LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
DEPARTMENT OF ELECTRICAL ENGINEERING

SYSTEM INVESTIGATION FOR HYBRID ELECTRIC VEHICLE

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ABSTRACT

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A hybrid electric vehicle is a fast-growing concept in the field of vehicle industry. Nowadays two global problems make manufactures to develop such systems. These problems are: the growing cost of a fuel and environmental pollution. Also development of controlled electric drive with high control accuracy and reliability allows improving of vehicle drive characteristics.

The objective of this Diploma Thesis is to investigate the possibilities of electrical drive application for new principle of parallel hybrid vehicle system. Electric motor calculations, selection of most suitable control system and other calculations are needed. This work is not final work for such topic. Further investigation with more precise calculations, modeling, measurements and cost calculations are needed to answer the question if such system is efficient.

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ABBRIVIATIONS AND SYMBOLS

Roman letters

S	duty cycle [%]
t	time [s]
T	torque [Nm]
P	power [W]
ω	angular speed (for electrical engineering) [s^{-1}]
Ω	angular speed (for mechanics) [s^{-1}]
n	rotational speed [rpm]
I	current [A]
Q	number of slots
D	diameter [m]
l	length [m]
p	number of pole pairs
N	number of conductors
a	number of parallel branches
q	number of slots per pole and phase
k	coefficient
B, b	flux density [T]
E	back electromotive force [V]
f	frequency [Hz], coefficient of friction
Φ	flux [Vs]
C	machine constant [Ws/m^3]
m	number of phases, mass [kg]
A	linear current density [A/m], cross sectional area [m^3]
h	height [m]

$\cos(j)$	power factor
U	voltage [V]
X	reactance [Ohm]
z	slot width [m]
b	conversion ratio
y	height of the rotor slot [m]
R	resistance [Ohm], radius [m]
J	current density [A/m^2]
r	per unit resistance
s	slip
j	deceleration value
g	acceleration of gravity force [m/s^2]
F	force [N]
u	gear ratio
V	linear speed
L	inductance

Greek letters

t	pole pitch [m], slot pitch [m]
a	angle [rad], temperature coefficient
x	winding factor
c	length ratio
s	tangential stress [Pa], specific conductivity $[\mathrm{m/Ohm \cdot m^2}]$
l	reactance factor, winding leakage permeance factor
d	air gap length [m]
j	angle, friction coefficient

r	density of iron [kg/m^3], air density [kg/m^3]
y	flux linkage [Vs]

Acronyms

ICE	internal combustion engine
AC	alternating current
DC	direct current
ECE	Economic Commission for Europe
EUDC	Extra Urban Driving Cycle
MVEG-A	Motor Vehicles Emissions Group
RPM	revolutions per minute
GTO	Gate Turn-off thyristor
IGBT	Insulated Gate Bipolar Transistor
MOSFET	metal oxide semiconductor field effect transistors
PWM	pulse width modulation
FCC	Flux Current Control
SVC	Sensorless Vector Control
VCU	variable control unit
VDU	variable definition unit
ICU	inverter control unit
IM	induction motor
DSP	digital control processor
ROM	read only memory
CPU	central processing unit

1 INTRODUCTION

1.1 Brief survey of existing hybrid systems

Nowadays a lot of automobile manufactures use a concept of hybrid internal combustion engine (ICE) and electric drive. The main idea of such a system is the employment of an ICE with maximum efficiency which is possible through the employment of an electric machine in the speed range where the efficiency of the ICE is low (especially at low speeds in cities). Such systems allow reducing the fuel consumption in a vehicle. The air pollution and carbon dioxide emission are an urgent problem of today.

There are three different ways in which electric motors and gas/petrol engine can be combined, namely the following:

1. Parallel hybrid system.
2. Series hybrid system.
3. Combined hybrid system.

Let us consider them briefly. A general feature of a parallel hybrid system is a combined work of combustion engine and an electrical motor for providing motive power. They are mechanically coupled through a mechanical transmission. The speed of a combustion engine and an electrical motor is the same because of mechanical coupling. The output torque is equal to the sum of the engine and the motor torques. The electrical drive is used during acceleration and deceleration time. During deceleration mode the braking energy is used for charging a battery bank through a frequency converter. In that way fuel consumption is decreased and energy saving becomes possible.

A series hybrid vehicle resembles full electric vehicles in greater extent than an internal combustion vehicle with a parallel hybrid system. In that type of a hybrid system the combustion engine is needed for setting in motion an electric generator instead of direct transferring of torque to the wheels. The electric generator supplies a battery and an electric motor which setting in motion the vehicle. In dynamic conditions when supplementary energy is needed (for instance during acceleration time) the electric motor gets the energy from both the battery and the generator. To store the braking energy a super capacitor, an accumulator, a flywheel or their combination is utilized. It enables to avoid the losses in the battery. Also, the engine and the wheels are not mechanically coupled and it is a great advantage. The engine runs at a constant speed at its most efficient rate in spite of the car speed changes. It is possible to use one electric motor for each wheel that eliminates the gearbox or other transmission elements. The ICE is stopped at low energy demand instants.

A combined hybrid system has features of both parallel hybrid system and serial hybrid system. There are new important elements such as power-split devices which allow getting power from the engine to wheels both in mechanical and electrical ways. A general peculiarity of this system is that the power supplied by the engine is separated from the power demanded by a driver. In combined hybrid vehicles, a smaller, less flexible and higher efficiency engine is used than in traditional vehicles because the electrical motor delivers its maximum torque at low RPM. It allows cancelling of the engine’s torque deficiency at low speeds.

1.2 Idea of new parallel hybrid system

Hybrid system to be considered in this diploma thesis is some kind of a parallel hybrid system where an existing vehicle is as a starting point. Extremely large changes in the vehicle construction are not attractive, and the electric motor is not connected with the transmission through the gear box of the vehicle. There are two relatively easy places where the electric motor can be installed in this case: To replace the original alternator or to be installed on the cardan shaft with or without gear. With the least modifications the electric drive may be installed on the cardan in this case. The motor is fitted into a cardan shaft directly or indirectly.

The second distinction is the mode of an electric machine work. The electric motor is in work only when a vehicle accelerates from zero to some value of speed and decelerates from some speed to complete stop. The electrical motor produces an additional torque that allows a vehicle to be accelerated faster. During deceleration time the energy is recuperated by the electric motor to a storage system. It makes it possible to reduce the fuel consumption of the internal combustion engine. During non-operative time instants the electric drive should generate the smallest possible losses to the system.

Such system is investigated for a vehicle driving in the urban conditions. It means that frequent acceleration from zero speed and braking to a full stop happen. There are special vehicle driving cycles which take into account the conditions of city traffic. Three different driving cycles are represented in Figure 1.1 [1].

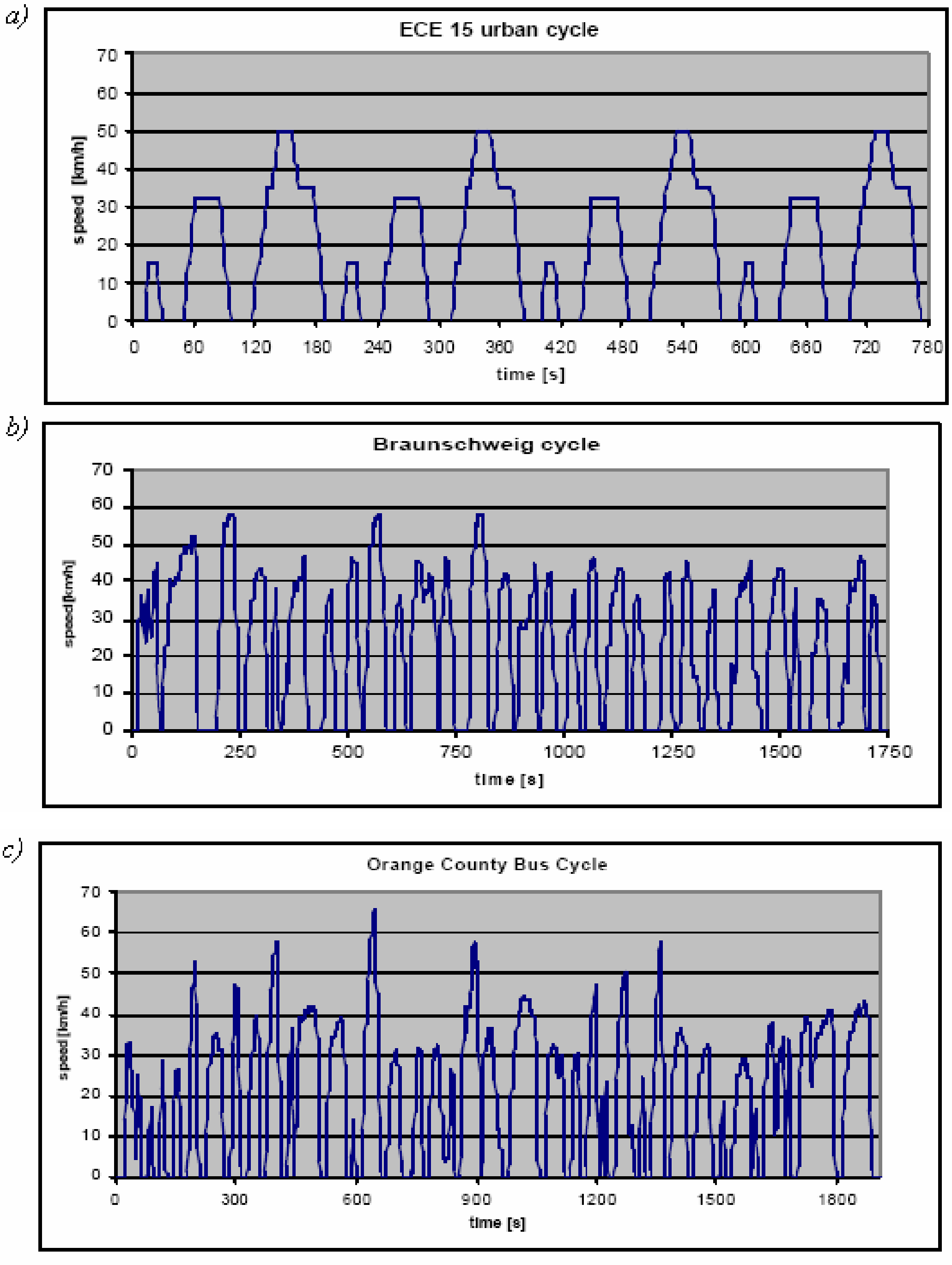


Figure 1.1 The driving cycles: *a)* the ECE15 cycle; *b)* the Braunschweig cycle; *c)* the Orange County cycle.

The Braunschweig cycle and the Orange County cycle are cycles for bus driving in urban conditions. The ECE15 cycle is a cycle for passenger cars. This cycle will be used for the investigation.

1.3 The main parts supposed for the hybrid system.

To achieve commercial acceptance, an electric vehicle system should provide the following features: sufficient control of the electric drive system; regenerative braking; high efficiency; low cost; self-cooling; fault detection and self-protection; self-test and diagnostics capability; safe operation and maintenance; flexible battery charging capability; and auxiliary 12 volt power from the main battery.

One of the important purposes in designing such a hybrid system is making the modification of a vehicle as small as possible. And thereby the idea is to design the system which can be integrated into almost any vehicle without considerable modifications.

The main components of the system to be integrated are:

- Electric machine
- Self-commutated inverter
- Super capacitors
- The basic charging system for the super capacitors using the 12 V DC system of the vehicle
- A controller for controlling of system operating
- Sensors

As an electric machine an induction motor or permanent magnet synchronous motor can be used. Permanent magnet synchronous machines are somewhat more expensive than induction machines because of magnetic material cost. Permanent magnet machines require vector control which makes them a bit more difficult in operation than an induction machine. The problem with permanent magnet machines is that they create iron losses whenever rotated. The maximum torque in correctly designed induction motor and permanent magnet motor is in the same range. Hence, for this system an induction motor will be considered. The rated voltage of the motor should be as low as possible to make system safer and to make the super capacitor selection easier.

The induction motor should be supplied and controlled by a self-commutated inverter. The inverter is supplied by DC voltage through the energy storage system. The energy storage system consists of set of super capacitors. The super capacitors have some advantages in comparison with a battery. They do not require a full-charge detection circuit. Super capacitors have a low internal resistance and inductance and hence they can be charged in seconds. Also they have a very high value of capacitance. For its high power it is possible to improve the power of the system.

For charging the super capacitors storage system through standard 12V DC system of a vehicle a DC/DC converter is needed. The function of a controller is a controlling of a self-commutated inverter and integrated hybrid system. The controller should be sufficient for realization of drive control.

2 SELECTION OF THE SUITABLE MOTOR

2.1 Criteria for the motor selection

The main idea of the parallel hybrid system is increasing the energy efficiency with minimal modifications of the car. The hybrid system may improve the energy efficiency most in urban traffic where the speeds are low and accelerations and decelerations take place very often. If we consider 50 – 60 km/h the most important cruising speed of an urban vehicle the electric auxiliary drive should be adapted to this maximum speed. At higher speeds the benefits brought by the electric auxiliary system in a parallel hybrid system get smaller and smaller. In a series hybrid the situation is different. There the dimensioning of the internal combustion engine may be changed so that it can run at its best efficiency all the time when used and the electric drive is utilized for all power transients.

In this case we, however, are talking about a simple parallel hybrid system where the basic construction of the vehicle is left unchanged. It means that the electric motor should be small but still produce a torque per motor volume as large as possible. It is the first criterion for designing of the motor. The second criterion is a high reliability in a difficult environment. The efficiency of the motor is somewhat less important. The dimensions of the motor should be small to fit the present construction. To avoid any gears and to save space the motor will be installed onto the cardan shaft.

An induction machine runs with very low losses when non-excited and hence it is more suitable for such conditions than e.g. a permanent magnet motor that generates some losses always whenever rotated and which also creates large voltages at the highest operating speeds of the vehicle. If the induction machine drive is designed for the maximum speed of 60 km/h it may easily rotate on the cardan without causing difficulties also when the speed of the car is increased to highway cruising speeds. Of course the mechanical stability has to be ensured by suitable mechanical couplings on the cardan but electrically we have e.g. no problems of high voltages of the induction machine. The losses of a non-magnetized induction machine are low. So an induction machine is more suitable for such conditions.

2.2 Electrical machine utilization

For the hybrid system to be developed the motor is in work during very short periods. It results from the ECE 15 urban cycle for street traffic. Let us consider this cycle and MVEG-A cycle which consists of ECE cycles and an EUDC cycle. MVEG-A cycle is developed for light duty vehicles in Europe. This cycle includes four ECE cycles followed by one EUDC cycle. One part of the ECE cycle is represented in Figure 2.1 [2].

