or Vector Control. Both options can manage the system. Based from the recommendations and development in the field of electrical motors for HEV, recommending applied by vector control system. This drive system should provide the optimal operating mode in all ranges of frequencies rotation, electromagnetic torque, slip and induction.

7.1. Induction motor control

An asynchronous machine drive includes several components in addition to the machine itself. These include the inverter, controller and associated sensors. Two current sensors give the phase current feedback to the controller, and a speed encoder provides the rotor angular position. The controller processes the sensor feedbacks and controls the inverter for desired operation. The control algorithm can be torque control or speed control. The speed control method allows direct speed control as well as indirect torque control. Here the machine actual speed is compared with the reference speed to generate the reference current, which is compared with the actual current to generate the duty cycles for PWM signals. Figure 14 shows an asynchronous machine drive structure with a vector controller.

There are two general methods of vector control. One is called the direct method, for which air gap flux is measured directly. A flux sensor is necessary for the direct method of vector control. Another method is known as indirect method of vector control; this method eliminates the measurement of air gap flux but requires knowledge of the angular position of the rotor. Therefore, a speed sensor is required to measure the rotor angle. In well developed versions the rotor speed or position are estimated with different algorithms and no extra sensors are needed.

In this method of the indirect method of vector control is used to control the induction machine. Figure 15 explains the indirect control principle with the help of a phase diagram in the rotor flux reference frame.

The electromagnetic coupling between the stator and rotor circuit depends on the rotor position; this coupling can be eliminated by referring stator and rotor equations to a common reference frame [17]. For easier algebraic manipulation and simple graphical interpretations, the three-phase or three-axis variables in an AC machine can be transformed to equivalent two-axis variables: quadrature axis − q and direct axis − d

variables. The superscript ^{s} is used to denote a stationary set of axes while the superscript e denotes electrically rotating axes with the applied voltage. The $d^s - q^s$ axes are fixed on the stator while the $d^e - q^e$ axes rotate at synchronous angular speed ω_e. The angle θ_e is given by the sum of rotor angular position θ_r and slip angular position θ_{sl}, where $\theta_e = \omega_e t$, $\theta_r = \omega_r t$, $\theta_{sl} = \omega_{sl} t$. The rotor flux linkage λ_r consisting of air gap flux linkage and the rotor leakage flux linkage is aligned with the d^e axis. Therefore, for decoupling control, the stator flux linkage component of current i_{ds} and the torque component i_{qs} are to be aligned with the d^e and q^e axes. In the indirect vector control method, slip speed is used to decouple the torque and flux components of stator current as well as to obtain the instantaneous rotor flux position.

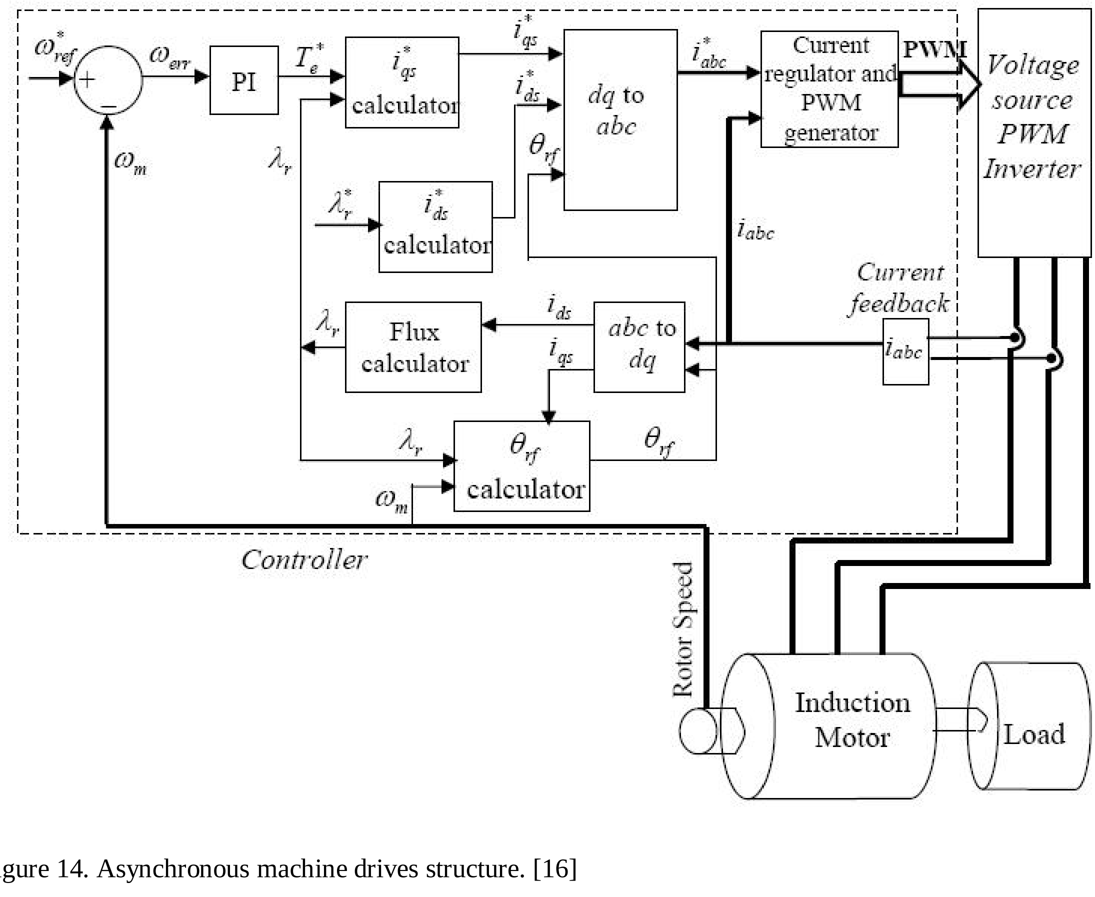

Figure 14. Asynchronous machine drives structure. [16]

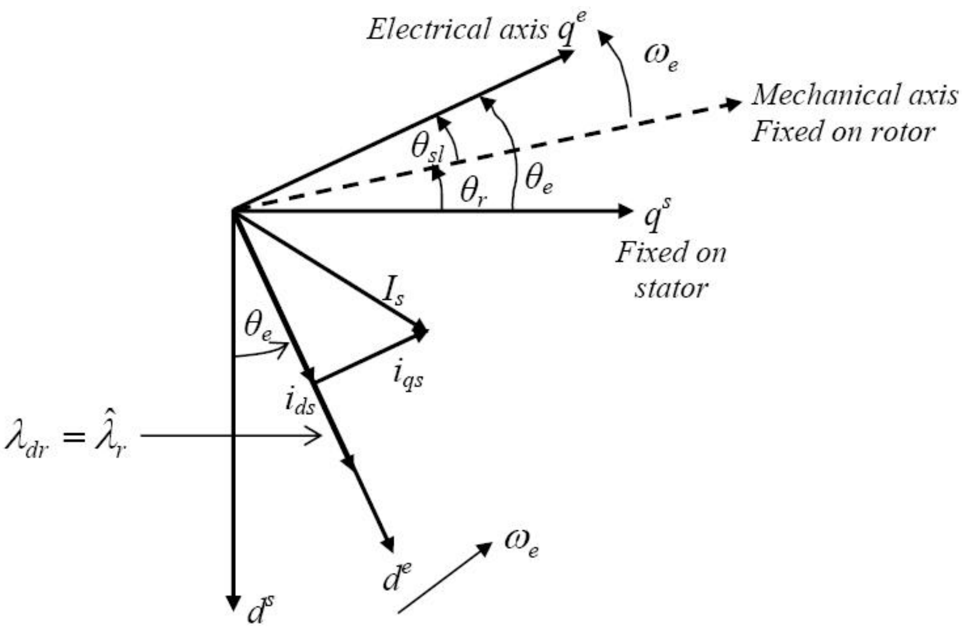

Figure 15. Phasor diagram for indirect vector control in rotor flux reference frame. [16]

