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DEPARTMENT OF POWER ELECTRICAL AND ELECTRONIC ENGINEERING

OPTIMALIZACE POHONU ZKRATOVAČE

SHORTING DEVICE DRIVE OPTIMALISATION

BAKALÁŘSKÁ PRÁCE
BACHELOR´S THESIS

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NÁZEV TÉMATU:

Optimalizace pohonu zkratovače

POKYNY PRO VYPRACOVÁNÍ:

1) Proveďte rozbor daného řešení pohonu zkratovače
2) Seznamte se s dalšími řešeními pohonu zkratovače VN (2 řešení)
3) Proveďte návrh měřícího přípravku.
4) Proveďte srovnání stávajícího a navrženého nového řešení.

DOPORUČENÁ LITERATURA:

[1] Havelka, Otto a kol. : Elektrické přístroje učebnice pro elektrotechnické fakulty vysokých škol technických, SNTL 1985
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UPOZORNĚNÍ:

ABSTRAKT

Tato bakalářská práce se zabývá optimalizací pohonu zkratovače ve vysokonapěťovém rozváděči ve spolupráci s firmou ABB s.r.o, pro kterou je tato práce zpracovávána. V první části se zabývá teoretickým rozborem spínacích přístrojů se zaměřením na bezobloukové spínací přístroje, kam patří i zmiňovaný zkratovač. V dalším textu jsou aktuální informace o teorii elektrických pohonů, které jsou později využité v praktické části. Podrobněji se práce zabývá teorií stejnosměrných strojů zejména motorů s permanentními magnety, jelikož tento druh motoru je použit i v pohonu, který pohání použitý zkratovač.

V další části je rozebrán celý pohon a všechny jeho části, několik odstravců je věnováno i výběru druhu optimalizace a zhodnocení současného stavu pohonu se zaměřením na jeho chyby a nedostatky. Jsou popsány parametry současného motoru a převodovek. V praktické části se dá nalézt protokol o zkoušce zkratovače, která proběhla v ABB s.r.o. V poslední části je k dispozici protokol z měření současného stavu nezatíženého pohonu. Jsou podrobně rozebrány a porovnány možnosti optimalizace pohonu. Všechna nabízená řešení byla důkladně konzultována se zástupci a techniky z průmyslových firem.

ABSTRACT

Objective of this bachelor thesis is optimalisation of shorting device drive located in high voltage switchboard in cooperation with company ABB s.r.o, for which this work is being done. First part is about theoretical analysis of switching devices with focus on switching devices without arc. Mentioned shorting device also belongs to this group. Work continues with current information from the field of electric drives, which are later used in practical part. Thesis contains theory about direct current motors in greater detail, especially group of direct current motors with permanent magnets, because this type of motor is currently used to drive the shorting device .

In final part it analyses whole drive and all of its parts, some paragraphs are dedicated to choosing type of optimalisation and evaluation of current drive solution with focus on its errors and problems. Nameplate parameters of current motor and gearboxes are described. In practical part there is protocol about test of shorting device, which took place in ABB s.r.o. In last part you can find results of unloaded drive measurement. Optimalisation options are carefully analysed and compared. All suggested solutions were discussed in detail with representatives and technicians from industrial companies.

KLÍČOVÁ SLOVA: vysokonapěťový rozváděč; zkratovač; elektrické pohony; stejnosměrný motor s permanentními magnety; optimalizace; měření

KEY WORDS: high voltage switchboard; shorting device; electric drives; direct current motor with permanent magnets; optimalisation; measurement

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V Brně dne …………………………… Podpis autora ………………………………..

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V Brně dne ....

....

Podpis

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LIST OF SYMBOLS AND ABBREVIATIONS

a [-] – constant determining type of winding

AC – alternating current

B [T] - magnetic induction

C_{ss} [V/Wb · min^{-1}] – constant of motor

DC – direct current

E [J] – energy

F [N] – force

i [-] – transmission constant

I [A] – electric current

IEC - international electrotechnical commission

J [kgm^2] – moment of inertia

L [H] – inductivity

M [Nm] – torque

N [-] – number of keeper threads

n [ot/min] – speed of motor

p [-] – number of poles

P [W] – power

PM – permanent magnets

r [m] – radius

R [Ω] – resistance

t [s] – time

U [V] – electric voltage

v [ms^{-1}] – velocity

ε [rad/s^2] – angle acceleration

η [%] – efficiency

φ [rad] – angle

ϕ [Wb] – magnetic flux

ω [rad/s] – angle velocity

z [-] – number of teeth

1 INTRODUCTION

With the advanced need for performance and reliability of modern society, every item of everyday use is being improved or optimalised. These demands will keep on increasing with time, so it is always important to find new ways how to improve a technical item. We can improve our devices in many ways. The key factors are purchase price and operation parameters. Error in improvement or optimalisation can result in damage of device.