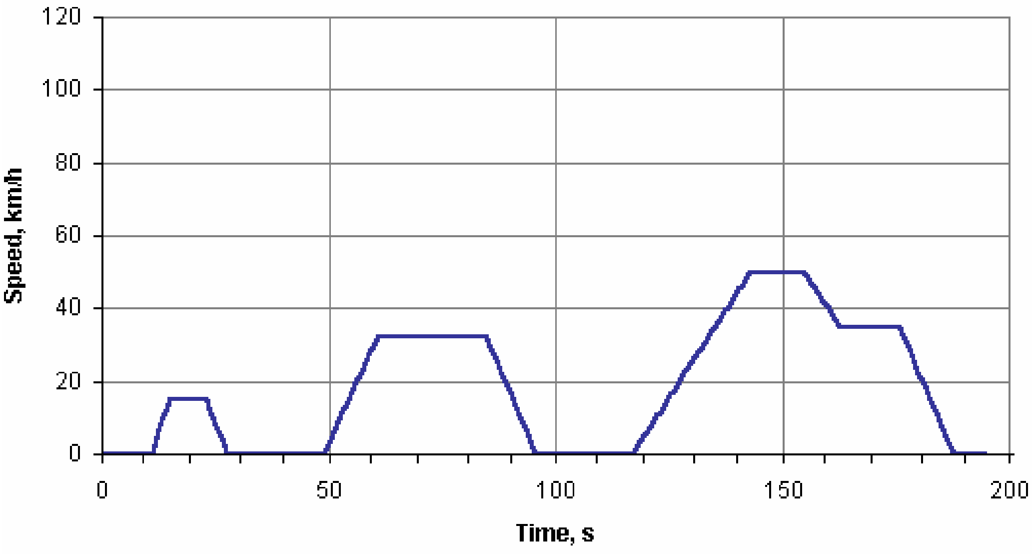


Figure 2.1. The ECE cycle segment.

The EUDC cycle segment is added after the fourth ECE segment to take into account more aggressive high speed driving mode. This segment is shown in Figure 2.2 [2]. The MVEG-A cycle can be used to define the ratio of acceleration/deceleration time and full driving time.

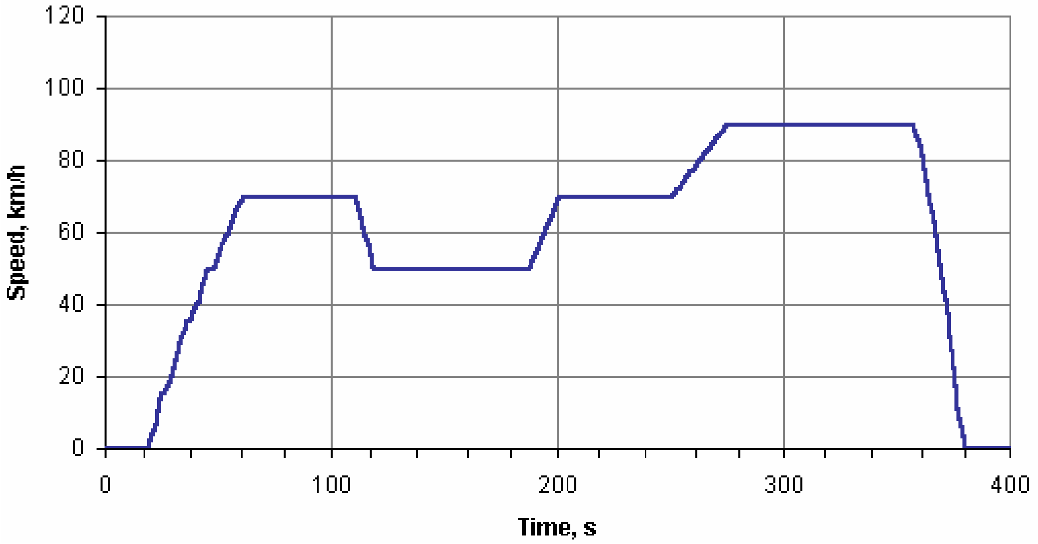


Figure 2.2. The EUDC cycle.

When we see the Fig. 2.2 acceleration from 0 to 50 km/h takes 27 s and braking from 50 to 0 km/h takes 17 s. But it is known also that modern vehicle can accelerate during 10 s from 0 to 50 km/h. Thereby we should take into account this possibility of vehicle because the force which is needed (that means the torque which is needed) depends on the vehicle acceleration. So a motor for hybrid vehicle have to produce such dynamic torque in compliance with vehicle acceleration possibilities.

Let us calculate MVEG-A cycle which consists of four ECE cycles and one EUDC cycle. The duration of acceleration and deceleration time of the ECE cycle is equal 344 s, the sum of acceleration and deceleration time of the EUDC cycle is 32 s. Full time of the MVEG-A cycle is 600 s. Thereby the ratio of acceleration/deceleration time and full time is equal:

$$S = \frac{t_{\mathrm{ECE\,ad}} + t_{\mathrm{EUDC\,ad}}}{t} \times 100\% = \frac{344 + 32}{1400} \times 100\% = 26.8\%, \tag{2.1}$$

where $t_{\mathrm{ECE\,ad}}$ is the sum of ECE acceleration and deceleration time; $t_{\mathrm{EUDC\,ad}}$ is the sum of EUDC acceleration and deceleration time; t is the total time of MVEG-A cycle.

2.3 Rated motor parameters

In this thesis we will assume that the car accelerates from 0 up to 50 km\h in 10 s, drives with speed *v* equal 50 km\h and then decelerate from 50 to 0 km\h in 10 s. And the motor is in work during acceleration and deceleration time only.

Let us define the torque which is needed for acceleration of the vehicle from 0 to 50 km/h in 10 s. 50 km/h is equal 13.89 m/s. Then the acceleration is:

$$a = \frac{v}{t} = \frac{13.89}{10} = 1.389 \text{ [m/s}^2\text{]}, \tag{2.2}$$

where v is a linear speed of the vehicle; t is an acceleration time.

Thereby the force which should acting on the vehicle is:

$$F = m \cdot a = 3000 \cdot 1.389 = 4167 \text{ [N]}, \tag{2.3}$$

where m is a mass of the vehicle.

The wheel torque is equal:

$$T_{\mathrm{w}} = F \cdot r_{\mathrm{w}} = 4167 \cdot 0.325 = 1354\ \text{[Nm]}, \tag{2.4}$$

where r_{w} is the radius of the vehicle wheels.

And the cardan torque taking into account transmission ratio 17/27 will be equal:

$$T_{\mathrm{c}} = \frac{17}{27} \cdot T_{\mathrm{w}} = \frac{17}{27} \cdot 1354 = 852\ \text{[Nm]}. \tag{2.5}$$

100 kg of additional load increases fuel consumption by 0.5 l per 100 km [19]. The average fuel consumption in urban conditions is 10 l/100 km. And the additional fuel consumption is equal 5%. Let us assume the combustion engine torque 300 Nm in average. If 20 % of the torque is replaced during accelerations by an electric motor it will allow decreasing of fuel consumption by 15% in average [20]. But according to the duty cycle calculated above additional torque by electric motor is acting only during acceleration time that is 13.4% of full driving time. So the full fuel consumption will be decreased only by about 2%. And the minimum additional torque should be about 50% of the combustion engine torque. Of cause it depends on the weight of the embedded system for hybrid electric drive.

Industrial induction motors for continuous duty (S1) with suitably small dimensions have too small a rated torque. The totally enclosed motors have usually also a very large finned cooling surface which makes the diameter large. Also as a rule the supply voltage is 400 V AC. In this case there is a need to use a motor with a low voltage to keep the system safe. In this work the Danaher motion motor TSP112/4-150-T is studied as a base motor. The motor parameters are represented in Table 2.1.

The rated torque of machine is:

$$T_{\mathrm{r}} = \frac{P}{W}, \tag{2.6}$$

where W is the rated speed of the motor and equal $\frac{\pi n}{30} = \frac{3.14 \cdot 2300}{30} = 240.3\ \mathrm{s}^{-1}$.

Now the rated torque is equal:

$$T_{\mathrm{r}} = \frac{P}{W} = \frac{10000}{240.3} = 41.3\ \mathrm{Nm}. \tag{2.7}$$

Table 2.1. Motor parameters.

Name of parameter	Value
Rated power P, kW	10
Rated voltage U, V	34
Rated speed n, rpm	2300
Rated current I, A	241
Duty ratio S3, %	15
Number of stator slots Q_{S}	36
Number of rotor slots Q_{r}	46
Air gap diameter D_{δ}, m	0,1101
Rotor diameter D_{r}, m	0,1096
Outer diameter D_{out}, m	0,204
Rotor length l_{r}, m	0,15
Number of pole pairs, p	2

As we see the motor can deliver 41,3 Nm continuously and for the acceleration 852 Nm is needed. As the electric motor studied may produce 1.6 – 2 times its rated torque for a short period of time we see that one tenth of the torque needed may be got from the electric motor without a gear. Gearing also causes problems as the speed of the electric motor may increase too large. Anyway a gear ratio of 1:4 might be used safely. At the top speed the vehicle travels 150 km/h which gives about 2000 rpm for the cardan. A gear ratio of 1:4 should give 8000 rpm for the electric motor which is a tolerable reading. Hence, about 41.3 Nm · 1.6 · 4 = 330 Nm could be exerted on the cardan by the studied motor equipped with a 1:4 gear.

If we allow 27 s for the acceleration from 0 to 50 km/h the acceleration torque needed on the cardan is 852 Nm/(27 s/10 s) = 316 Nm. As we see, now the motor studied is, with a gear, capable of delivering the torque needed for the acceleration.

3 DECELERATION ENERGY OF A VEHICLE

3.1 Forces acting upon a vehicle

The letter j is set for value of deceleration of a vehicle. This value for the deceleration mode on a horizontal good road when the braking force of a vehicle is used in maximum and forces of windage are neglected can be calculated through the equation [3]:

$$j = j \cdot g, \tag{3.1}$$

where j is friction coefficient for wheels and road; g is the acceleration of gravity force. From the equation above it can be assumed that the deceleration is a constant value depending only on the friction coefficient.

Brake systems of modern vehicles are 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 electrical motor will not be capable of achieving such a deceleration. The most common mode of deceleration is the mode when the deceleration value does not exceed 1.5 – 5 m/s^2. In common safe braking is applied. Deceleration during safe brake application is about 1-1.5 m/s^2 [3].

During vehicle motion the forces acting on the vehicle are: resistance force of rolling motion, windage force, force of inertia and driving force of a combustion engine. When a vehicle starts decelerating the engine force is not acting but the force of brake system and windage are acting on the vehicle.

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

$$T_{\mathrm{d}} = R \cdot (F_{\mathrm{i}} - F_{\mathrm{f}} - F_{\mathrm{air}} - F_{\mathrm{bs}}), \tag{3.2}$$

where F_{air} - the windage force; F_{i} - the force of vehicle inertia; F_{f} - the resistance force of rolling motion; F_{bs} - the force of brake system and R is the wheel radius. The force of the vehicle inertia is equal [4]:

$$F_{\mathrm{i}} = m \cdot j \cdot s_{\mathrm{rev}}, \tag{3.3}$$

where s_{rev} - the coefficient taking into account rotating parts of a vehicle; it can be found from the equation: $s_{\mathrm{rev}} = 1.05 + 0.05 \cdot u_{\mathrm{g}}^2$; u_{g} - gear ratio [4].

Assume the car decelerates when the combustion engine in uncoupled so the gear ratio is not taken into account. The resistance force of rolling motion is equal [4]:

$$F_{\mathrm{f}} = f \cdot m \cdot g \cdot \cos a, \tag{3.4}$$

where f is the coefficient of rolling friction; the average value of the friction coefficient for good quality road with asphalt or concrete pavement and 50 km/h vehicle speed is 0.014; a is the angle a road slope; it is assumed that the angle is equal to zero.

The windage force can be found through the empirical formula [4]:

$$F_{\mathrm{air}} = C_{\mathrm{x}} \cdot A \cdot r \cdot \frac{v^2}{2}, \tag{3.5}$$

where C_x is a coefficient of air resistance (coefficient of streamlining); s is a frontal area of a vehicle; r is an air density and is equal 1.29 [kg/m^3] in normal conditions; v is a speed of a vehicle.

The coefficient of air resistance for a modern vehicle varies from 0.17 of Toyota Prius to 0.28 – 0.3 [5]. The frontal area of the vehicle is defined as a carbody plane projection which is perpendicular to a longitudinal axis.

The force of the brake system can be found through an empirical equation which defines relative deceleration force of the vehicle [12]:

$$g = \frac{4 \cdot F_{bs}}{m_v \cdot g} = 0.59, \tag{3.6}$$

where g is a constant value taking into account demands making for sage braking of a vehicle; F_{bs} is the force of the braking system; m_v is the mass of the vehicle. The relative deceleration force must not be less than 0.59 for passenger vehicle and 0.51 for trucks [13]. Thereby the force of the braking system is equal:

$$F_{bs} = \frac{0.59mg}{4} = \frac{0.59 \cdot 3000 \cdot 9.8}{4} = 3894 \text{ N}. \tag{3.7}$$

3.2 Cardan torque and deceleration energy

Now we have the equation for definition of the wheels shaft torque:

$$T_{\mathrm{d}} = R \cdot (m \cdot j \cdot s_{\mathrm{rev}} - f \cdot m \cdot g \cdot \cos a - C_{\mathrm{x}} \cdot s \cdot r \cdot \frac{v^2}{2} - F_{\mathrm{bs}}) \,. \tag{3.8}$$

To calculate the torque acting on the cardan of the vehicle during deceleration time the transmission ration of the cardan must be taken into account. The ratio is equal to 17/27. Thereby the torque acting on the cardan is:

$$T_{\mathrm{c}} = R \cdot (m \cdot j \cdot s_{\mathrm{rev}} - f \cdot m \cdot g \cdot \cos a - C_{\mathrm{x}} \cdot s \cdot r \cdot \frac{v^2}{2} - F_{\mathrm{bs}}) \cdot \frac{17}{27} \,. \tag{3.9}$$

And the power which can be recuperated by the electric motor can be found through the equation:

$$P_{\mathrm{r}} = T_{\mathrm{c}} \cdot W_{\mathrm{c}} \,, \tag{3.10}$$

where W_{c} is the angular speed of the cardan of a vehicle.

The angular speed of the cardan is changing during deceleration time. Assume the deceleration starts at 50 km/h. The deceleration time is 10 s. Then the value of the vehicle deceleration is equal to 1.6 m/s.

Alteration of the power which can be recuperated to the storage system during deceleration of a vehicle is represented in the Appendix A. The maximum power at speed 50 km/h is equal 6.227 kW.

4 STORAGE SYSTEM

The storage system for energy saving can be designed by battery or supercapacitors implementation. The supercapacitors have some advantages in comparison with the battery system. These advantages are: high level of charge and discharge currents (about 200 A or more), supercapacitors have no toxic electrolytic fluid, the supercapacitors can be charged during a very short time and they tolerate a high amount of charge and discharge cycles. The main disadvantage for our application is dimensions. The dimensions of a supercapacitor module which can save the same energy as the battery are remarkably larger.