7.2. Permanent magnet synchronous motor control.

To be able to coordinate all of the functions in a vehicle, an overall control system is used. This control system is named the hybrid controller (HC). One task of the HC is to control the different torque sources, so that the requested torque from the driver is accomplished. The HC delivers a reference torque and depending on the torque reference, instantaneous vehicle speed and battery voltage the task of the field weakening controller (FWC) is to produce current references for the current controller (CC). The current references are chosen to give an optimal current, optimal in that the torque-per-current ratio is maximized, under the restriction of keeping the stator voltage and current within their limits [17]. By minimizing the torque-per-current ratio, the copper losses are minimized.

The FWC implemented in the control software is based on comprehensive measures of the machine. An algorithm is used to process the data from the measurements. The output from the algorithm is lookup tables that are implementing in the inverter control software. The block diagram for the electrical drive is shown in Figure 16.

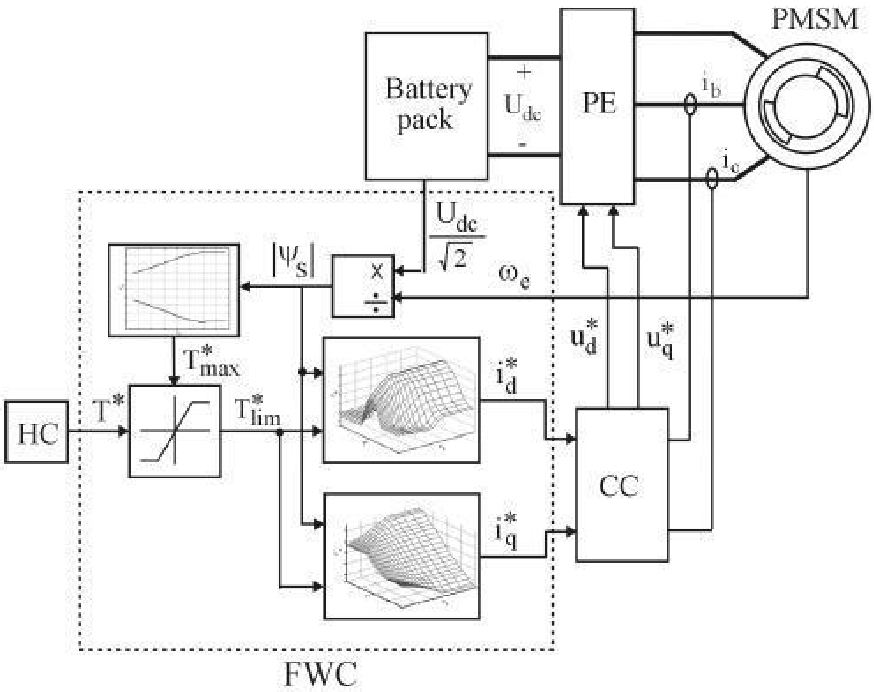

Figure 16. The PM synchronous machine drives structure.

The PMSM will be showed in a synchronously rotating reference frame, linked to the rotor of the machine. One of the axis of the reference frame, denoted the $d-$ axis, is assumed to be aligned with the flux linkage of the rotor [18]. The other axis, referred to as the $q-$ axis, is orthogonal to the $d-$ axis. It was concluded from the low current measurements that the machine is constructed with buried magnets. Since permanent magnets have almost the same permeability as air, the experienced air gap along the $d-$ axis will be wider than along the $q-$ axis. The result from this is that the $q-$ axis inductance, L_q, will be higher than the $d-$ axis inductance, L_d. Apart from the magnetic torque, this salience ($L_q>L_d$) will give rise to a torque called the reluctance torque [19]. The total mechanical torque of the PMSM, T_m, can be expressed as

$$T_m = \frac{p}{2} \cdot \left(\psi_m i_q + (L_d - L_q) \cdot i_d \cdot i_q \right) \tag{7.1}$$

Where, ψ_m is the permanent magnet flux linkage and i_d and i_q are the $d-$ and q axis stator currents. The reluctance torque can be used to reduce the stator current for a given torque, to maximize a torque-per-current ratio.

The stator current a combination that maximizes the torque-per-current ratio can be calculated according to the following equations. [20] Where, i_s - is the stator current, T^*_m − is the reference torque. The currents i^*_d and i^*_q are the d − and q − axis current references. The currents i^*_d and i^*_q are the references sent to the current controller for obtaining the desired reference torque T^*.

$$
\begin{aligned}
&|i_s| = f(T_m{}^*) \\
&i_d^* = \frac{-\psi_m + \sqrt{\psi_m^2 + 8(L_d - L_q)^2 \cdot i_s}}{4 \cdot (L_d - L_q)} \\
&i_q^* = \sqrt{i_s^2 + i_d^2}
\end{aligned}
\tag{7.2}
$$

The maximum torque and speed of the PMSM are limited by the maximum output voltage, U_{smax}, and the maximum output current, I_{smax}, of the inverter and temperature of the machine. The required voltage needed to control the PMSM depends both on the stator current and on the frequency. By assuming steady state and neglecting the influence of the stator resistance the relation between required voltages, current and electrical frequency can be expressed as follows

$$
\begin{aligned}
u_d &= -\omega_e \cdot L_q \cdot i_q \\
u_q &= \omega_e \cdot (\psi_m + L_d \cdot i_d)
\end{aligned}
\tag{7.3}
$$

The PMSM can be operated with constant torque as long as the required voltage does not exceed the maximum output voltage of the inverter. The maximum output of the inverter is determined by the DC-link voltage, U_{dc}, and the type of PWM − modulation. In order to fully utilize the DC-link voltage, modulation with zero sequence injection is used [19]. This will give a maximum output voltage of the inverter equal to $U_{dc/2}$.