My bachelor work should follow all steps that are needed in an optimalisation. I will optimalise parameters of drive. Energy of this drive is used in shorting device, located in high voltage switchboard. First, I will write theory about drives and switch devices in general, then I will analyse current solution and parameters of shorting device and drive. We will remeasure parameters of current drive and then proceed to optimalisation.

I have several ideas how to optimalise current drive. First I want to try optimalising it on energy. I will try to decrease amount of energy consumption while retaining demanded parameters and efficiency of drive. Preliminary objective is to at least half the energy needed in drive. There are many ways how to achieve that.

Optimalisation on energy consumption is important because in modern times we are trying to save as much energy as we can and use it somewhere else. With saving energy we can also save our finances. A lot of organizations and companies are trying to find new ways of how to save energy which leads to better quality of environment, increase of financial capital and efficient and maximalised income. In my work I will show that with proper optimalisation we can lower energy consumption of each electrical appliance and make it even more efficient.

Other optimalisation option is to use different type of motor. There are some problems occurring with current motor, which will be described later. DC motor with permanent magnets is currently being used. If we use series DC motor we can eliminate current problems of motor and increase all attributes of motor. But on the other hand series motor will probably be more expensive.

Lastly we will try to change current gearbox system. Drive uses two gearboxes which takes a lot of place and costs money. I will try to use one special transmission instead. This option should greatly save space and money.

I chose this thesis because I'm very interested in drive optimalisation and it is very similar to what I want to do in future. I also like that it has a practical part and that I can learn how to do this correctly.

2 THEORY

2.1 Switching devices

Switching devices are the largest device group. The reason is simple, switching in various voltage levels is different so it requires special construction. Also the devices are usually built exactly for specified use and parameters which explains why there are so many of them. We can also have different quality of used material which mirrors its final price.

Each switching device usually should have up to five parts. They are: current paths, isolation parts, mechanism, quencher and armour. The last two are not compulsory, they are included with switching devices which are required to break circuit with current. [1]

Construction, materials and parameters of switching device must be correctly chosen to endure effects of voltages and currents both operational and faulty while being safe and economic. These effects are dynamical (the device material must be able to repeatedly withstand force effects created with interaction of two or more current paths, this applies mainly with high currents) and Joules loses (the current is heating conductor and resistance is getting higher, material must be able to withstand heat, the most vulnerable to heat are insulators of course). When switched on, device must be able to transfer current with as little resistance of contacts as possible and force that pushes contacts together has to be strong enough. When switched off, device must isolate both contacts sufficiently and isolation strength must be high, otherwise current can glide between contacts when they are switched off and cause problems. [1]

We can divide devices into three groups. First group are devices without arc, second are operation devices and third are power devices. The division is based on voltage levels for which they are constructed. [2][3]

1. Devices without arc – their function is to connect and disconnect circuit without load or with very small current which can never produce an arc. Because there should never be arc

created between contacts, these devices do not need a quencher. Of course these devices can't disconnect high currents and shorts but they should be able to transfer them without being damaged or destroyed. Disconnecting path is usually clearly visible. [1] In this group we have disconnectors, earthing switches, control switches, cross-switches and shorting devices. [3] We can see typical inner disconnector on image 2.3.

Image 2.1 – High voltage three poled contactor [6]

2. operation devices – they should be able to connect and disconnect operation (or nominal) currents and overload (k multiples of nominal) currents, but not shorts. They should be able to transfer and withstand all kinds of currents including shorts. They have quencher to quench arc as soon as possible and to prevent damage to the circuit and device itself. [1] Typical examples of operation devices include

contactor (low and high voltage), disconnector, cross-switch, low voltage switch or high voltage motor switch. We can see one of many contactors on image 2.1.

Image 2.2 - High voltage switch for outer use [7]

3. Power devices – they should be able to connect and disconnect faulty circuit and circuit with shorts. We have power devices for one use or for multiple uses. [1] One time use power devices are fuses. Multiple time use are breakers or residual current circuit breakers (RCCB's) or protectors. From switching devices we use restrictive low voltage switch, high and very high voltage switches. We can see high voltage switch on image 2.2.

In next paragraphs we will concentrate on devices without arc, because that will be one of main points of this thesis. I will be optimalising motor for earthing switch (or shorting device).

2.1.1 Switching devices without arc

Switching devices without arc are large and important group of electrical devices, which are mainly used in distribution network of high voltage and very high voltage. Their function is to protect and under certain circumstances to switch on circuit under current. [2][3]

These devices are built as one, two or three pole units with simple construction, mechanically and electrically strong. Because of requirement to transfer even short currents, the current paths, especially contacts, need to be properly rated. Contacts have two options in construction design. They are either friction knife contacts or lamellar. Their movement is sliding, collapsible or rotational. Current paths are usually copper, sometimes bronze with silver plating. The shape of moving contacts is flat knives which are used in inner devices or contacts are made from copper tubes flattened on ends which are used in outer devices. [2]