To select the most suitable supercapacitor module it is needed to determine the next parameters: operating voltage levels (maximum and minimum levels), discharge time and power or current level.

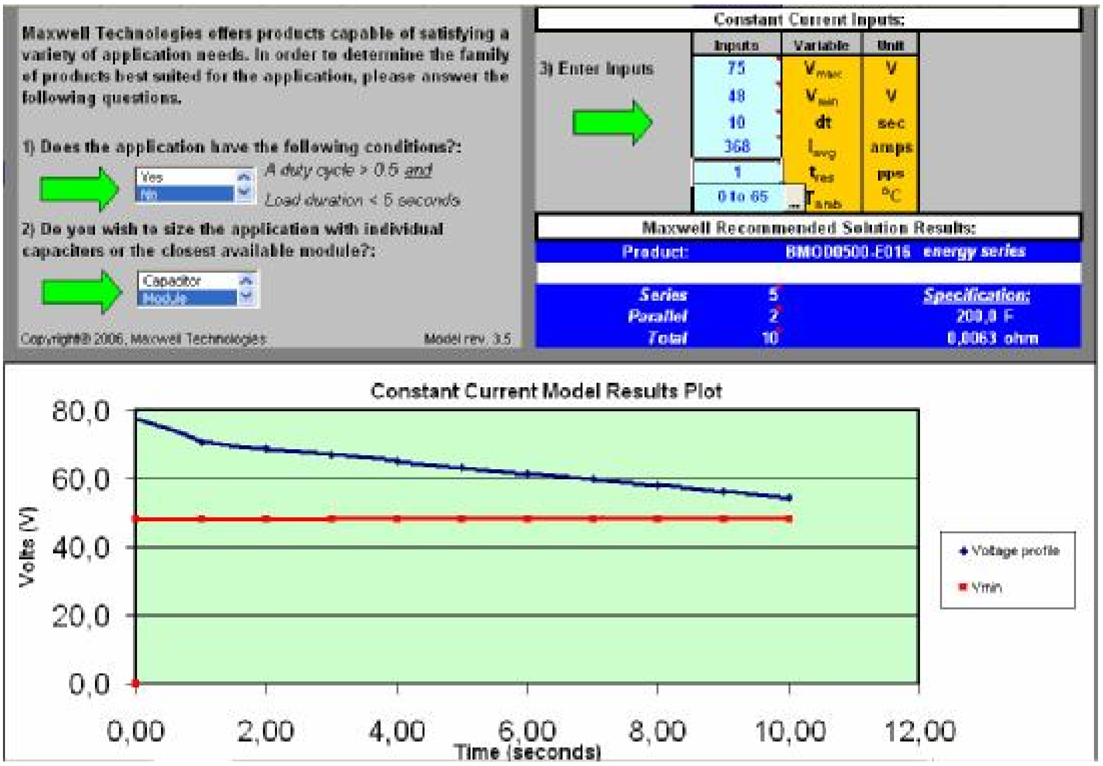
The maximum operating voltage level is 80 V and the minimum operating voltage level is 48 V. It will be shown below that the typical DC link voltage for the selected converter module is from 48 V up to 110 V.

The capacitance of the supercapacitor module must be capable of storing the vehicle kinetic energy with the voltage range of 48 V to 80 V. If we have a 3000 kg vehicle Braking from 50 km/h to zero the energy stored is 290 kJ and the capacitance needed will be

$$C = \frac{2W_{\mathrm{kin}}}{U_{\mathrm{do.1}}^2 - U_{\mathrm{do.2}}^2} = \frac{2 \cdot 290\mathrm{kJ}}{\left(80^2 - 48^2\right)} \approx 140\ \mathrm{F} \tag{4.1}$$

where $U_{\mathrm{do.1}}$ - maximum operating voltage; $U_{\mathrm{do.2}}$ - minimum admissible operating voltage.

There is also a special tool for definition of most suitable supercapacitor modules on the MAXWELL website. Below in Figure 4.1 this tool is shown.



Maxwell Technologies offers products capable of satisfying a variety of application needs. In order to determine the family of products best suited for the application, please answer the following questions.

1) Does the application have the following conditions?:

A duty cycle > 0.5 and
Load duration < 5 seconds

Yes [✓ No]

2) Do you wish to size the application with individual capacitors or the closest available module?:

Capacitor [✓ Module]

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Constant Current Inputs:

3) Enter Inputs

Inputs	Variable	Unit
75	V_{max}	V
48	V_{min}	V
10	dt	sec
368	I_{avg}	amps
1	t_{res}	pps
0 to 65	T_{amb}	°C

Maxwell Recommended Solution Results:

Product:	BMOD0500-E016	*energy series*
Series	5	*Specification:*
Parallel	2	200,0 F
Total	10	0,0063 ohm

Figure 4.1 Maxwell tool for supercapacitor module selection

The electric drive is a constant torque source and it discharges the capacitor about according to the discharge curve which is represented in Figure 4.2.

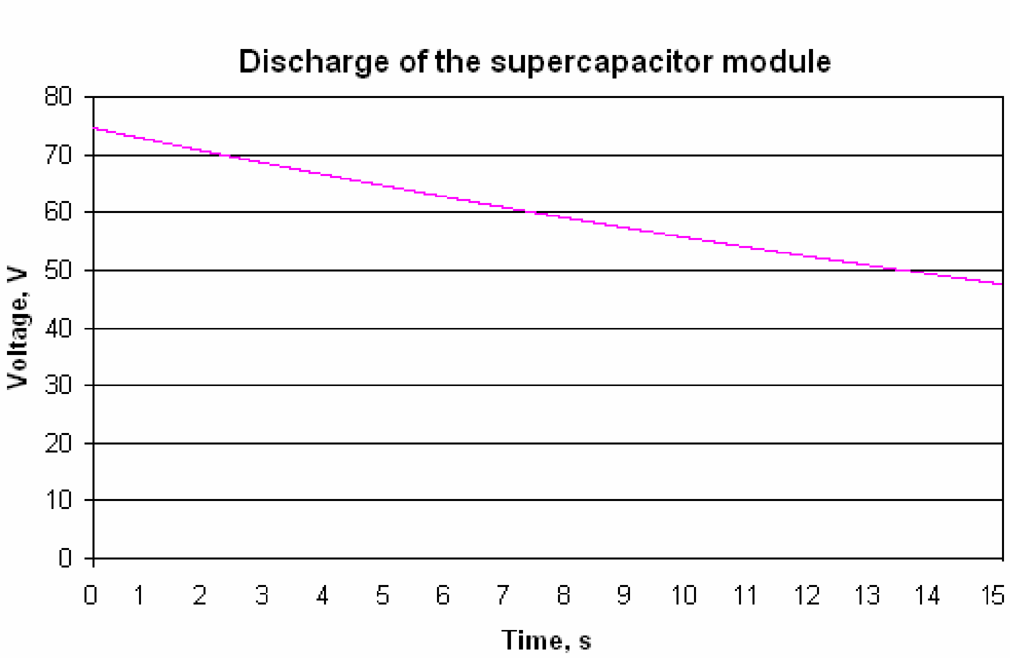


Figure 4.2 Discharge curve of the supercapacitor module

5 MOTOR CALCULATIONS

It is possible to utilize the maximum torque producing capability of the motor in an intermittent drive. To define how much torque it is possible to get the electro magnetic design of machine must be investigated.

5.1 Torque expansion by increasing of the flux density

The phase winding consists of 9 turns connected in series (N_s) and two parallel branches (a). There are three slots per phase and pole q. The number of parallel conductors per stator slot is 48. The pole pitch τ_p of the machine is:

$$t_{\mathrm{P}} = \frac{\pi D_{\delta}}{2p} = \frac{3.14 \cdot 0.1101}{4} = 0.086\ \mathrm{m}. \qquad (5.1)$$

And the induced voltage E is equal $0.96U$ that is 32.64 V. Now let us define the slot angle:

$$a_{\mathrm{us}} = p\frac{2\pi}{Q_{\mathrm{S}}} = 2 \cdot \frac{2 \cdot 3.14}{36} = 0.349. \qquad (5.2)$$

Then the winding factor k_{w} can be defined as:

$$k_{\mathrm{w}} = \frac{\sin\left(\frac{\pi}{2}\right)}{z}\sum_{p=1}^{z}\cos(a_{\mathrm{p}}) = \frac{1}{3}\cdot(2\cos 20 + 1) = 0.959. \qquad (5.3)$$

And the maximum flux density in the air gap assuming no saturation is:

$$B_{\delta\mathrm{max}} = \frac{\sqrt{2}E}{2\pi l t_{\mathrm{p}} f k_{\mathrm{w}} N} = \frac{\sqrt{2}\cdot 32.64}{2 \cdot 3.14 \cdot 0.15 \cdot 0.086 \cdot 80 \cdot 0.959 \cdot 9} = 0.825\ \mathrm{T}. \qquad (5.4)$$

Now the peak value for the main flux penetrating the winding in the stator and rotor is:

$$\Phi_{\mathrm{hmax}} = \frac{\sqrt{2}E}{2\pi f x(1) N} = \frac{\sqrt{2}\cdot 32.64}{2 \cdot 3.14 \cdot 80 \cdot 0.959 \cdot 9} = 10.6 \cdot 10^{-3}\ \mathrm{Vs}. \qquad (5.5)$$

Let us define the machine constant. To define it we have to know length ratio c .

$$c = \frac{l'}{D_{\delta}} = \frac{0.15}{0.1101} = 1.363. \qquad (5.6)$$

Thereby the machine constant will be equal:

$$C=\frac{m\cdot E\cdot I_{\mathrm{S}}\cdot p}{f\cdot c\cdot D_{\delta}^{3}}=\frac{3\cdot 32{,}64\cdot 241\cdot 2}{80\cdot 1{,}362\cdot 1{,}33\cdot 10^{-3}}=325686\ \mathrm{Ws/m^{3}}. \tag{5.7}$$

In normal industrial motors the machine constant with a 2.5 kW pole power remains in the range of 100 – 150 kWs/m^3. The figure in equation (5.7) is, hence very high. This large machine constant means that all the possible is taken out of iron.

Now it is possible to define the linear current density *A*. Then the linear current density *A* is:

$$A=\frac{\sqrt{2}\cdot C}{\pi^{2}\cdot x(1)\cdot B_{\delta\mathrm{m}}}=\frac{1.41\cdot 325686}{9.86\cdot 0.959\cdot 0.825}=58.8\ \mathrm{kA/m}. \tag{5.8}$$

Now to define how much torque it is possible to get it is need to find out what the flux density of the stator and rotor yokes and stator and rotor teeth is. The height of the stator yoke is:

$$h_{\mathrm{ys}}=\frac{D_{\mathrm{out}}-D_{\delta}}{2}-h_{\mathrm{zs}}=\frac{0.204-0.1101}{2}-0.02=0.0269\ \mathrm{m}. \tag{5.9}$$

The maximum flux density in the stator yoke is:

$$B_{\mathrm{ysmax}}=\frac{\Phi_{\mathrm{hmax}}}{2\cdot A_{\mathrm{ys}}}=\frac{\Phi_{\mathrm{hmax}}}{2\cdot l\cdot h_{\mathrm{ys}}}=\frac{10.6\cdot 10^{-3}}{2\cdot 0.15\cdot 0.0269}=1.3\ \mathrm{T}. \tag{5.10}$$

The apparent tooth flux passing through the stator slot is:

$$\Phi_{\mathrm{z}}^{'}=l\cdot t_{\mathrm{u}}\cdot B_{\delta\mathrm{max}}=0.15\cdot 0.0096\cdot 0.825=1.19\cdot 10^{-3}\ \mathrm{T}. \tag{5.11}$$

The cross sectional area of the tooth is:

$$A_{\mathrm{z}} = l \cdot z = 0.15 \cdot 0.005 = 0.75 \cdot 10^{-3}\ \mathrm{m}^2, \qquad (5.12)$$

where z is the width of the tooth. The apparent flux density of the tooth is:

$$B_{\mathrm{z}}^{'} = \frac{\Phi_{\mathrm{z}}^{'}}{A_{\mathrm{z}}} = \frac{1.19 \cdot 10^{-3}}{0.75 \cdot 10^{-3}} = 1.59\ \mathrm{T}. \qquad (5.13)$$

The maximum flux density of the rotor yoke is:

$$B_{\mathrm{yr}} = \frac{\Phi_{\mathrm{m}}}{2 \cdot A_{\mathrm{yr}}} = \frac{\Phi_{\mathrm{m}}}{2 \cdot l \cdot h_{\mathrm{yr}}} = \frac{10.6 \cdot 10^{-3}}{2 \cdot 0.15 \cdot 0.021} = 1.54\ \mathrm{T}, \qquad (5.14)$$

where h_{yr} is the height of the rotor yoke. The permissible values of flux density for magnetic circuit of the asynchronous machine are higher. The range of the maximum flux density in the air gap is typically 0.55...0.9 T. For the stator yoke it is 1.3…2T, for teeth (apparent maximum value) – 1.4…2.1 (stator), 1.5…2.2 (rotor) and for the rotor yoke – 0.4…1.6 T. Now let us define the tangential stress $s_{\mathrm{F\,tan}}$ of the machine.

$$s_{\mathrm{F\,tan}} = \frac{\vec{A} \cdot \vec{B}_{\mathrm{m}}}{2} \cdot \cos(j) = \frac{58800 \cdot 0.825}{2} \cdot 0.705 = 17.099\ \mathrm{kPa}, \qquad (5.15)$$

where $\cos j = \dfrac{T_{\mathrm{r}} \cdot W_{\mathrm{r}}}{\sqrt{3} \cdot U_{\mathrm{r}} \cdot I_{\mathrm{r}}} = \dfrac{41.3 \cdot 240.73}{\sqrt{3} \cdot 34 \cdot 241} = 0.705.$

Then the rated torque of the machine is:

$$T = s_{\mathrm{F\,tan}} \cdot \pi \cdot \frac{D_{\mathrm{r}}^2}{2} \cdot l = 17099 \cdot 3.14 \cdot \frac{0.1096^2}{2} \cdot 0.15 = 48.3\ \mathrm{Nm}. \qquad (5.16)$$

As we see it is possible to increase the flux density of the machine in intermittent drive with a short duty ratio. The flux density of the teeth is 1.59 T. The densities in the yokes are lower. In ultimate drive we can increase the flux density of the teeth to about 2 T which is 25 % higher than the rated value. Let us assume the air gap flux density is equal 1.25 times 0.825 T which gives 1.03 T. Then the tangential stress with the previous linear current density should be:

$$s_{\mathrm{F\,tan}} = \frac{\hat{A} \cdot \hat{B}_{\mathrm{m}}}{2} \cdot \cos(j) = \frac{58800 \cdot 1.03}{2} \cdot 0.705 = 20.312\ \mathrm{kPa}. \qquad (5.17)$$

And the possible torque is:

$$T = s_{\mathrm{F\,tan}} \cdot \pi \cdot \frac{D_{\mathrm{r}}^2}{2} \cdot l = 20312 \cdot 3.14 \cdot \frac{0.1096^2}{2} \cdot 0.15 = 57.4\ \mathrm{Nm}. \qquad (5.18)$$

Still more torque may be found by increasing the linear current density fundamental. It will be showed below.