If not used the field weakening, the consequence of reaching the voltage limit is that the torque will fall to zero. A more severe consequence might be the current controller becomes unstable. To prevent this and to be able to operate the machine for the extended speed range field weakening must be used. The required stator voltage should be limited to the maximum output voltage of the converter, yielding the following relation

$$(L_q \cdot i_q)^2 + (\psi_m + L_d \cdot i_d)^2 \le \left(\frac{U_{s\max}}{\omega_e}\right)^2 \tag{7.4}$$

Field weakening with constant torque can be accomplished by forcing the *d* axis current. The $d-$ axis current can be seen as a demagnetizing current countervailing the flux from the permanent magnets keeping the stator voltage its limit. The current in the field weakening region is not optimal, maximizes the torque-per-current ratio, but the machine can be operated with constant torque in an extended speed range. By combining equation (7.1) and (7.4) we can see that the current references depend on the reference torque, the maximum output voltage of the inverter and the frequency. This can be writing in the following relations:

$$\begin{aligned} i_d^* &= f_d(T, \omega_e, U_{smax}) \\ i_q^* &= f_q(T, \omega_e, U_{smax}) \end{aligned} \tag{7.5}$$

The current references will not be calculated using equation (7.1) and (7.4), but will be based on the measurements mentioned earlier. This will guarantee that the saturation effects of the stator inductances are included in the control. If the relation in equation (7.5) is used, three dimensional look-up tables have to be implemented in the inverter control software. That can however be avoided by using the relation between stator flux, electrical frequency and maximum output voltage of the inverter. The quantities are related according to

$$|\psi_s| = \frac{U_{smax}}{\omega_e} = \frac{U_{dc}}{\sqrt{2} \cdot \omega_e} \tag{7.6}$$

7.3. Clutch

The clutch is a mechanical device which is using to smoothly engage or disengage the power transmission between a traction motor or ICE and the load. The most common use of a clutch is in the transmission system of a vehicle, where it links the IC engine or traction motor with the rest of the system of the vehicle.

The clutch activated or deactivated, depending on the mode of operation of an internal combustion engine and traction motor. Hybrid controller takes the basic function of management unit and determines when to include the work of IC engine or traction motor operating mode. Four states of working are the IC engine, traction motor, and hybrid (ECI and traction motor) shows in the *Appendix 8* and shows the mode operating of clutches, as well as in *Appendix 9* presented the Configuration of the parallel hybrid with optimal electric drive system and clutches.

• Motor drive (when driving in urban districts)

• Engine drive (when driving in urban districts)

• Engine + Power assist drive

• Regeneration

The clutch in the automotive transmission is an example of a positive clutch. There is a second general type of clutch, which is known as friction clutches, used to bring the rotational speed of one disk another disk. The clutching action can be brought about by electrical, mechanical, pneumatic, or hydraulic action.

8. CONCLUSION

The Thesis is representing the idea of hybrid electrical vehicle, development of this area in the automotive industry, different types of hybrid vehicles with specific design features, electric energy storage system and describing the vector control.

The main aim of researching was to concentrate in the design of a traction motor for a parallel hybrid system. The advantage of the parallel hybrid is that the system needs only one electrical machine which could work both in generator and motor mode, in comparison with the series hybrid, which always needs two electrical machines.

In this parallel system case the traction motor is installed between the mechanical gearbox and the cardan shaft or after the cardan shaft before the final drive. For this case I have chosen the scheme of installing the electrical machine after the cardan shaft before the final drive, with out an electrical machine extra gear box. A gear box should make this system more complicated from the mechanical point of view. This type is giving the possibility to design the electric motor with different lengths, but the diameter of motor is limited by the construction of vehicle.

According to the aim of Thesis I have designed an induction motor and permanent magnet synchronous motor. In both motors have done the valuations parameters of pre-designing from the basic calculation and basis of design: power, speed, active length, torque and number of pole pairs. Then I have chosen the optimal variants of motors for further calculation.

After obtaining the result motors were evaluated by their technical characteristics and dimensions in the parallel system. Both motors are suitable to be use in the parallel hybrid, but after careful consideration decided to favour the permanent magnet synchronous machine. It is better in the following characteristics than induction motor: efficiency, power factor, and the length in 50 % lower than in the induction motor and starting maximum torque closer to our requirement for acceleration during 12 second. Then, I have described the vector control an induction motor and permanent magnet synchronous motor.

The main objectives of this work have been achieved but there is still a huge gap for further researching in the creating system for designing of IM and PMSM for hybrid vehicle, developments of cooling system and winding insulation, creating new generation of Lithium-Ion batteries, development of intellectual hybrid controller etc.

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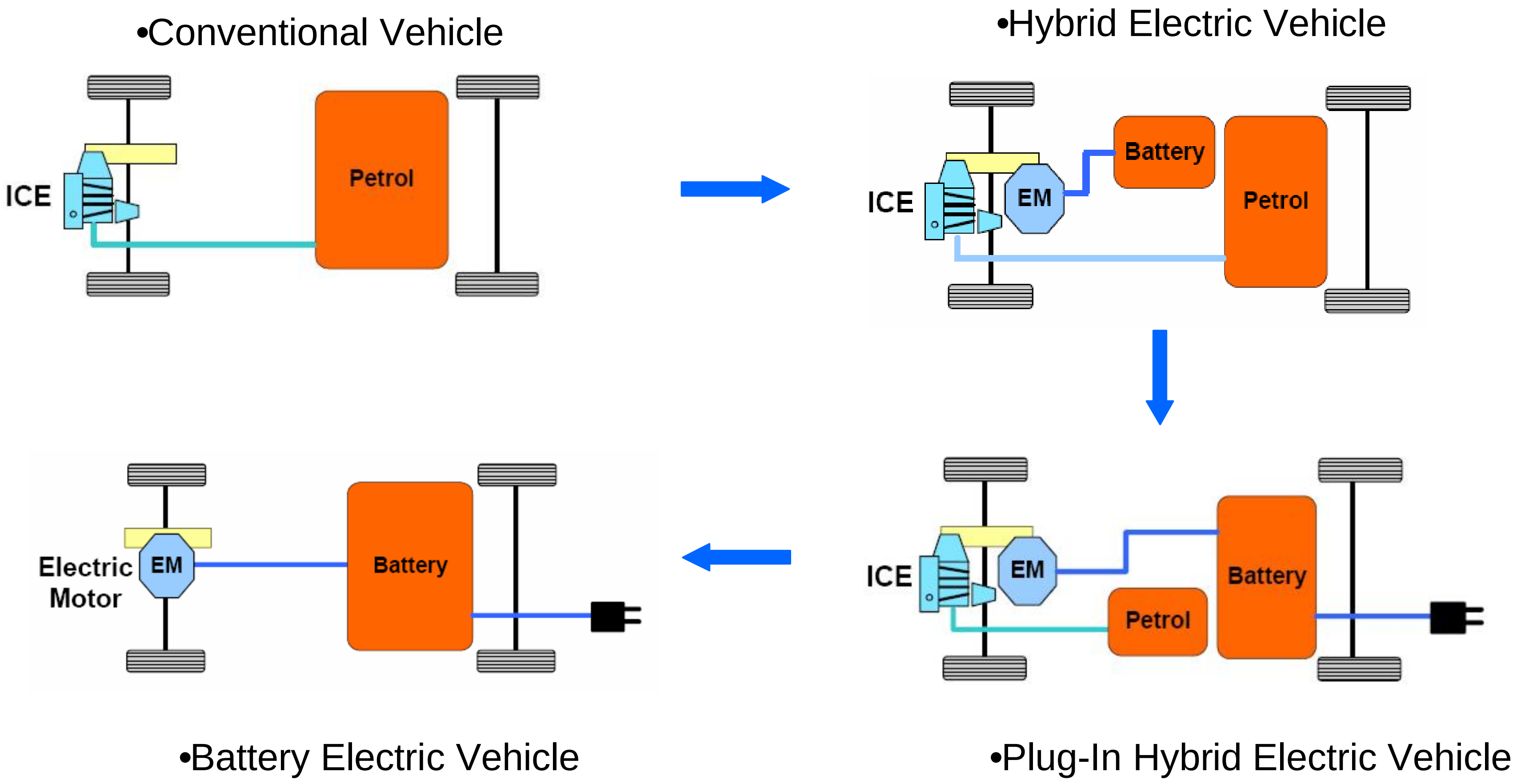
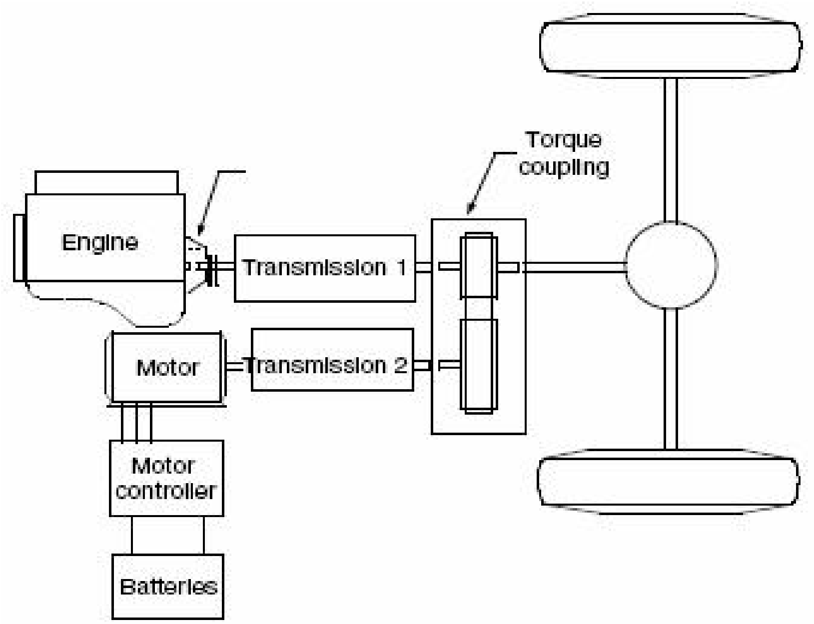
10. APPENDIXES