5.2 Verification of the motor saturation

Now it is needed to check up if the magnetic circuit is not saturated. It is known that if the flux is forced to increase the iron core of the machine is driven progressively into saturation. This increases iron losses due to hysteresis and eddy currents and also can lead to a very marked increase in stator current with corresponding resistive losses.

Since most machines are designed to work with the minimum of material their magnetic circuit is very close to saturation and saturation is a condition which must be carefully avoided. Assuming the flux density is equal 1.03 T let us define the corresponding flux. To increase the flux density up to 1.03 T the frequency *f* has to be lower with the same voltage. The rated frequency should be equal:

$$f = \frac{\sqrt{2}E}{2\pi l t_{\mathrm{p}} B_{\delta\mathrm{max}} k_{\mathrm{w}} N} = \frac{\sqrt{2}\cdot 32.64}{2\cdot 3.14\cdot 0.15\cdot 0.086\cdot 1.03\cdot 0.959\cdot 9} = 64\ \mathrm{Hz}. \qquad (5.19)$$

Then the flux will be equal:

$$\Phi_{\mathrm{hmax}} = \frac{\sqrt{2}E}{2\pi f x(1) N} = \frac{\sqrt{2}\cdot 32.64}{2\cdot 3.14\cdot 64\cdot 0.959\cdot 9} = 12.7\cdot 10^{-3}\ \mathrm{Vs}. \qquad (5.20)$$

And then it is possible to check the flux density up in the magnetic circuit. The maximum flux density in the stator yoke is:

$$B_{\mathrm{ysmax}} = \frac{\Phi_{\mathrm{hmax}}}{2\cdot A_{\mathrm{ys}}} = \frac{\Phi_{\mathrm{hmax}}}{2\cdot l\cdot h_{\mathrm{ys}}} = \frac{12.7\cdot 10^{-3}}{2\cdot 0.15\cdot 0.0269} = 1.57\ \mathrm{T}. \qquad (5.21)$$

The apparent tooth flux passed the stator slot is:

$$\Phi_{\mathrm{z}}' = l\cdot t_{\mathrm{u}}\cdot B_{\delta\mathrm{max}} = 0.15\cdot 0.0096\cdot 1.03 = 1.4\cdot 10^{-3}\ \mathrm{T}. \qquad (5.22)$$

The cross sectional area of the tooth is:

$$A_{\mathrm{z}} = l\cdot z = 0.15\cdot 0.005 = 0.75\cdot 10^{-3}\ \mathrm{m}^2, \qquad (5.23)$$

where *z* is the width of the tooth.

The apparent flux density of the tooth is:

$$B_{\mathrm{z}}' = \frac{\Phi_{\mathrm{z}}'}{A_{\mathrm{z}}} = \frac{1.4\cdot 10^{-3}}{0.75\cdot 10^{-3}} = 1.86\ \mathrm{T}. \qquad (5.24)$$

The maximum flux density of the rotor yoke is:

$$B_{\mathrm{yr}} = \frac{\Phi_{\mathrm{m}}}{2\cdot A_{\mathrm{yr}}} = \frac{\Phi_{\mathrm{m}}}{2\cdot l\cdot h_{\mathrm{yr}}} = \frac{12.7\cdot 10^{-3}}{2\cdot 0.15\cdot 0.021} = 2\ \mathrm{T}, \qquad (5.25)$$

where h_{yr} is the height of the rotor yoke. We see that the rotor yoke starts first limiting the flux increasing.

5.3 Calculations of the parameters for the steady-state equivalent circuit

It is needed to define the parameters of steady-state equivalent circuit of asynchronous machine per phase to find out the maximum possible torque of the motor. At first let us define the magnetizing reactance of the main flux. To be able to define this value it is needed to know the magnetizing current. The magnetizing current can be calculated through the equation:

$$\begin{aligned} I_{\mathrm{m}} &= \frac{\Phi_{\mathrm{m}} \cdot \pi \cdot p^2 \cdot d}{\mu_0 \cdot m \cdot D_\delta \cdot l' \cdot x(1) \cdot N \cdot \sqrt{2}} \\ &= \frac{11.7 \cdot 10^{-3} \cdot 3.14 \cdot 4 \cdot 0.25 \cdot 10^{-3}}{12.56 \cdot 10^{-7} \cdot 3 \cdot 0.11 \cdot 0.15 \cdot 0.959 \cdot 3 \cdot \sqrt{2}} = 222 \text{ A}. \end{aligned} \tag{5.26}$$

Then the magnetizing reactance is:

$$X_{\mathrm{m}} = \frac{E}{I_{\mathrm{m}}} = \frac{32.64}{222} = 0.147 \text{ Ohm}. \tag{5.27}$$

where E is back EMF and equal $0.96U$. The current of the rotor referred to the stator winding is equal:

$$I_{\mathrm{r}}' = I_{\mathrm{s}} \cos(j) = 241 \cdot 0.705 = 169.9 \text{ A}. \tag{5.28}$$

The air gap reactance of the stator winding is:

$$\begin{aligned} X_{\delta\mathrm{s}} &= \mu_0 \cdot 2 \cdot f \cdot \frac{m}{d} \cdot D_\delta \cdot l \cdot \left(\frac{N}{p}\right)^2 \cdot (\text{harmonics}) \\ &= 12.56 \cdot 10^{-7} \cdot 2 \cdot 80 \cdot \frac{3}{2.5 \cdot 10^{-4}} \cdot 0.11 \cdot 0.15 \cdot \left(\frac{3}{2}\right)^2 \cdot (\text{harmonics}) = 1.27 \cdot 10^{-3} \text{ Ohm}. \end{aligned} \tag{5.29}$$

where harmonics are defined in the Appendix B. The air gap reactance of the rotor referred to the stator winding is obtained from equation:

$$X'_{\delta \mathrm{r}} = s_{\delta \mathrm{r}} \cdot X_{\mathrm{m}} = 6.2 \cdot 10^{-3} \cdot 0.147 = 9.11 \cdot 10^{-4} \text{ Ohm}, \tag{5.30}$$

where $s_{\delta \mathrm{r}}$ is the leakage factor which can be found through the equation:

$$s_{\delta \mathrm{r}} = \frac{\pi^2}{3} \cdot \left(\frac{p}{Q_{\mathrm{r}}} \right)^2 = \frac{3.14^2}{3} \cdot \left(\frac{2}{46} \right)^2 = 6.2 \cdot 10^{-3}. \tag{5.31}$$

The slot reactance of the stator is:

$$\begin{aligned} X_{\mathrm{ns}} &= \mu_0 \cdot l \cdot N_{\mathrm{u}}^2 \cdot \frac{y_{\mathrm{s}}}{3 \cdot \frac{z_{\mathrm{usmin}} + z_{\mathrm{usmax}}}{2}} \cdot 2 \cdot \pi \cdot f \\ &= 12.56 \cdot 10^{-7} \cdot 0.15 \cdot 4^2 \cdot \frac{0.02}{1.5 \cdot (0.004 + 0.007)} \cdot 2 \cdot 3.14 \cdot 80 = 1.47 \cdot 10^{-3} \text{ Ohm}. \end{aligned} \tag{5.32}$$

Correspondingly the slot reactance of the rotor is:

$$\begin{aligned} X_{\mathrm{nr}} &= \mu_0 \cdot l \cdot N_{\mathrm{ur}}^2 \cdot \frac{y_{\mathrm{r}}}{3 \cdot \frac{z_{\mathrm{urmin}} + z_{\mathrm{urmax}}}{2}} \cdot 2 \cdot \pi \cdot f \\ &= 12.56 \cdot 10^{-7} \cdot 0.15 \cdot 1^2 \cdot \frac{0.02}{1.5 \cdot (0.002 + 0.006)} \cdot 2 \cdot 3.14 \cdot 64 = 1.9 \cdot 10^{-4}. \end{aligned} \tag{5.33}$$

Now let us define the conversion ratio for referring reactance and resistance to stator:

$$b=\frac{4\cdot m}{Q_{\mathrm{r}}}\cdot(x(1)\cdot N)^2=\frac{4\cdot 3}{46}\cdot(0.959\cdot 3)^2=2.16. \qquad (5.34)$$

Slot reactance of the rotor referred to the stator can be calculated through the equation:

$$X'_{\mathrm{nr}}=b\cdot X_{\mathrm{nr}}=2.16\cdot 4.5\cdot 10^{-4}=4.1\cdot 10^{-4}\ \mathrm{Ohm}. \qquad (5.35)$$

To be able to calculate the tooth tip reactance the reactance factor should be defined. The reactance factor is equal:

$$l_{\mathrm{zs}}=\frac{5\cdot\frac{z_{\mathrm{usmin}}}{d}}{5+4\cdot\frac{z_{\mathrm{usmin}}}{d}}=\frac{5\cdot\frac{4\cdot 10^{-3}}{2.5\cdot 10^{-4}}}{5+4\cdot\frac{4\cdot 10^{-3}}{2.5\cdot 10^{-4}}}=1.15. \qquad (5.36)$$

Then the tooth tip reactance is:

$$\begin{aligned}X_{\mathrm{zs}}&=\frac{4\cdot m}{Q_{\mathrm{s}}}\cdot\mu_0\cdot 2\cdot\pi\cdot f\cdot l\cdot l_{\mathrm{zs}}\cdot N^2\\&=\frac{4\cdot 3}{36}\cdot 12.56\cdot 10^{-7}\cdot 2\cdot 80\cdot 3.14\cdot 0.15\cdot 1.15\cdot 3^2=3.3\cdot 10^{-4}\ \mathrm{Ohm}.\end{aligned} \qquad (5.37)$$

From table for cylindrical three-phase diamond winding and cage winding type of rotor winding the winding leakage permeance factors are: $l_{\mathrm{e}}=0.5$ and $l_{\mathrm{w}}=0.2$. Then the winding reactance is:

$$\begin{aligned}X_{\mathrm{ws}}&=\frac{4\cdot m}{Q_{\mathrm{s}}}\cdot\mu_0\cdot q\cdot 2\cdot\pi\cdot f\cdot N^2\cdot(2E_{\mathrm{s}}\cdot l_{\mathrm{e}}+t_{\mathrm{p}}\cdot l_{\mathrm{w}})\\&=\frac{4\cdot 3}{36}\cdot 12.56\cdot 10^{-7}\cdot 2\cdot 80\cdot 3.14\cdot 3\cdot 9^2\cdot(2\cdot 0.036\cdot 0.5+0.086\cdot 0.2)=3\cdot 10^{-4}\ \mathrm{Ohm}.\end{aligned} \qquad (5.38)$$

Now let us define the end ring reactance of the rotor.

$$X_{r'} = \mu_0 \cdot \frac{Q_r}{m \cdot 3 \cdot p^2} \cdot (0.36 \cdot \frac{\pi \cdot D_{pr}}{2 \cdot p}) \cdot 2 \cdot \pi \cdot f$$
$$= 12.56 \cdot 10^{-7} \cdot \frac{46}{3 \cdot 3 \cdot 4} \cdot \left(0.36 \cdot \frac{3.14 \cdot 0.094}{4}\right) \cdot 2 \cdot 3.14 \cdot 80 = 2.14 \cdot 10^{-5}, \tag{5.39}$$

where D_{pr} is the diameter of the end ring and equal $D_r - y_r = 0.109 - 0.015 = 0.094$ m. Then the reactance of the end ring is:

$$X_{wr} = \frac{X_{r'}}{2 \cdot Q_r \cdot \sin\left(\frac{p \cdot \pi}{Q_r}\right)^2} = \frac{2.14 \cdot 10^{-5}}{2 \cdot 46 \cdot \sin\left(\frac{2 \cdot 3.14}{46}\right)^2} = 1.25 \cdot 10^{-5} \text{ Ohm}. \tag{5.40}$$

And the end ring reactance referred to the stator winding is:

$$X'_{wr} = b \cdot X_{wr} = 19.45 \cdot 1.25 \cdot 10^{-5} = 2.72 \cdot 10^{-5} \text{ Ohm}. \tag{5.41}$$

The skew reactance can be calculated through the equation below:

$$X_\chi = X_m (1 - c_1^2). \tag{5.42}$$

To define c_1 it is need to know arc length of the skew a_{uv}.

$$a_{uv} = \frac{D_\delta}{2} \cdot a_{us} = \frac{0.11}{2} \cdot 0.349 = 0.019 \text{ m}. \tag{5.43}$$

Then c_1 is:

$$c_1 = \frac{\sin\left(\frac{a_{\text{uv}}}{t_{\text{p}}} \cdot \frac{\pi}{2}\right)}{\frac{a_{\text{uv}}}{t_{\text{p}}} \cdot \frac{\pi}{2}} = \frac{\sin\left(\frac{0.019}{0.086} \cdot \frac{3.14}{2}\right)}{\frac{0.019}{0.086} \cdot \frac{3.14}{2}} = 0.98 \tag{5.44}$$

And the skew reactance is:

$$X_{\chi} = X_{\text{m}}(1 - c_1^2) = 0.147 \cdot (1 - 0.98^2) = 5.85 \cdot 10^{-3} \text{ Ohm}. \tag{5.45}$$

The leakage reactance of the stator is equal:

$$X_{\sigma\text{s}} = X_{\delta\text{s}} + X_{\text{ns}} + X_{\text{zs}} + X_{\text{ws}} + X_{\chi} = 9.086 \cdot 10^{-3} \text{ Ohm}. \tag{5.46}$$

Correspondingly the leakage reactance of the rotor referred to the stator winding can be calculated:

$$X'_{\sigma\text{r}} = X'_{\delta\text{r}} + X'_{\text{nr}} + X'_{\text{zr}} + X'_{\text{wr}} + X_{\chi} = 7.2 \cdot 10^{-3} \text{ Ohm}. \tag{5.47}$$

Let us define the resistances of the motor. The length of a single turn of the slot winding is:

$$l_{\text{m}} = 2L + 2.4t_{\text{p}} + 0.1 = 2 \cdot 0.15 + 2.4 \cdot 0.086 + 0.1 = 0.607 \text{ m}. \tag{5.48}$$

Resistance of the stator winding in a cold and hot machine is obtained from the equation:

$$R_{\text{s}} = \frac{l_{\text{m}}}{a \cdot A_{\text{js}} \cdot s_{\text{Cu}}} \cdot N = \frac{0.607}{2 \cdot 3.2 \cdot 10^{-6} \cdot 5.7 \cdot 10^{7}} \cdot 3 = 0.004 \text{ Ohm}, \tag{5.49}$$

where A_{js} is the cross-sectional area of one conductor of the stator winding, s_{Cu} - specific conductivity of copper. The diameter of one conductor as it was measured is 2 mm. Then the cross-sectional area of one conductor is:

$$A_{\mathrm{js}} = \frac{\pi \cdot d^2}{4} = \frac{3.14 \cdot 0.002^2}{4} = 3.2 \cdot 10^{-6}\ \mathrm{m}^2 . \qquad (5.50)$$

For the hot machine assuming initial temperature +20ºC and final temperature 125ºC (correspondingly $\Delta T = 105^{\circ}\mathrm{C}$) :

$$\begin{aligned} R_{sH} &= \frac{l_{\mathrm{m}}}{a \cdot A_{\mathrm{js}} \cdot [s_{\mathrm{Cu}} \cdot (1 - a_{\mathrm{Cu}} \Delta T)]} \cdot N \\ &= \frac{0.607}{2 \cdot 3.2 \cdot 10^{-6} \cdot [5.7 \cdot 10^{7} \cdot (1 - 3.81 \cdot 10^{-3} \cdot 105)]} \cdot 3 = 0.007\ \mathrm{Ohm}. \end{aligned} \qquad (5.51)$$

The DC resistance of the rotor bar is:

$$R_{\mathrm{r'}} = \frac{l_{\mathrm{b}}}{A_{\mathrm{jr}} \cdot s_{\mathrm{Al}}} \cdot N_{\mathrm{ur}} = \frac{0.15}{3.8 \cdot 10^{-5} \cdot 3.7 \cdot 10^{7}} \cdot 1 = 1.1 \cdot 10^{-4}\ \mathrm{Ohm}, \qquad (5.52)$$

where l_{b} is the length of rotor bar, it is assumed that l_{b} is equal the length of the stack; A_{jr} is the cross-sectional area of the rotor bar and $A_{\mathrm{jr}} = \frac{I_{\mathrm{r}}}{J_{\mathrm{r}}} = \frac{191}{5 \cdot 10^{6}} = 3.8 \cdot 10^{-5}\ \mathrm{m}^2$.

Assume $J_{\mathrm{r}} = 5 \cdot 10^{6}\ \mathrm{A/m}^2$. The rotor bar current can be calculated through the equation below:

$$I_{\mathrm{r}} = m_{\mathrm{rs}} \cdot I_{\mathrm{r}}^{'} = 1.5 \cdot 169.9 = 255\ \mathrm{A}, \qquad (5.53)$$

where m_{rs} can be defined as:

$$m_{\mathrm{rs}} = \frac{N_{\mathrm{u}}}{a} \cdot \frac{Q_{\mathrm{s}}}{Q_{\mathrm{r}}} \cdot x(1) = \frac{48}{2} \cdot \frac{36}{46} \cdot 0.959 = 1.5\,. \tag{5.53}$$

To define the end ring resistance of the rotor it is need to calculate the peak current of the end ring of the rotor. Let us define coefficient k_{pr} used for the calculation of the peak current.

$$l_{\mathrm{e\,r}} = 0.7 \cdot \pi \cdot \frac{D_{\mathrm{r}}}{Q_{\mathrm{r}}} = 0.7 \cdot 3.14 \cdot \frac{0.109}{46} = 5.216 \cdot 10^{-3}\ \mathrm{m}. \tag{5.54}$$

$$a_{\mathrm{ur}} = \frac{2 \cdot \pi \cdot p}{Q_{\mathrm{r}}} = \frac{2 \cdot 3.14 \cdot 2}{46} = 0.273. \tag{5.55}$$

Assume $a_{r1} = 0$.

$$a_{\mathrm{r\,n+1}} = a_{\mathrm{rn}} + a_{\mathrm{ur}}, \tag{5.56}$$

where $n = 1 \ldots Q_{\mathrm{r}}$.

Assume $k_{\mathrm{pr1}} = 0.5$. The algorithm of k_{pr} definition is shown below.

$$k_{\mathrm{pr\,n+1}} = k_{\mathrm{pr\,n}} + \cos(a_{\mathrm{r\,n+1}}). \tag{5.57}$$

$$k_{\mathrm{pr}} = \max(k_{\mathrm{pr}}). \tag{5.58}$$

And the coefficient for definition of the peak current $k_{\mathrm{pr}} = 3.6$.

Then peak value of the end ring current is:

$$I_{\text{pmax}} = k_{\text{pr}} \cdot I_{\text{r}} = 3.6 \times 255 = 935 \text{ A}. \tag{5.59}$$

Correspondingly the cross-sectional area should be:

$$A_{\text{pr}} = \frac{I_{\text{pr max}}}{J_{\text{pr}}} = \frac{935}{3 \cdot 10^{6}} = 3.1 \cdot 10^{-4} \text{ m}^{2}. \tag{5.60}$$

Then resistance of the end ring is:

$$R_{\text{pr'}} = \frac{2 \cdot l_{\text{er}}}{A_{\text{pr}} \cdot s_{\text{Al}}} = \frac{2 \cdot 5.216 \cdot 10^{-3}}{3.1 \cdot 10^{-4} \cdot 3.7 \cdot 10^{7}} = 2.57 \cdot 10^{-4} \text{ Ohm}. \tag{5.61}$$

$$R_{\text{pr}} = \frac{R_{\text{pr'}}}{2 \cdot \sin\left(\frac{\pi \cdot p}{Q_{\text{r}}}\right)^{2}} = \frac{2.57 \cdot 10^{-4}}{2 \cdot \sin\left(\frac{3.14 \cdot 2}{46}\right)^{2}} = 1.28 \cdot 10^{-5} \text{ Ohm}. \tag{5.62}$$

Thereby rotor resistance is:

$$R_{\text{r}} = R_{\text{r'}} + R_{\text{pr}} = 1.1 \cdot 10^{-4} + 1.28 \cdot 10^{-5} = 1.189 \cdot 10^{-4} \text{ Ohm}. \tag{5.63}$$

Correspondingly the rotor resistance referred to the stator winding is equal:

$$R_{\text{r}}^{'} = b \cdot R_{\text{r}} = 2.163 \cdot 1.189 \cdot 10^{-4} = 2.571 \cdot 10^{-4} \text{ Ohm}. \tag{5.64}$$

To define R_{m} it is need to calculate the iron losses of the machine. Length of the stator yoke is obtained from the equation below:

$$l_{\mathrm{is}} = (D_{\mathrm{s}} - h_{\mathrm{ys}}) \cdot \pi = (0.204 - 0.026) \cdot 3.14 = 0.559 \text{ m}. \tag{5.65}$$

The area of the stator yoke is equal:

$$A_{\mathrm{is}} = h_{\mathrm{ys}} \cdot l = 0.026 \cdot 0.15 = 3.9 \cdot 10^{-3} \text{ m}^2. \tag{5.66}$$

The peak values of flux density for stator yoke and teeth are $b_{\mathrm{is}} = 1.65$ T and $b_{\mathrm{ir}} = 1.8$ T correspondingly. Correction coefficient of the stator and stator teeth are $k_{\mathrm{sb}} = 1.6$ and $k_{\mathrm{st}} = 1.8$. The loss index $P_{15} = 6.5$ W/kg and the density of iron $r_{\mathrm{Fe}} = 7.75 \cdot 10^3$ kg/m^3.

The iron losses can be obtained from the equation:

$$\begin{aligned} P_{\mathrm{is}} &= k_{\mathrm{sb}} \cdot P_{15} \cdot \left(\frac{b_{\mathrm{is}}}{1.5}\right)^2 \cdot A_{\mathrm{is}} \cdot l_{\mathrm{is}} \cdot r_{\mathrm{Fe}} \\ &= 1.6 \cdot 6.5 \cdot \left(\frac{1.65}{1.5}\right)^2 \cdot 3.9 \cdot 10^{-3} \cdot 0.559 \cdot 7.75 \cdot 10^3 = 212.6 \text{ W}. \end{aligned} \tag{5.67}$$

For stator teeth:

$$\begin{aligned} P_{\mathrm{hs}} &= k_{\mathrm{st}} \cdot P_{15} \cdot \left(\frac{b_{\mathrm{rs}}}{1.5}\right)^2 \cdot A_{\mathrm{zs}} \cdot Q_{\mathrm{s}} \cdot y_{\mathrm{s}} \cdot r_{\mathrm{Fe}} \\ &= 1.8 \cdot 6.5 \cdot \left(\frac{1.8}{1.5}\right)^2 \cdot 7.5 \cdot 10^{-4} \cdot 36 \cdot 0.02 \cdot 7.75 \cdot 10^3 = 56.4 \text{ W}. \end{aligned} \tag{5.68}$$

Thereby iron losses can be calculated:

$$P_{\text{iron}} = P_{\text{hs}} + P_{\text{is}} = 269.1\ \text{W}. \tag{5.69}$$

Then R_{m} is:

$$R_{\text{m}} = \frac{E^2 \cdot 3}{P_{\text{iron}}} = \frac{32.64^2 \cdot 3}{269.1} = 11\ \text{Ohm}. \tag{5.70}$$

5.4 Per unit parameters

Let us recalculate the parameters of the motor equivalent circuit into per unit values. For the calculation it is possible to use the rated power as the base value. Then the per unit stator resistance is:

$$r_{\text{s,pu}} = \frac{R_{\text{s}} \cdot I_{\text{N}} / \sqrt{3}}{U_{\text{N}}} = \frac{0.004 \cdot 241/\sqrt{3}}{34} = 0.016. \tag{5.71}$$

The relative values of other parameters can be defined in the same way.

$$l_{\text{m}} = \frac{X_{\text{m}} \cdot I_{\text{N}} / \sqrt{3}}{U_{\text{N}}} = \frac{0.147 \cdot 241/\sqrt{3}}{34} = 0.6. \tag{5.72}$$

$$l_{\sigma \text{s}} = \frac{X_{\sigma \text{s}} \cdot I_{\text{N}}}{U_{\text{N}}} = \frac{9.1 \cdot 10^{-3} \cdot 241/\sqrt{3}}{34} = 0.038. \tag{5.73}$$

$$l_{\sigma \text{r}}^{'} = \frac{X_{\sigma \text{r}}^{'} \cdot I_{\text{N}}}{U_{\text{N}}} = \frac{7.2 \cdot 10^{-3} \cdot 241/\sqrt{3}}{34} = 0.029. \tag{5.74}$$

$$r_{\mathrm{r,pu}} = \frac{R_{\mathrm{r}}^{'} \cdot I_{\mathrm{N}}}{U_{\mathrm{N}}} = \frac{2.57 \cdot 10^{-4} \cdot 241/\sqrt{3}}{34} = 0.001. \tag{5.75}$$

$$r_{\mathrm{m}} = \frac{R_{\mathrm{m}} \cdot I_{\mathrm{N}}}{U_{\mathrm{N}}} = \frac{11 \cdot 241/\sqrt{3}}{34} = 45 \tag{5.76}$$

5.5 Motor torque-slip curve

Now it is possible to define rated electromagnetic torque. It is equal:

$$T_{\mathrm{em}} \approx \frac{m_{\mathrm{s}} \cdot U_{\mathrm{s}}}{w_{\mathrm{s}} / p} \cdot \frac{R_{\mathrm{r}}^{'} / s}{\left(R_{\mathrm{s}} + \frac{R_{\mathrm{r}}^{'}}{s}\right)^2 + \left(w_{\mathrm{s}} L_{\mathrm{k}}\right)^2} = 48.4 \text{ Nm}, \tag{5.77}$$

where $L_{\mathrm{k}} \approx L_{\mathrm{s\sigma}} + L_{\mathrm{r\sigma}}^{'} = 1.8 \cdot 10^{-5} + 1.43 \cdot 10^{-5} = 3.24 \cdot 10^{-5}$ H.

The leakage inductance of the stator $L_{\mathrm{s\sigma}}$ and the leakage inductance of the rotor referred to the stator can be calculated as shown below.

$$L_{\mathrm{s\sigma}} = \frac{X_{\sigma \mathrm{s}}}{2\pi f} = \frac{9.1 \cdot 10^{-3}}{2 \cdot 3.14 \cdot 80} = 1.8 \cdot 10^{-5} \text{ H}. \tag{5.78}$$

$$L_{\mathrm{r\sigma}}^{'} = \frac{X_{\sigma \mathrm{r}}^{'}}{2\pi f} = \frac{7.2 \cdot 10^{-3}}{2 \cdot 3.14 \cdot 80} = 1.43 \cdot 10^{-5} \text{ H}. \tag{5.79}$$

The rated speed of the machine is:

$$W_{\mathrm{r}} = \frac{\pi \cdot n_{\mathrm{r}}}{30} = \frac{3.14 \cdot 2300}{30} = 241\,[\mathrm{s}^{-1}]. \tag{5.80}$$

The synchronous speed is:

$$W_{\mathrm{s}} = \frac{2\pi \cdot f}{p} = \frac{2 \cdot 3.14 \cdot 80}{2} = 251\,[\mathrm{s}^{-1}]. \tag{5.81}$$

The slip of the machine is equal:

$$s = \frac{W_{\mathrm{s}} - W_{\mathrm{r}}}{W_{\mathrm{s}}} = \frac{251 - 241}{251} = 0.039. \tag{5.82}$$

Using Mathcad it is possible to get the electromechanical characteristic of the electric motor. We can get the torque relative to the slip of the machine. In Figure 5.1 the electromechanical characteristic is represented.

$$T := \left(\frac{m \cdot U^{2} \cdot p}{\omega_{s}}\right) \cdot \frac{\frac{R'_{rH}}{s}}{\left(R_{s} + \frac{R'_{rH}}{s}\right)^{2} + \left(\omega_{s} \cdot L_{k}\right)^{2}}$$

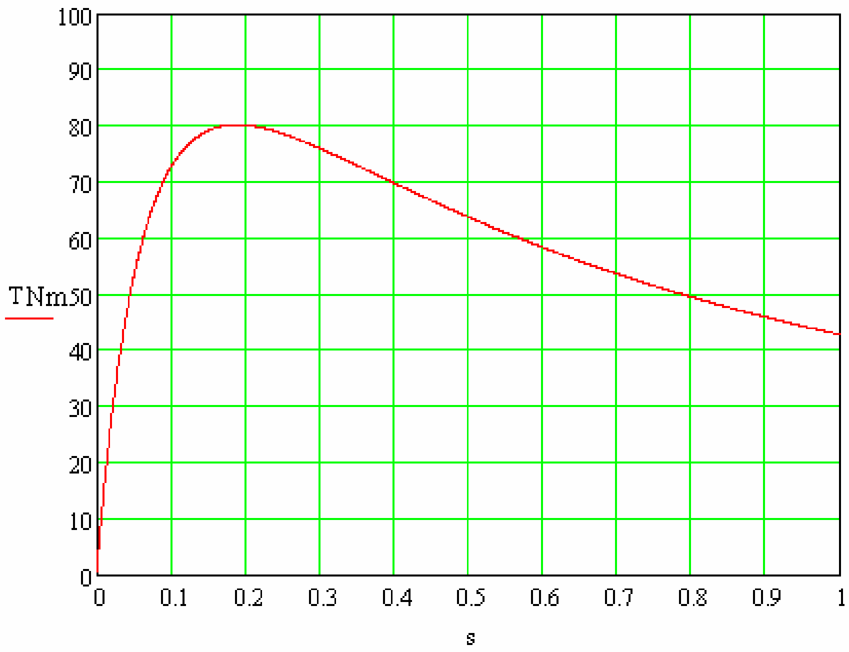


Figure 5.1. The electromechanical characteristic of the motor; *T* is the electromagnetic torque [Nm]; *s* – slip of the machine.