APPENDIX 1: History of motion from basic vehicle to electrical vehicle

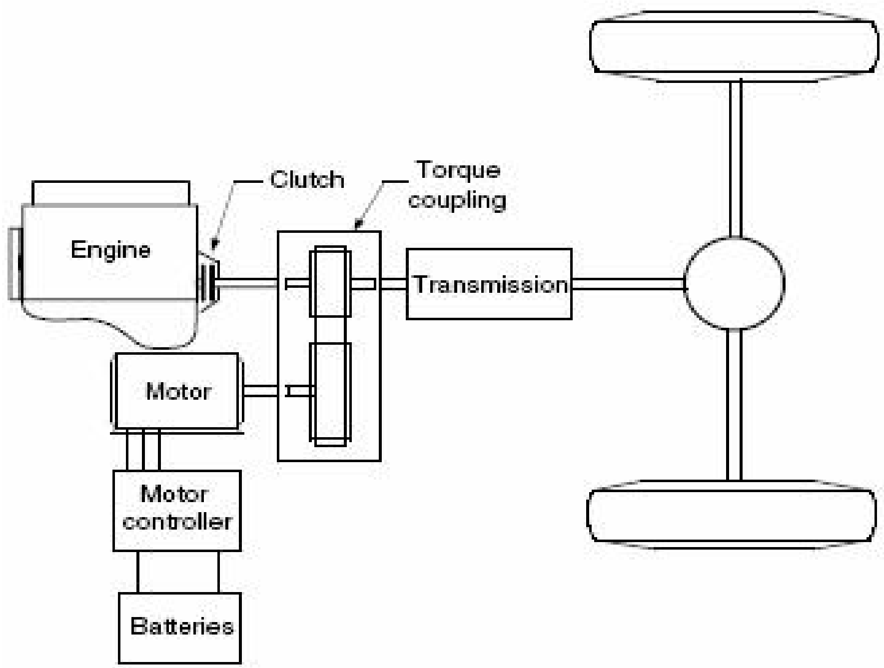


APPENDIX 2: Configurations designing of parallel hybrid vehicle

Two-axel configuration

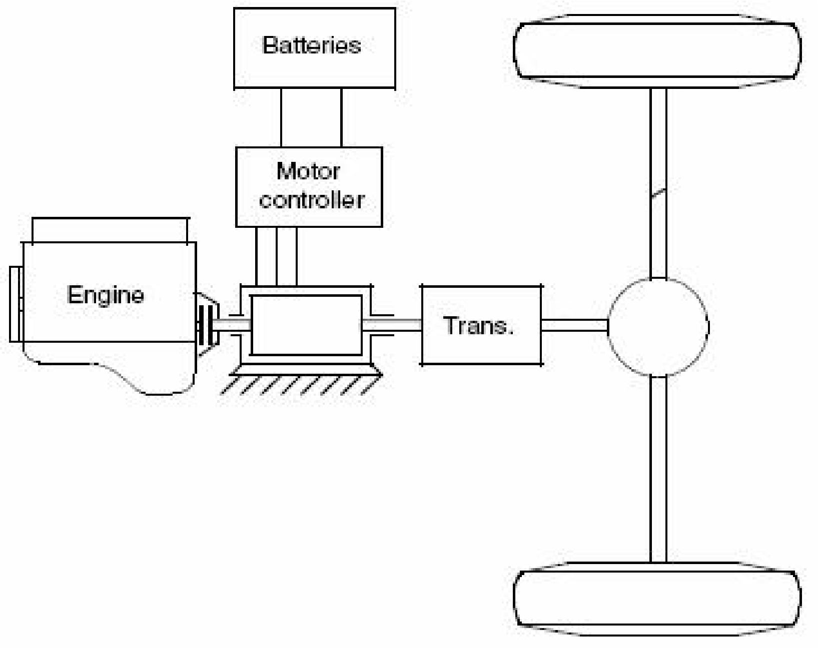


Two-shaft configuration

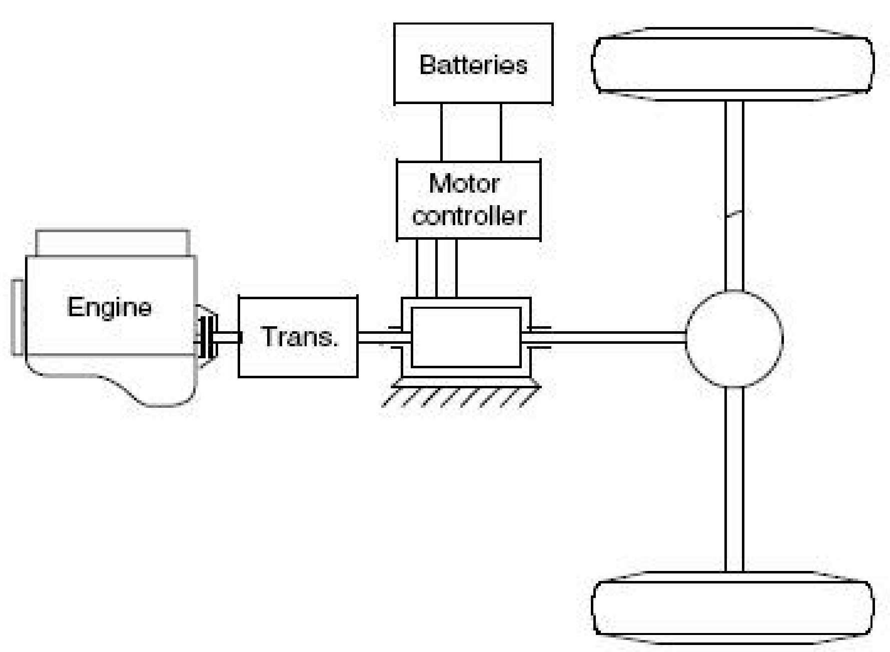


APPENDIX 2: Configurations designing of parallel hybrid vehicle

Pretransmission single-shaft torque



Posttransmission single-shaft torque



APPENDIX 3: The calculation of recuperated power

Times	Linear speed	Value of deceleration	Cardan torque	Angular speed	Recuperated
t [s]	*v* [m/s]	*j* [m/s^2]	*T* [Nm]	*Ω* [s^{-1}]	*P* [W]
0	13,8	1,6	117,14	81,18	9509
0,1	13,64	1,6	118,35	80,24	9496
0,2	13,48	1,6	119,55	79,29	9480
0,3	13,32	1,6	120,74	78,35	9460
0,4	13,16	1,6	121,91	77,41	9437
0,5	13	1,6	123,07	76,47	9411
0,6	12,84	1,6	124,21	75,53	9382
0,7	12,68	1,6	125,34	74,59	9349
0,8	12,52	1,6	126,46	73,65	9313
0,9	12,36	1,6	127,56	72,71	9274
1	12,2	1,6	128,65	71,76	9232
1,1	12,04	1,6	129,72	70,82	9187
1,2	11,88	1,6	130,78	69,88	9139
1,3	11,72	1,6	131,82	68,94	9088
1,4	11,56	1,6	132,85	68,00	9034
1,5	11,4	1,6	133,87	67,06	8977
1,6	11,24	1,6	134,87	66,12	8917
1,7	11,08	1,6	135,86	65,18	8855
1,8	10,92	1,6	136,83	64,24	8789
1,9	10,76	1,6	137,79	63,29	8721
2	10,6	1,6	138,74	62,35	8651
2,1	10,44	1,6	139,67	61,41	8577
2,2	10,28	1,6	140,58	60,47	8501
2,3	10,12	1,6	141,49	59,53	8423
2,4	9,96	1,6	142,38	58,59	8342
2,5	9,8	1,6	143,25	57,65	8258
2,6	9,64	1,6	144,11	56,71	8172
2,7	9,48	1,6	144,96	55,76	8083
2,8	9,32	1,6	145,79	54,82	7993
2,9	9,16	1,6	146,61	53,88	7900
3	9	1,6	147,41	52,94	7804
3,1	8,84	1,6	148,20	52,00	7706
3,2	8,68	1,6	148,98	51,06	7606
3,3	8,52	1,6	149,74	50,12	7504
3,4	8,36	1,6	150,48	49,18	7400
3,5	8,2	1,6	151,22	48,24	7294
3,6	8,04	1,6	151,93	47,29	7186
3,7	7,88	1,6	152,64	46,35	7075
3,8	7,72	1,6	153,33	45,41	6963
3,9	7,56	1,6	154,01	44,47	6849

APPENDIX 3: The calculation of recuperated power

Times	Linear speed	Value of deceleration	Cardan torque	Angular speed	Recuperated
t [s]	*v* [m/s]	*j* [m/s^2]	*T* [Nm]	*Ω* [s^{-1}]	*P* [W]
4	7,4	1,6	154,67	43,53	6733
4,1	7,24	1,6	155,32	42,59	6615
4,2	7,08	1,6	155,95	41,65	6495
4,3	6,92	1,6	156,57	40,71	6373
4,4	6,76	1,6	157,17	39,76	6250
4,5	6,6	1,6	157,77	38,82	6125
4,6	6,44	1,6	158,34	37,88	5998
4,7	6,28	1,6	158,91	36,94	5870
4,8	6,12	1,6	159,45	36,00	5740
4,9	5,96	1,6	159,99	35,06	5609
5	5,8	1,6	160,51	34,12	5476
5,1	5,64	1,6	161,02	33,18	5342
5,2	5,48	1,6	161,51	32,24	5206
5,3	5,32	1,6	161,99	31,29	5069
5,4	5,16	1,6	162,45	30,35	4931
5,5	5	1,6	162,90	29,41	4791
5,6	4,84	1,6	163,33	28,47	4650
5,7	4,68	1,6	163,76	27,53	4508
5,8	4,52	1,6	164,16	26,59	4365
5,9	4,36	1,6	164,56	25,65	4220
6	4,2	1,6	164,94	24,71	4075
6,1	4,04	1,6	165,30	23,76	3928
6,2	3,88	1,6	165,65	22,82	3781
6,3	3,72	1,6	165,99	21,88	3632
6,4	3,56	1,6	166,31	20,94	3483
6,5	3,4	1,6	166,62	20,00	3332
6,6	3,24	1,6	166,91	19,06	3181
6,7	3,08	1,6	167,19	18,12	3029
6,8	2,92	1,6	167,46	17,18	2876
6,9	2,76	1,6	167,71	16,24	2723
7	2,6	1,6	167,94	15,29	2569
7,1	2,44	1,6	168,17	14,35	2414
7,2	2,28	1,6	168,38	13,41	2258
7,3	2,12	1,6	168,57	12,47	2102
7,4	1,96	1,6	168,75	11,53	1946
7,5	1,8	1,6	168,92	10,59	1789
7,6	1,64	1,6	169,07	9,65	1631
7,7	1,48	1,6	169,21	8,71	1473
7,8	1,32	1,6	169,33	7,76	1315
7,9	1,16	1,6	169,44	6,82	1156
8	1	1,6	169,54	5,88	997
8,1	0,84	1,6	169,62	4,94	838
8,2	0,68	1,6	169,69	4,00	679
8,3	0,52	1,6	169,74	3,06	519
8,4	0,36	1,6	169,78	2,12	360
8,5	0,2	1,6	169,80	1,18	200
8,6	0,04	1,6	169,81	0,24	40

APPENDIX 4: Analysis available motors for parallel hybrid vehicle

INDUCTION MACHINE						
P	*n*	*p*	*f*	*l'*	*T*	D_s
kW	rpm		Hz	m	Nm	m
35	1000	4	66	0,84	344,00	0,130
35	1000	6	100	0,78	344,00	0,135
35	1000	8	133	0,75	344,00	0,138
35	1000	10	166	0,73	344,00	0,140
P	*n*	*p*	*f*	*l'*	*T*	D_s
kW	rpm		Hz	m	Nm	m
35	1500	4	100	0,56	227,00	0,130
35	1500	6	150	0,52	227,00	0,135
35	1500	8	200	0,50	227,00	0,137
35	1500	10	250	0,43	227,00	0,139
P	*n*	*p*	*f*	*l'*	*T*	D_s
kW	rpm		Hz	m	Nm	m
45	1000	4	66	1,00	443,00	0,130
45	1000	6	100	1,10	443,00	0,135
45	1000	8	133	0,97	443,00	0,138
45	1000	10	166	0,95	443,00	0,139
P	*n*	*p*	*f*	*l'*	*T*	D_s
kW	rpm		Hz	m	Nm	m
45	1500	4	100	0,73	292,00	0,130
45	1500	6	150	0,68	292,00	0,135
45	1500	8	200	0,65	292,00	0,138
45	1500	10	250	0,64	292,00	0,140
P	*n*	*p*	*f*	*l'*	*T*	D_s
kW	rpm		Hz	m	Nm	m
65	1000	4	66	1,59	639,00	0,130
65	1000	6	100	1,47	639,00	0,135
65	1000	8	133	1,40	639,00	0,137
65	1000	10	166	1,37	639,00	0,140
P	*n*	*p*	*f*	*l'*	*T*	D_s
kW	rpm		Hz	m	Nm	m
65	1500	4	100	1,06	422,00	0,130
65	1500	6	150	0,98	422,00	0,135
65	1500	8	200	0,94	422,00	0,138
65	1500	10	250	0,90	422,00	0,140