In Figure 5.1 we can see that the maximum possible operating torque of the motor is about 70 Nm.

5.6 Torque expansion by increasing of the current density

Let us define the maximum torque which can be got. The rated linear current density of the machine is 58800 A/m. Assume the linear current density of 65000 A/m. Then the tangential stress is:

$$s_{\mathrm{Ftan}} = \frac{\hat{A}\cdot\hat{B}_{\mathrm{m}}}{2}\cdot\cos(j) = \frac{65000\cdot 1.03}{2}\cdot 0.705 = 22.454\ \mathrm{kPa}. \qquad (5.83)$$

And the possible torque is:

$$T = s_{\mathrm{Ftan}}\cdot\pi\cdot\frac{D_{\mathrm{r}}^{2}}{2}\cdot l = 22454\cdot 3.14\cdot\frac{0.1096^{2}}{2}\cdot 0.15 = 64\ \mathrm{Nm}. \qquad (5.84)$$

Also to get extra torque it is possible to increase the current density more than in usual applications. As the motor is used for a short time the current density can be increased up to 12 A/mm^2 for a few seconds. Let us define the current density of the stator when the motor is working about at its rated mode. The current density of the stator winding about rated operation mode of the motor is:

$$J_{\mathrm{s}} = \frac{I_{\mathrm{s}}}{a\cdot A_{\mathrm{js}}} = \frac{241}{32\cdot 7.85\cdot 10^{-7}} = 9.5\cdot 10^{6}\ \mathrm{A/m^{2}}. \qquad (5.85)$$

If we increase the current density up to 12 A/mm^2, the stator current will be equal:

$$I_{\mathrm{s}} = J_{\mathrm{s}}\cdot a\cdot A_{\mathrm{js}} = 12\cdot 10^{6}\cdot 32\cdot 7.85\cdot 10^{-7} = 301\ \mathrm{A}. \qquad (5.86)$$

The current was increased by 25% which means that the liner current density would be increased in the same extent and will be equal 73500 A/m. It makes possible to get additional torque. The tangential stress is now:

$$\sigma_{\mathrm{F\,tan}} = \frac{\hat{A} \cdot \hat{B}_{\mathrm{m}}}{2} \cdot \cos\varphi = \frac{73500 \cdot 1.03}{2} \cdot 0.705 = 25.390\ \mathrm{kPa}. \tag{5.87}$$

And the torque is:

$$T = \sigma_{\mathrm{F\,tan}} \cdot \pi \cdot \frac{D_{\mathrm{r}}^{2}}{2} \cdot l = 25390 \cdot 3.14 \cdot \frac{0.1096^{2}}{2} \cdot 0.15 = 71.8\ \mathrm{Nm}. \tag{5.88}$$

6 TRANSMISSION

6.1 Gear calculations

As it was defined the maximum possible short time torque of this asynchronous motor is 71.8 Nm. Gear boxes are used to increase the torque and reduce the output speed of the motor. To be able to select a suitable reducer it is needed to define the gear ratio. At first, let us calculate the maximum cardan speed. If the vehicle’s speed is 150 km/h it means the linear speed of the vehicle is 41.6 m/s. The angular speed of the wheels shaft can be defined through the equation:

$$W_{\mathrm{w}} = \frac{V_{\mathrm{w}}}{R_{\mathrm{w}}} = \frac{41.6}{0.325} = 128.2\ \mathrm{s}^{-1}. \tag{6.1}$$

Taking the ratio of transmission between the wheels shaft and the cardan into account we will get the angular speed of the cardan:

$$W_{\mathrm{c}} = W_{\mathrm{w}} \cdot \frac{27}{17} = 128.2 \cdot \frac{27}{17} = 203.6\ \mathrm{s}^{-1}. \tag{6.2}$$

Thereby the motor speed in revolutions per minute without gear is equal:

$$n_{\mathrm{m}} = \frac{30 \cdot W_{\mathrm{c}}}{\pi} = \frac{30 \cdot 203.6}{3.14} = 1945.2\ \mathrm{rpm}. \tag{6.3}$$

Now it is clear that the maximum cardan speed is about the rated motor speed which is equal to 2300 rpm. The most important working area of the motor should be in the range from 0 to 50 km/h which gives the rotational speed area 0 – 650 rpm. Here we see that a gear ration 1:4 brings the motor to its rated rotational speed when the car is operating between 0 and 50 km/h.

The gear should increase the torque and reduce the speed of the motor. So the motor speed will be the gear’s ratio value times more than the output of the gear. To avoid a damage of the motor its speed should not be more than 8000-9000 rpm. Thereby the gear’s ratio can be about equal to 1:4.

6.2 Gear selection

During analyzing of gearboxes to be produced by different manufactures it was not found any suitable industrial reducer for such application. Thereby the appropriate reducer has to be designed for the problem decision. A special gearbox can be made on the basis more suitable existing reducer.

The main demands for such a reducer are: small dimensions, 1:4 gear ratio, output speed about 2000 rpm, input speed about 8000 rpm and the output torque should be large enough to correspond to possible cardan torque.

Browning and Morse bevel gear reducers are more appropriate for hybrid drive application. This kind of gear reducer is shown in Figure 6.1 [11]

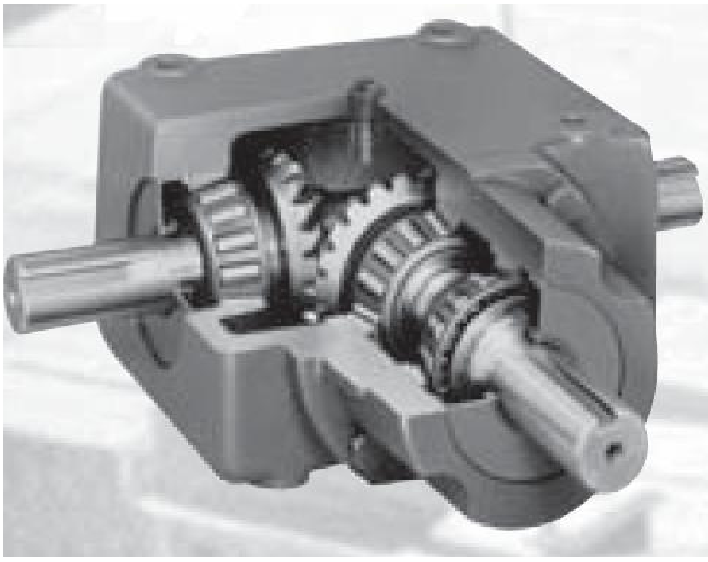


Figure 6.1 The bevel gear speed reducer

Such a gear might be suitable because the cardan shaft may run directly trough the gear and the electric motor may be installed 90 degrees from the cardan.

7 MOTOR LOAD CALCULATION

The thermal load of the motor depends on the current. The motor will not overheat if RMS current is in the limit of tolerance. To define the RMS current of the motor the term of equivalent current is used. If the equivalent current does not exceed the rated current of the motor it is possible to say that the motor will not be overheated.

During the acceleration time current of the motor, as it was shown above, is equal to 301 A. We need to define the current during deceleration time. The maximum torque of recuperation as it will be shown in Appendix A is 36 Nm (taking the gear ratio 1:4 into account). Let us calculate the current of the motor during deceleration time. At first let us define tangential stress.

$$s_{\mathrm{F\,tan}} = \frac{2T}{\pi \cdot D_{\mathrm{r}}^2 \cdot l} = \frac{2 \cdot 36}{3.14 \cdot 0.1096^2 \cdot 0.15} = 13 \text{ kPa} \tag{7.1}$$

As it was shown above 25 kPa of the tangential stress corresponds to the current which is equal 301 A. It is assumed also that such a value of the current is the maximum possible which is not too dangerous for the motor. Thereby, the motor current should be limited to this value. So we will assume that the maximum possible deceleration current is equal to the acceleration current (otherwise the motor will be overheated). But when tangential stress is equal 13 kPa it means that current is two times less 301A. It is about 150 A.

The equation for definition of the equivalent current is:

$$I_{\mathrm{e}} = \sqrt{\frac{1}{T}\int_0^T i^2 \mathrm{d}t}\,, \tag{7.2}$$

where T is a time of the full cycle.

The integration in this case can be replaced by addition. Thereby the equation for equivalent current of the motor is equal:

$$I_{\mathrm{e}} = \sqrt{\frac{I_{\mathrm{sa}}^2 \cdot t_{\mathrm{a}} + I_{\mathrm{sd}}^2 \cdot t_{\mathrm{a}}}{T}} = \sqrt{\frac{301^2 \cdot 188 + 150^2 \cdot 188}{1400}} = 123\,[\mathrm{A}], \qquad (7.3)$$

where I_{sa} is the current during acceleration time, t_{a} is the acceleration time, I_{sd} is the current during deceleration time, t_{d} is the deceleration time. The equivalent current is less than rated current of the motor. Thereby there is no current overload of the motor.

8 POWER ELECTRIC CONVERTER FOR THE DRIVE SYSTEM

8.1 Converter selection principles

A self-commutated inverter is needed for supplying the selected induction motor. There are no industrial inverters which could supply the motor with 34V DC. Thereby it is need to select power pack and control system to design the inverter.

There are self-induction inverters founded GTO thyristors and IGBT transistors. Nowadays inverters based on IGBT transistors are most common inverters. IGBT transistors have better rates as compared with thyristors. Its advantages are: full controllability, easier and no power-consuming control system, highest operating frequency. IGBT transistors allow increasing operation speed of a drive system in whole. Inverters based on IGBT can operate without feedback during low speed operation. Use of IGBT with higher operating frequency and microprocessor control system reduces high harmonic components that results in decreasing of additional losses in a winding and magnet circuit of an electrical machine. Also it decreases heating of a machine and a torque rippling. The reduction of a torque rippling results in elimination of so called torque “pacing” in the range of low frequency. The consequence of it is also the decreasing of losses in a storage capacitor system. The weight and the dimensions of inverters with IGBT are lower in comparison with GTO inverters.

But in our case MOSFET transistors based inverter may be more suitable. MOSFET has almost all the same advantages and it is better solution for low power applications. Figure 8.1 represents different power and frequency range for application of different transistors.

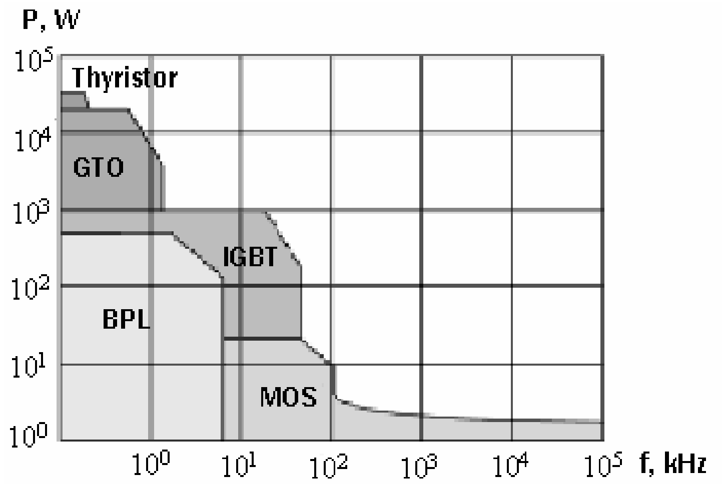


Figure 8.1. The application ranges of different types of powerful semiconductors [6]

The self-commutated inverter converts DC voltage of a storage super capacitor system to AC voltage of an induction machine. The transistors of the inverter are controlled by a pulse-width modulation control system. A voltage amplitude and frequency is defined by parameters of modulating sine wave. When working at high carrier frequency the motor winding operate like a filter because of its high inductance. It results in almost sine motor current. Thereby there is no need to use an output filter to smoothen an output voltage of the inverter.

The circuit of a self-commutated inverter is represented in Figure 8.2.

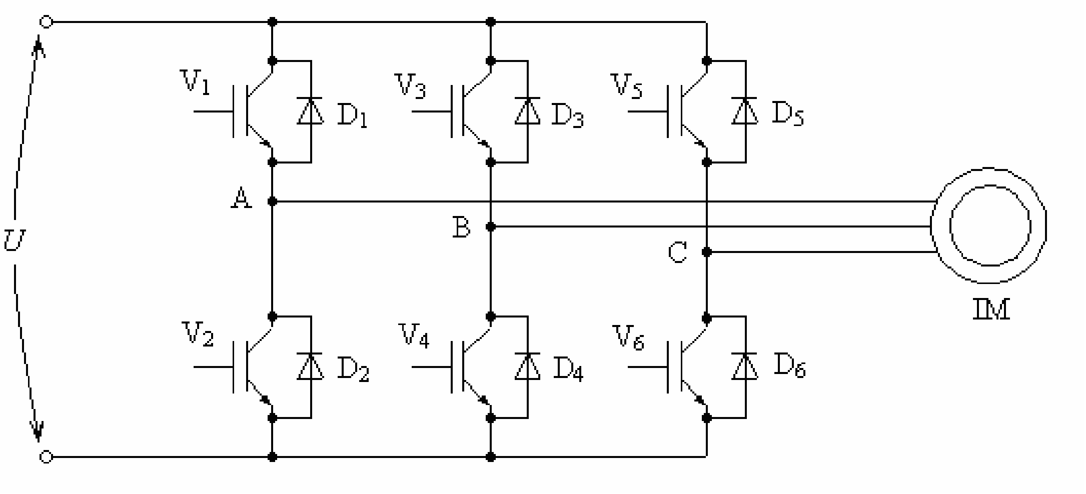


Figure 8.2. Self-commutated inverter. In the capacity of power switches V_1 – V_6 IGBTs or MOSFETs can be used. D_1 – D_6 are bypass diodes; IM means an induction motor and *U* – supply voltage [V] (the voltage of the super capacitors storage system) [14].

8.2 Self-commutated inverter

The circuit can be designed with separate MOSFET modules or it is possible to use six-pack integrated ready-to-wear power module. There are many manufactures of such kind of separate and integrated modules. SEMICRON produces special full-integrated IGBT and MOSFET modules for hybrid vehicle application. It is SKAI^{TM} product line. These modules include a gate driver for power circuit. The arrangement of the system with such self-commutated module is represented in Figure 8.3 [7].