APPENDIX 4: Analysis available motors for parallel hybrid vehicle

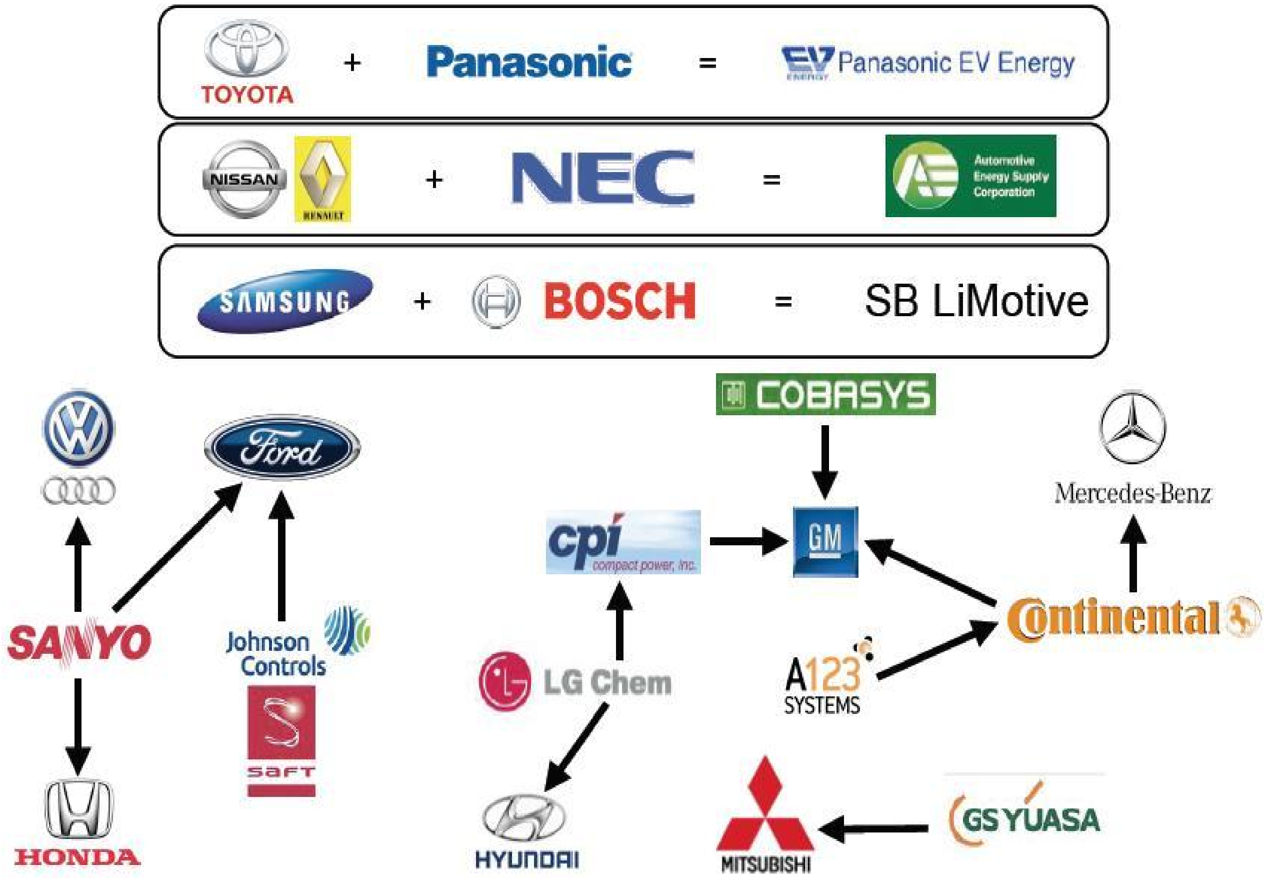
PM SYNHRONOUS MACHINE							
P	*n*	*p*	*f*	*T*	D_r	*l'*	T_m
kW	rpm		Hz	Nm	m	m	Nm
35	1000	4	66	327,00	0,130	0,56	1500,00
35	1000	6	100	327,00	0,134	0,52	1140,00
35	1000	8	133	327,00	0,137	0,50	1121,00
35	1000	10	166	327,00	0,139	0,43	740,00
35	1000	4	66	327,00	0,130	0,28	460,00
35	1000	6	100	327,00	0,134	0,26	463,00
35	1000	8	133	327,00	0,137	0,25	468,00
P	*n*	*p*	*f*	*T*	D_r	*l'*	T_m
kW	rpm		Hz	Nm	m	m	Nm
35	1500	4	100	222,00	0,130	0,56	1200,00
35	1500	6	150	222,00	0,134	0,52	1300,00
35	1500	8	200	222,00	0,137	0,50	677,00
35	1500	10	250	222,00	0,139	0,43	440,00
35	1500	4	100	222,00	0,130	0,28	550,00
35	1500	6	150	222,00	0,135	0,26	534,00

APPENDIX 5: HEV Specefication[1]

Vehicle	Platform	Engine	Motor/Gen[2]	Motor/Gen[3]	Motor/Gen[4]	Battery
		hp/kW	kW[5]	kW[5]	kW[5]	type - voltage
Chevrolet Silverado HEV[6]	Silverado	295/220	n.a./10	none	none	PbA 36
Chevrolet Tahoe HEV[6a]	Tahoe	n.a./n.a	n.a./60	none	n.a./60	NiMH 288
2008 Ford Escape HEV[7]	Escape	133/99	70/n.a	45/n.a	none	NiMH 330
Honda Accord HEV	Accord	253/189	12/21	none	none	NiMH 144
Honda Civic HEV	Civic	110/82	15/15	none	none	NiMH 158
Honda Insight	Dedicated	73/54	10/10	none	none	NiMH 144
Lexus GS450h	GS450	292/218	48[8]/147	n.a./n.a	none	NiMH 288
Lexus RX400h 4WD	RX400	208/155	32[8]/123	n.a./n.a	12[8]/50	NiMH 288
2007 Nissan Altima HEV	Altima	158/118	n.a./105	n.a./n.a	none	NiMH 245
Saturn Aura HEV	Aura	170/127	3/4	none	none	NiMH 36
Saturn VUE HEV	VUE	170/127	3/4	none	none	NiMH 36
Toyota Camry HEV	Camry	148/110	24[8]/105	n.a./n.a	none	Lit-Ion 245
Toyota Highlander HEV 4WD	Highlander	208/155	32[8]/123	n.a./n.a	12[8/]50	Lit-Ion 288
Toyota Prius	Dedicated	76/57	29[8]/50	n.a./n.a	none	Lit-Ion 288

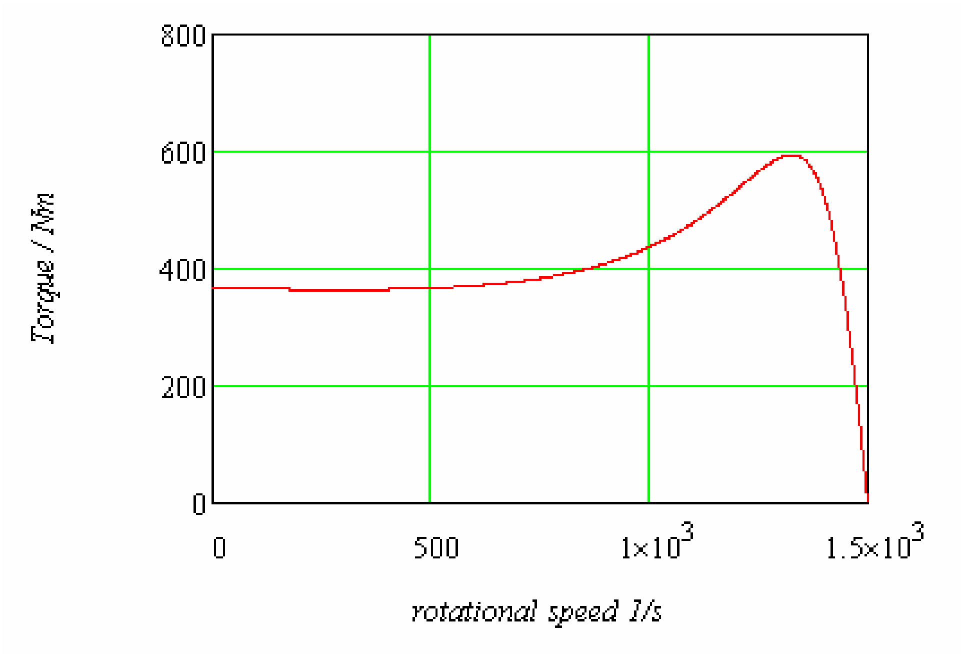
1. Source: manufacturer data, Automotive News, http://www.whybuyhybrid.com/current-hybrid-vehicles.htm
2. Traction motor/generator
3. Power split system sun gear motor/generator
4. Second traction motor/generator
5. Continuous power/peak power
6. Also GMC Sierra HEV
6a. Also GMC Yukon HEV
7. Also Mercury Mariner HEV and Mazda Tribute HEV
8. One hour rated output by Japanese Motor Output Measurement Test Procedure

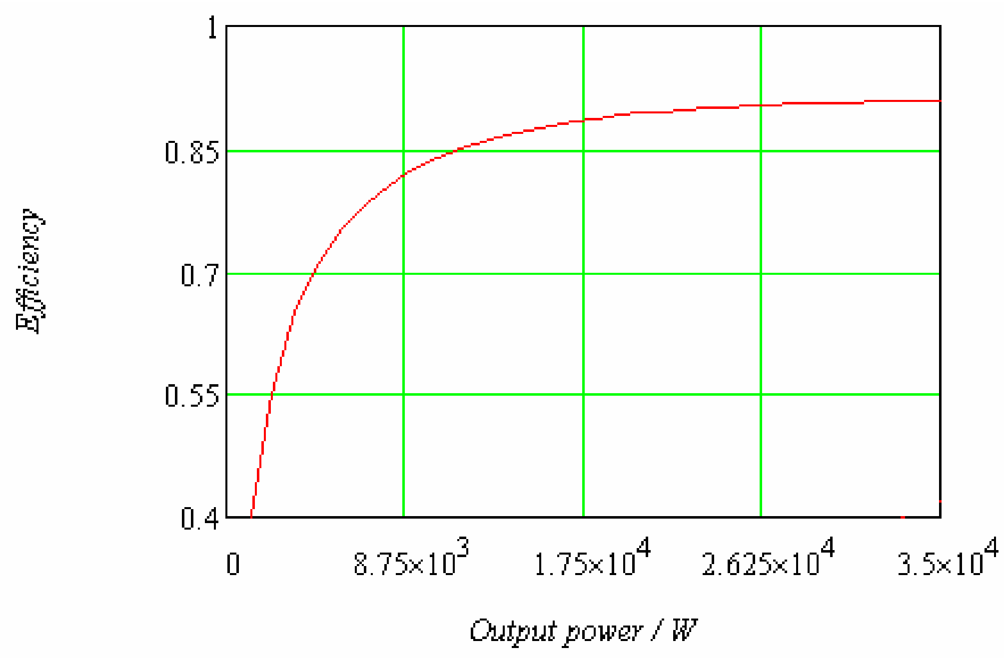
APPENDIX 6: Analysis market for HEV and PHEV