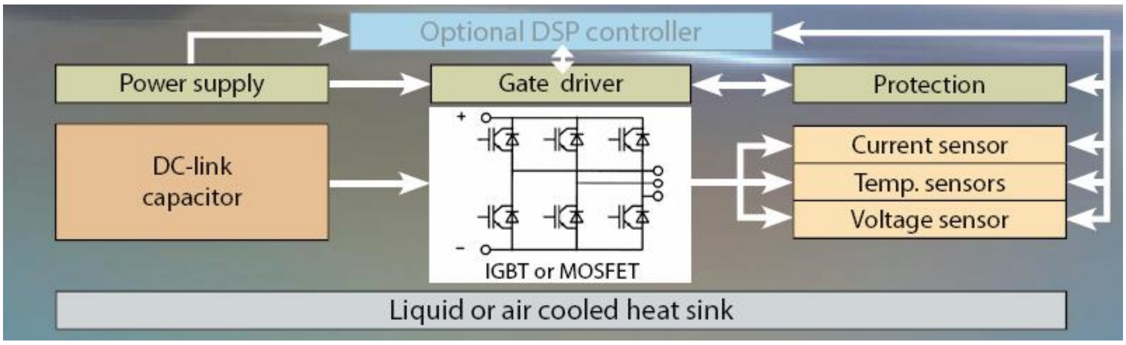
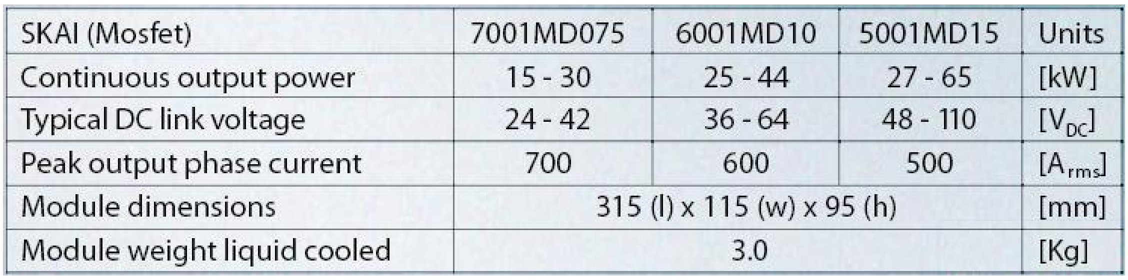


Figure 8.3. The arrangement of the self-commutated inverter [7].

SEMICRON produces three types of low-voltage power circuits. MOSFET transistors are used in the capacity of power keys. In Table 8.1 characteristics of these modules are represented.

Table 8.1. The characteristics of SKAI^{TM} low voltage product line [7].



SKAI (Mosfet)	7001MD075	6001MD10	5001MD15	Units
Continuous output power	15 - 30	25 - 44	27 - 65	[kW]
Typical DC link voltage	24 - 42	36 - 64	48 - 110	[V_{DC}]
Peak output phase current	700	600	500	[A_{rms}]
Module dimensions	315 (l) x 115 (w) x 95 (h)			[mm]
Module weight liquid cooled	3.0			[Kg]

To select more suitable MOSFET module the input voltage and current for the circuit must be known. The input voltage for the inverter can be calculated through the equation below [8]:

$$U_{\mathrm{do}} = \frac{1}{\pi/3}\int_{-\pi/6}^{\pi/6} \sqrt{2}\cdot U_{\mathrm{LL}}\cdot\cos(wt)\,\mathrm{d}(wt) = \frac{3}{\pi}\cdot\sqrt{2}\cdot U_{\mathrm{LL}} = 1.35U_{\mathrm{LL}}\ , \tag{8.1}$$

where U_{do} is an input voltage; U_{LL} is an output voltage, which is equal 34 V. Thereby the input voltage is:

$$U_{\mathrm{do}} = 1.35 U_{\mathrm{LL}} = 1.35 \cdot 34 = 45.9 \text{ V}. \tag{8.2}$$

And the direct input current can be defined through the equation [8]:

$$I_{\mathrm{s}} = \sqrt{\frac{2}{3}} \cdot I_{\mathrm{d}} = 0.816 I_{\mathrm{d}}, \tag{8.3}$$

where I_{d} is the input current of the inverter. So it is equal:

$$I_{\mathrm{d}} = \frac{I_{\mathrm{s}}}{0.816} = \frac{301}{0.816} = 368 \text{ A}. \tag{8.4}$$

After these calculations it is clear that 6001MD10 is the most suitable because of its voltage range.

8.3 Control principles of the inverter

There are two methods for implementation of the output voltage control of the self-commutated inverter: control of the input voltage magnitude and pulse-width modulation by special way of power switches commutation when the input voltage is constant. In our case the PWM should be used. It is possible to describe PWM through the figure representing basic switching vectors diagram of the inverter. The diagram is represented in Figure 8.4. The figures on the diagram denote the numbers of the MOSFET transistors represented in Figure 8.2 above. The switching of transistors groups occur every $\pi/3$ part of the period.

The special PWM algorithm also implements improvement of harmonic composition for output voltage. The range of PWM frequency is from 2 to 12 kHz that is bigger in order than output frequency. The curve of the output voltage looks like a high-frequency bipolar sequence of rectangular pulses. The current curve will be almost sine wave.

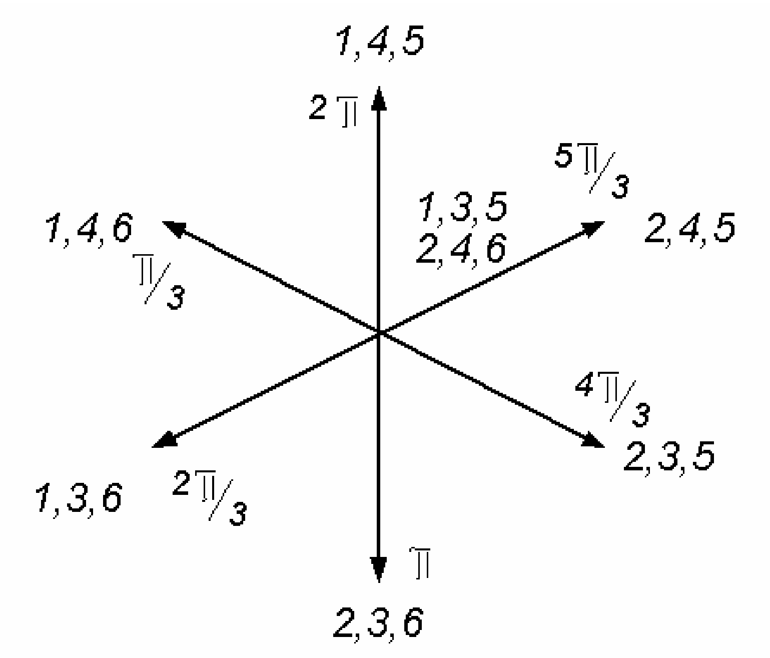


Figure 8.4. The diagram of the power switches commutation for PWM [14].

When the motor is working in regenerative mode the inverter should work like rectifier. The rectification is provided by reverse diodes and the MOSFET transistors supply the motor with reactive power for excitation.

9 DRIVE CONTROL MODE

9.1 Selection of the drive control mode

The control system of the self-induction inverter can provide different types of control. Selection of the control type depends on load characteristics and requirements in the field of control accuracy. The most simple drive control mode is the mode with linear relation between voltage and frequency of the inverter. Such control law can be represented through the equation:

$$\frac{U_s}{f} = \text{const}. \tag{9.1}$$

This type of control makes possible to keep the constant torque of the machine. But when the frequency get too low the maximum torque of the motor starts decreasing. To increase the torque in the range of low frequency it is possible to implement the function of start-up voltage increment.

To get more high quality of drive control it is need to use more perfect control mode. It can be for instance Flux Current Control mode (FCC) or Sensorless Vector Control mode (SVC). Both methods are adaptive motor model implementation based. SVC is most precise and efficient control method.

DC machines have two windings: stator winding and rotor winding, that makes it possible to control the speed of the machine (excitation current) and the torque of the machine (armature current). Squirrel cage induction motors have only one stator winding.

Excitation magnetic field and the torque of the machine is defined by the stator winding only. That’s the main challenge of the induction motor control. The main idea of the SVC is control of the magnitude and phase of the stator current i.e. the vector of a stator current should be controlled. But to control the stator current phase or the phase of the stator magnetic field relative to a rotating rotor it is need to know position of the rotor at any moment of time.

This problem can be solved with employment of a position sensor for instance some kind of encoder. But usage of such sensor results in complication of motor construction and significant rise in cost of the system.

Employment of the modern vector control technology allows avoiding these limitations through the usage of a mathematical adaptive motor model to predict the rotor position. It is need the control system to be able to make measurements of output current and voltage with high precision and provide fast calculation of the motor parameters.

The diagram of vector control system with main control blocks is represented in Figure 9.1.

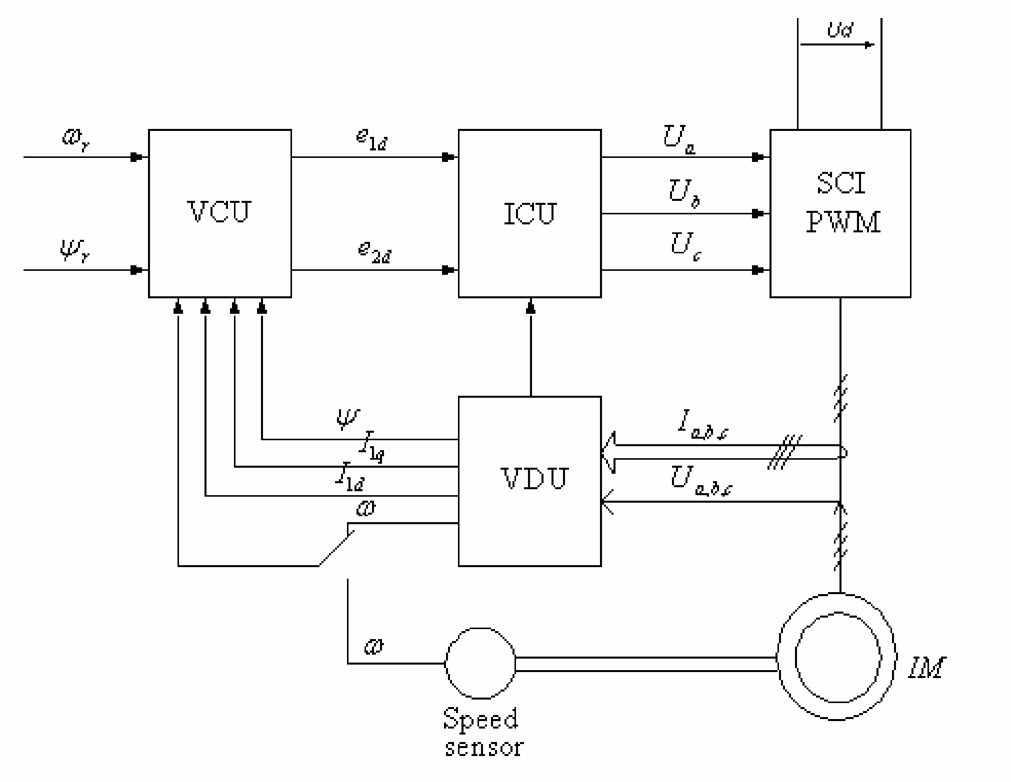


Figure 9.1. Block diagram of vector control system. The main units of the system are: VCU – variable control unit; VDU – variable definition unit; ICU – inverter control unit [14].

Input parameters for VCU are reference signals of speed w_s and flux linkagey_s, feedback signals (the stator current q and d components, the flux linkage of the rotor and speed). Generally VCU comprises set of control blocks such as a linkage control unit, torque and current control units. These units generate reference signals for stator current components.

ICU accomplishes phase and coordinate conversation of q and d components from two-phase system to three-phase system to generate control signals for the inverter. And VDU makes conversation of measured signals from real coordinates of three-phase system to two-phase system.

The minimum number of measured feedback variables for realization of the vector control algorithm is equal two variables. The variables which are available for measurement are:

- the stator current of an induction motor;
- the line-to-line voltage of an induction motor;
- angular speed of a rotor;
- angular position of a rotor.

9.2 Controller

9.2.1 Overview of special controllers

Nowadays a lot of manufactures produces special controller for different electrical drive system. Selection of such controller depends on demands raised to control system possibilities. Let us consider briefly some different types of controllers for drive system.

Microcontroller 68HC908MR24 of Motorola is developed for one- and three-phase motor drive applications. This microcontroller has special characteristics which allow implementing it for asynchronous drive control systems. It has 6-channel 12-bit PWM module, input port with high load-carrying current ability and 10-channel 10-bit analog-digital converter.

In one-phase drive system microcontroller can be used without speed sensor. This controller is developed for simple drive system to control the speed of an asynchronous machine with indirect speed feedback. But there is no need to use speed sensor because controller has special function to measure the motor current. This function allows indirect estimation of the motor speed.

In three-phase drive system microcontroller 68HC908MR24 controls the speed of asynchronous motor. It uses a feedback signal of a speed sensor. The controller can provide different types of linear relation between voltage and frequency of the inverter. It can be for instance such lows as U / f = const or U / f^2 = const.

Atmel also produces such kind of controllers. This manufacture developed two special controllers for typical applications with induction motor. They are AVR494 (for AC induction motor using the constant U / f principle and a natural PWM algorithm) and AVR495 (for AC induction motor using the constant U / f principle and a space vector PWM algorithm). This controller allows building of a speed control loop. If the measured speed differs from reference speed PI controller changes the stator voltage frequency to eliminate an error.

It is the simplest mode of induction motor drive control. As it was said above for precision torque control of the motor it is need to implement vector control principles. Thereby the controller should allow using these principles.

9.2.2 Digital signal processor with vector control possibility

Texas Instruments developed TMS320F241 digital signal processor (DSP) for power-electronics applications. This microprocessor is suitable for motor drive applications also. The Digital Signal Processor has special circuit for PWM to generate control analog signals for an inverter, the quadrature encoder circuit to decode the rotational distance and speed. The PWM modules can be combined to generate a three phase signals to drive the three phase power electronics applications such as a self-commutated inverter for three-phase asynchronous motor drive. The three phase signals are the six digital signals combined into three pairs. Each pair the signal for each phase and its inverted signal can be directly fed to the power devices such as IGBT driver [9].

The embedded quadrature encoder pulse circuit makes the speed and position measurement easier and faster than writing the detection into software. The encoder is the equipment for conversation of the rotational mechanical movement into the series of 2-bit binary code. The circuit accepts the maximum frequency more than 2 million pulses per second allowing the ability of capturing the speed and position of the motor at the precision of 1/10000 revolution at the speed of 12,000 rpm [9].

There are three types of programming which are available to use in this controller. They are: Assembly language, C language and visual development. There is own assembler and compiler supported by Texas Instruments. Visual development tools are available by the third party. After the compilation the binary code will be generated into the form of Intel Hex file format. The file can be loaded into the flash ROM of the digital signal processor [9].