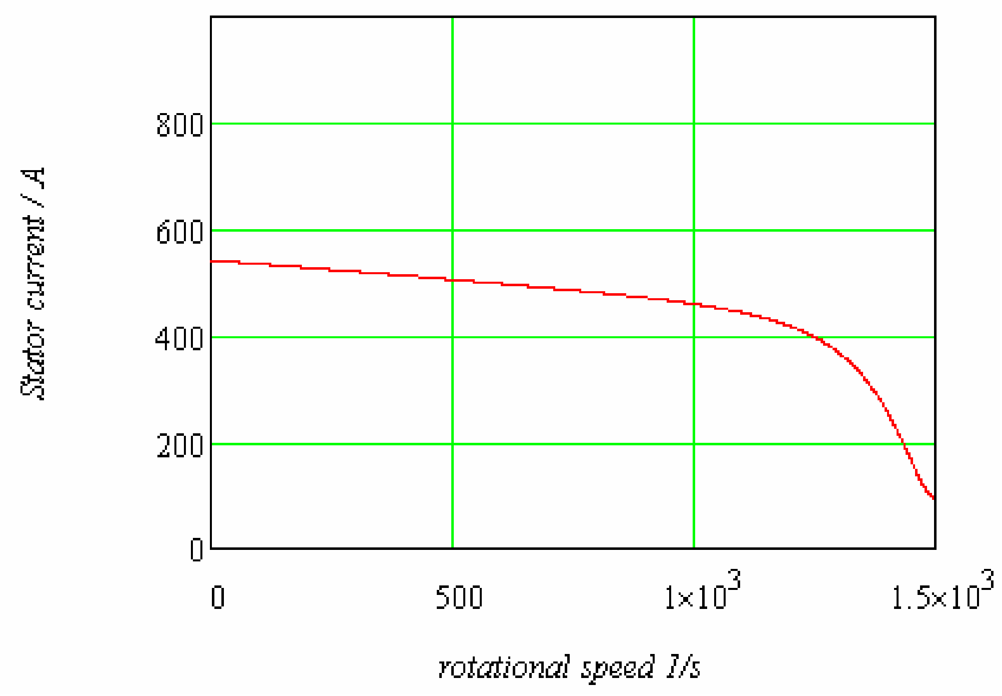


APPENDIX 7: Main characteristics of IM and PMSM

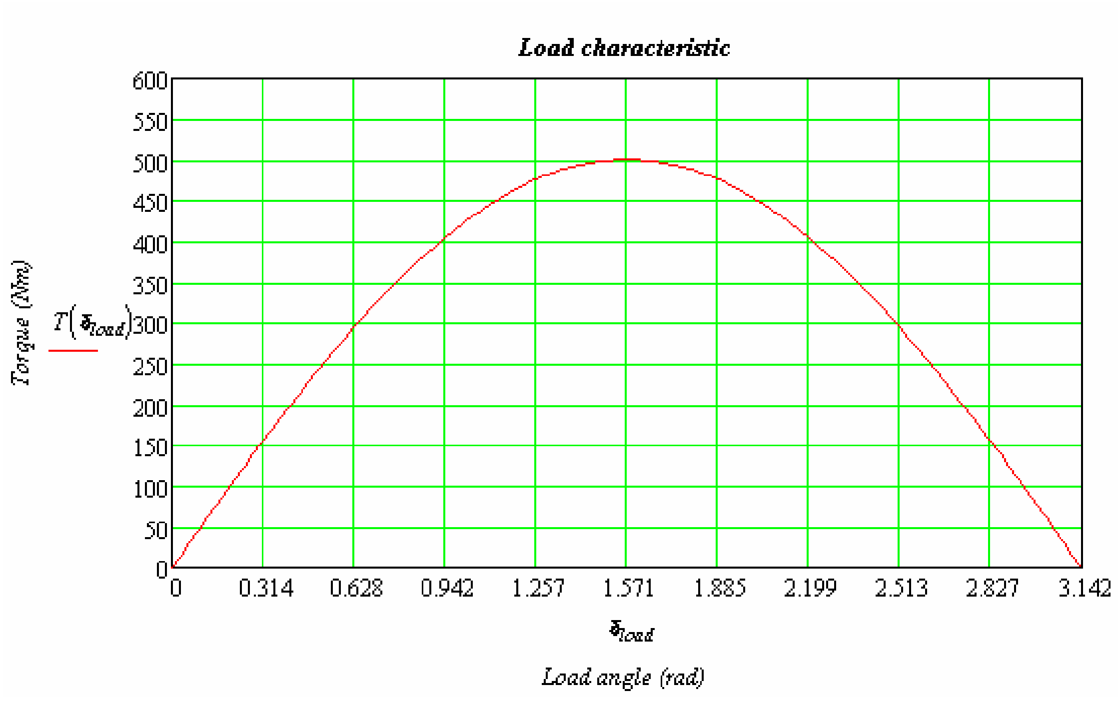
Asynchronous machine







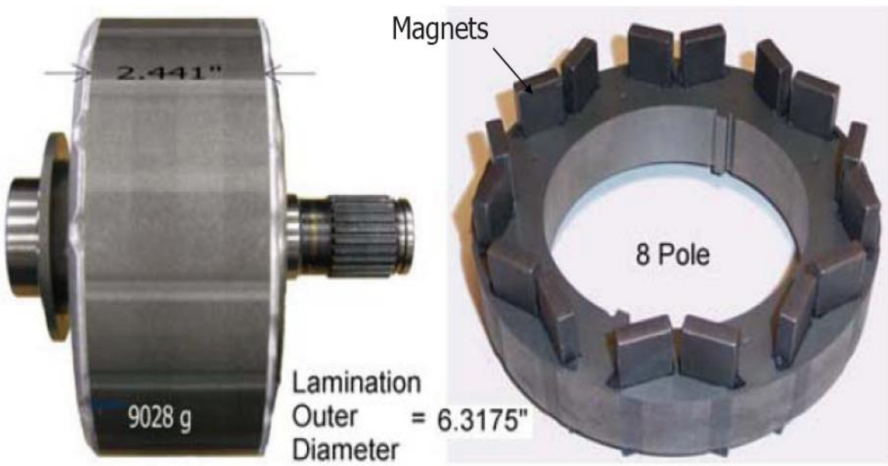
Permanent magnet synchronous machine

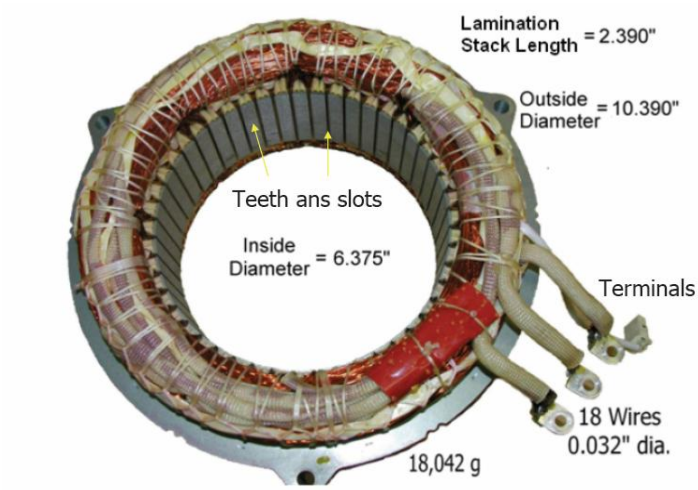


APPENDIX 8: The interior which is using in Toyota Prius, Toyota Camry and Lexus

1. Installation the PMSM in the engine combustion, in Toyota Camry

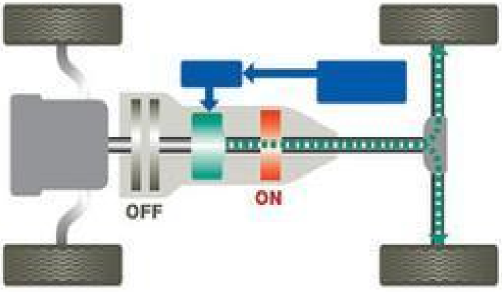
2. Specific design features of using PMSM in the Toyota Prius, Camry and Lexus



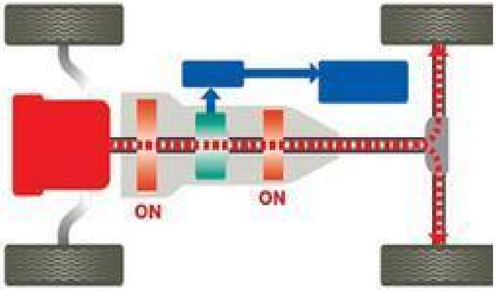


APPENDIX 9: The mode operating of clutches.

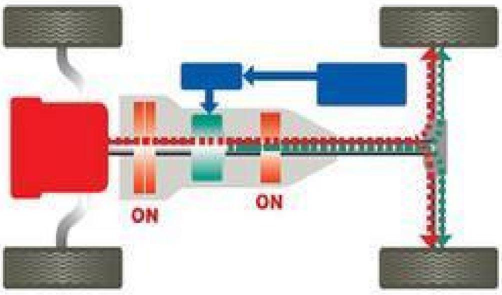
1 Motor drive (when driving in urban districts)



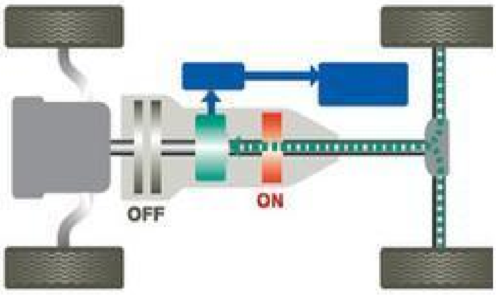
2 Engine drive (when driving in urban districts)



3 Engine + Power assist drive (when accelerating)



4 Regeneration (when decelerating)



APPENDIX 10: Configuration of the parallel hybrid with optimal electrical drive system and clutches.