One of the significant characteristics of this microcontroller is a facility of efficient direct digital control for all the power keys of the inverter simultaneously. That makes possible to regenerate the energy of motor braking mode effectively. So it is possible to build the control drive system based on this digital signal process.

The dimensions of the chip are 90x60 mm. The face of the chip is represented in Figure 9.2.

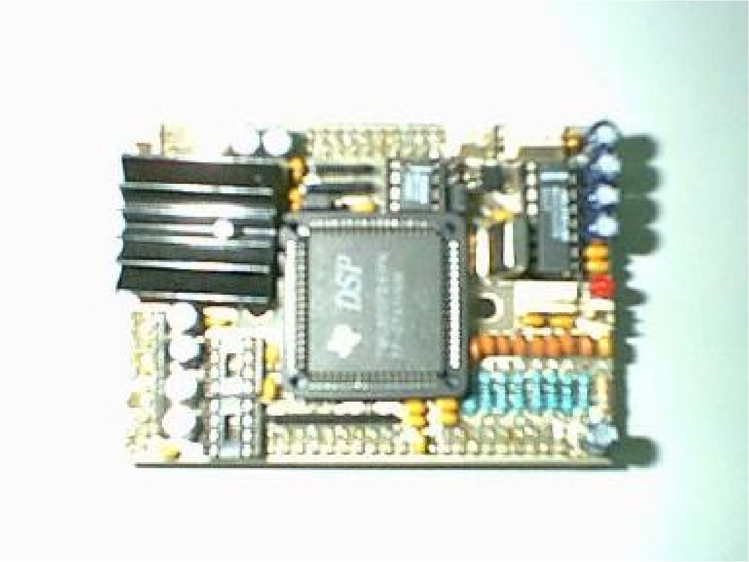


Figure 9.2. TMS320F241 digital signal processor [9].

9.2.3 DSP based microcontroller

The Educational Scientific Center “Texas Instruments – MEI” (Moscow) developed special TMS320F241 digital signal processor based microcontroller. It was developed for different type’s motor drive systems such as asynchronous and synchronous machines. The name of this microcontroller is MK9.1. The microcontroller is optimized for efficient motor drive control. The power range of drive system with MK9.1 is from hundreds watts to 150 kW. The general field of such systems implementation comprises high-quality quick-operating vector control systems. It can be used in traction electrical drive (electric vehicle, trolleybus, and tram), lift, and elevator drive system.

This microcontroller is a four-layer circuit board with dimensions 150x120 mm. The general view of the board is represented in Figure 9.3.

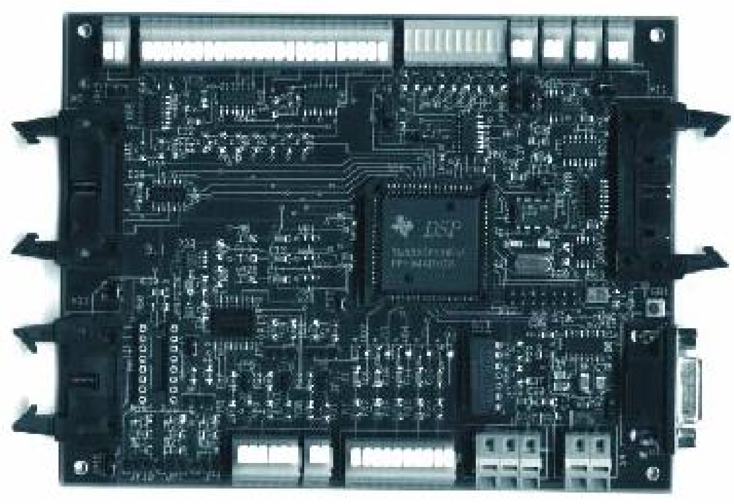


Figure 9.3. TMS320F241 DSP based MK9.1 microcontroller [10].

TMS320F241 digital signal processor has the enhanced Harvard architecture with special set of command for efficient real-time operation mode.

Before the microcontroller was started developing the estimation of the CPU recourses (the program memory size, data memory size, efficiency) was performed. The estimation was needed to find out if the signal processor was able to solve such typical problems as:

- vector control principles of asynchronous motor with motor position and speed observation, mathematical model of the stator and rotor of the machine, electromotive force compensation unit, vector PWM unit, coordinate conversion unit, digital control and filter units, unit controlling the regenerative energy reception, unit of typical protection, interface unit for high-level control system communication;

- vector control of synchronous and stepper motor including support of position and contour control (also the same characteristics described above) [10].

The first problem is most difficult and resource-intensive problem. To be able to solve this problem it is need to have 6-7kWords code memory. TMS320F241 DSP composes of standard features which are 8kWords of programmable flash ROM, 512 words of RAM and the embedded multiplier units. The efficiency of the processor should be not lower than 15 million instructions per second. And this chip can operate at the speed of 20 million operations per second. Thereby TMS320F241 is suitable for solving the problem of vector control principles. Moreover this chip can be used for solving other applied problems simultaneously with drive control operation.

10 CONCLUSION

The idea of new parallel hybrid system is represented and described in this Diploma Thesis. It is also showed which kind of motor can be used for such a system. Also possible control system is described in the Thesis. It is only beginning for further investigation. Here is represented the basic principles of system that can be efficient enough. Further investigations are needed to solve next problems: 1. standard 12 V storage system which can be used together with common vehicle storage system; 2. cost and efficiency calculation of the system.

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APPENDIX A. TABLE OF RECUPERATED POWER CALCULATION

In Table A1 variation of deceleration power is shown. During deceleration time a vehicle is acted by different forces which produce braking torque *T* on the cardan. It is assumed the vehicle starts decelerating from 60 km/h The linear speed of 16.6 m/s corresponds to 60 km/h.

Table A1. Recuperated power calculation

Time *t* [s]	Linear speed *V* [m/s]	Value of deceleration *j* [m/s2]	Cardan torque *T* [Nm]	Angular speed *Ω*[s-1]	Requperated power *P* [W]
0	16,67	1,60	121,44	51,28	6227,27
0,1	16,51	1,60	121,98	50,79	6195,28
0,2	16,35	1,60	122,53	50,30	6162,49
0,3	16,19	1,60	123,06	49,80	6128,89
0,4	16,03	1,60	123,59	49,31	6094,51
0,5	15,87	1,60	124,12	48,82	6059,35
0,6	15,71	1,60	124,64	48,33	6023,42
0,7	15,55	1,60	125,16	47,83	5986,72
0,8	15,39	1,60	125,67	47,34	5949,26
0,9	15,23	1,60	126,17	46,85	5911,05
1	15,07	1,60	126,67	46,36	5872,10
1,1	14,91	1,60	127,17	45,86	5832,42
1,2	14,75	1,60	127,66	45,37	5792,01
1,3	14,59	1,60	128,14	44,88	5750,88
1,4	14,43	1,60	128,62	44,39	5709,04
1,5	14,27	1,60	129,09	43,90	5666,50
1,6	14,11	1,60	129,56	43,40	5623,26
1,7	13,95	1,60	130,02	42,91	5579,34
1,8	13,79	1,60	130,48	42,42	5534,73
1,9	13,63	1,60	130,93	41,93	5489,46
2	13,47	1,60	131,38	41,43	5443,52
2,1	13,31	1,60	131,82	40,94	5396,92
2,2	13,15	1,60	132,26	40,45	5349,68
2,3	12,99	1,60	132,69	39,96	5301,79
2,4	12,83	1,60	133,11	39,46	5253,27
2,5	12,67	1,60	133,53	38,97	5204,13

Table A1. Recuperated power calculation (continuation)

Time t [s]	Linear speed V [m/s]	Value of deceleration j [m/s2]	Cardan torque T [Nm]	Angular speed Ω [s-1]	Requperated power P [W]
2,6	12,51	1,60	133,95	38,48	5154,37
2,7	12,35	1,60	134,36	37,99	5104,00
2,8	12,19	1,60	134,76	37,50	5053,03
2,9	12,03	1,60	135,16	37,00	5001,46
3	11,87	1,60	135,56	36,51	4949,31
3,1	11,71	1,60	135,95	36,02	4896,58
3,2	11,55	1,60	136,33	35,53	4843,28
3,3	11,39	1,60	136,71	35,03	4789,42
3,4	11,23	1,60	137,08	34,54	4735,00
3,5	11,07	1,60	137,45	34,05	4680,04
3,6	10,91	1,60	137,81	33,56	4624,54
3,7	10,75	1,60	138,17	33,06	4568,50
3,8	10,59	1,60	138,52	32,57	4511,94
3,9	10,43	1,60	138,87	32,08	4454,87
4	10,27	1,60	139,21	31,59	4397,28
4,1	10,11	1,60	139,54	31,10	4339,20
4,2	9,95	1,60	139,88	30,60	4280,63
4,3	9,79	1,60	140,20	30,11	4221,57
4,4	9,63	1,60	140,52	29,62	4162,03
4,5	9,47	1,60	140,84	29,13	4102,02
4,6	9,31	1,60	141,15	28,63	4041,56
4,7	9,15	1,60	141,45	28,14	3980,63
4,8	8,99	1,60	141,75	27,65	3919,27
4,9	8,83	1,60	142,04	27,16	3857,46
5	8,67	1,60	142,33	26,66	3795,23
5,1	8,51	1,60	142,62	26,17	3732,57
5,2	8,35	1,60	142,89	25,68	3669,50
5,3	8,19	1,60	143,17	25,19	3606,02
5,4	8,03	1,60	143,43	24,70	3542,15
5,5	7,87	1,60	143,70	24,20	3477,88
5,6	7,71	1,60	143,95	23,71	3413,23

Table A1. Recuperated power calculation (continuation)

Time *t* [s]	Linear speed *V* [m/s]	Value of deceleration *j* [m/s2]	Cardan torque *T* [Nm]	Angular speed *Ω* [s-1]	Requperated power *P* [W]
5,7	7,55	1,60	144,20	23,22	3348,20
5,8	7,39	1,60	144,45	22,73	3282,81
5,9	7,23	1,60	144,69	22,23	3217,05
6	7,07	1,60	144,93	21,74	3150,94
6,1	6,91	1,60	145,16	21,25	3084,49
6,2	6,75	1,60	145,38	20,76	3017,71
6,3	6,59	1,60	145,60	20,26	2950,59
6,4	6,43	1,60	145,82	19,77	2883,15
6,5	6,27	1,60	146,03	19,28	2815,40
6,6	6,11	1,60	146,23	18,79	2747,35
6,7	5,95	1,60	146,43	18,30	2678,99
6,8	5,79	1,60	146,62	17,80	2610,35
6,9	5,63	1,60	146,81	17,31	2541,43
7	5,47	1,60	146,99	16,82	2472,23
7,1	5,31	1,60	147,17	16,33	2402,76
7,2	5,15	1,60	147,34	15,83	2333,04
7,3	4,99	1,60	147,51	15,34	2263,06
7,4	4,83	1,60	147,67	14,85	2192,84
7,5	4,67	1,60	147,83	14,36	2122,39
7,6	4,51	1,60	147,98	13,86	2051,71
7,7	4,35	1,60	148,13	13,37	1980,81
7,8	4,19	1,60	148,27	12,88	1909,70
7,9	4,03	1,60	148,40	12,39	1838,38
8	3,87	1,60	148,53	11,90	1766,87
8,1	3,71	1,60	148,66	11,40	1695,17
8,2	3,55	1,60	148,78	10,91	1623,29
8,3	3,39	1,60	148,89	10,42	1551,24
8,4	3,23	1,60	149,00	9,93	1479,02
8,5	3,07	1,60	149,11	9,43	1406,64
8,6	2,91	1,60	149,20	8,94	1334,12

Table A1. Recuperated power calculation (continuation)

Time *t* [s]	Linear speed *V* [m/s]	Value of deceleration *j* [m/s2]	Cardan torque *T* [Nm]	Angular speed *Ω* [s-1]	Requperated power *P* [W]
8,7	2,75	1,60	149,30	8,45	1261,45
8,8	2,59	1,60	149,39	7,96	1188,65
8,9	2,43	1,60	149,47	7,46	1115,73
9	2,27	1,60	149,55	6,97	1042,68
9,1	2,11	1,60	149,62	6,48	969,53
9,2	1,95	1,60	149,68	5,99	896,27
9,3	1,79	1,60	149,75	5,50	822,91
9,4	1,63	1,60	149,80	5,00	749,47
9,5	1,47	1,60	149,85	4,51	675,96
9,6	1,31	1,60	149,90	4,02	602,37
9,7	1,15	1,60	149,94	3,53	528,71
9,8	0,99	1,60	149,98	3,03	455,00
9,9	0,83	1,60	150,01	2,54	381,24
10	0,67	1,60	150,03	2,05	307,45
10,1	0,51	1,60	150,05	1,56	233,61
10,2	0,35	1,60	150,06	1,06	159,76
10,3	0,19	1,60	150,07	0,57	85,89

APPENDIX B

To define the ‘harmonics’ it is need to calculate winding factor at first. The winding factor is calculated for the harmonics -300…300. Below the calculations from Mathcad are showed.

$\nu := -300..300$

$W := \tau_p$

$$\xi(\nu) := \frac{2\sin\left(\nu\cdot\frac{\pi\cdot W}{2\cdot\tau_p}\right)\cdot\sin\left(\frac{\nu\cdot\pi}{m\cdot 2}\right)}{\frac{Q_s}{m\cdot p}\cdot\sin\left(\nu\cdot\pi\cdot\frac{p}{Q_s}\right)}$$

$\xi(1) = 0.96$

$\xi(5) = 0.218$

$\xi(7) = 0.177$

$\nu := 1$ not short pitched

$$\xi(\nu) := \frac{\sin\left(\nu\cdot q\cdot\frac{\alpha_{us}}{2}\right)}{q\cdot\sin\left(\nu\cdot\frac{\alpha_{us}}{2}\right)}$$

$\xi(1) = 0.96$

Necessary superharmonics are selected

$all := -300..300$

$even := -300, -298..300$

$three := -297, -291..297$

$negat := -295, -289..295$

$$\text{harmonics}_1 := \sum_{\text{all}} \left(\frac{\xi(\text{all})}{\text{all}} \right)^2$$

$$\text{harmonics}_2 := \sum_{\text{even}} \left(\frac{\xi(\text{even})}{\text{even}} \right)^2$$

$$\text{harmonics}_3 := \sum_{\text{three}} \left(\frac{\xi(\text{three})}{\text{three}} \right)^2$$

$$\text{harmonics}_4 := \left(\frac{\xi(1)}{1} \right)^2$$

$$\text{harmonics}_5 := \sum_{\text{negat}} \left(\frac{\xi(\text{negat})}{\text{negat}} \right)^2$$

$$\text{harmonics} := \text{harmonics}_1 - \text{harmonics}_2 - \text{harmonics}_3 - \text{harmonics}_4 - \text{harmonics}_5$$

$$\text{harmonics} = 0.013$$