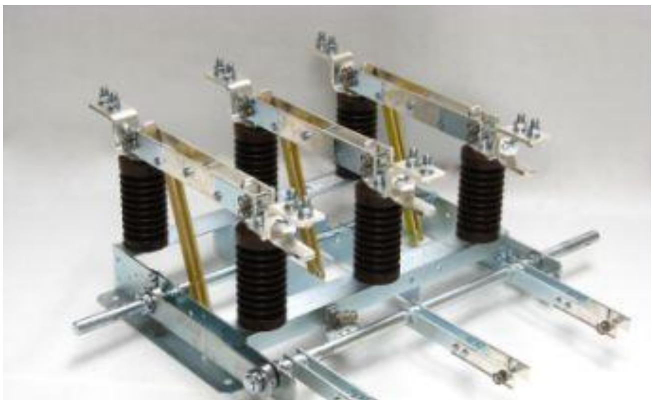

Image 2.3 – Typical disconnector for inner use [5]

Material of shorting knives is generally steel. Current paths are tightly mounted on support insulators. Supports for inner use are made of ceramics or epoxide resin in newer devices. For outer use we use glazed steatite ceramics. Supports are attached to metal frame. On this frame we can usually find mechanism for movement of contacts all at once or one at a time. Drive of this mechanism is either manual or they are motor driven. Except for motor we can also use drives based on use of compressed air. The purpose of this thesis is to optimalise this motor for shorting device. [2]

Shorting device is earthing switch with instant switching on movement and with guaranteed connective ability. They are typically used in metal encapsulated switchboards or other types of insulated or hermetized switchboards and in input fields of switchboards for safety reasons, in our case it is in high voltage switchboard, which contains both, the shorting device and its drive. In outer switchboards they are used rarely. When there is work on switchboard, it is necessary to earthen appropriate part for ensuring safety of workers. The primary conductors are in cases or compartments, which means we can't earth appropriate part of circuit with movable shorting kit. When there is an arc in switchboard, the shorting device will turn on and earthen circuit, transferring arc short current to metal short current, which must be switched off in power station. [2] Shorting device has lower requirements on rated current because its operation time is very short. That means the usual temperature rise tests are not needed. But it must have better endurance against short current and its dynamical effects. That means the tests on withstand short current are needed.

2.2 Electrical drives

Electrical drive is a system of components used for electromechanical change of energy and for creation, transfer and processing of signals that are controlling this change of energy. Input signals are chosen by service workers or superior automatization unit. Output signals are parameters of mechanical motion. Purpose of drive is to establish optimal behaviour for machines in technological process. Each drive has many parts:

1. power input
2. switching devices, fuses, breakers
3. semiconductor frequency converter
4. electromotor
5. gear
6. driven load
7. control unit

Control unit includes signalization, crash protections, service controllers or connection to superior system. Switching devices and breakers protect conductors of drive. Semiconductor converter is usually used to convert electrical energy of one parameter to electrical energy of other parameter or can sometimes be used as regulation device for electromotor. [4]

When deciding to choose an electrical drive for a mechanism, we must consider all its positive and negative properties. Positive properties are many. Electrical drive can be used in large scales of performances and torques, it does not produce harmful gases, it is customizable to various outer conditions, it is not extremely noisy, service and control is very easy, drive characteristics can be easily adjusted to special needs of customer, it works in all quadrants of speed – torque (ω-M) diagram, service life is long (sources states more than 20 years) and it has lowest no-load losses. Negative properties are few, mostly stated ones are: immediate dependency on supply of electrical energy from network and backup systems are usually very expensive and bad performance/weight ratio. [4]

We can divide electrical drives based on various parameters. We will be concerning only with the most important ones.

1) type of motion

A. linear

B. rotational

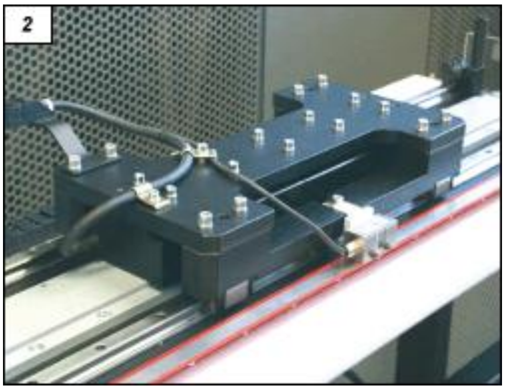

Image 2.4 – Linear motor [8]

There are not many linear drives, we can skip this option with rotational drives and convert rotational energy to linear in mechanical part of drive. Most of the drives in world create rotational motion. Linear engines have many poles and stator is spread to length of travel track. Is it used for drives of railway trains or subway trains. It is also used to swing bells. Rotational drives have stator and rotor close to each other. Based on electro-magnetical induction rotor starts to rotate and creates mechanical energy on shaft. Rotational drives are dominant in world and have many uses and applications. [13]

2) way of controlling engine speed

A. single speed
B. multiple speed
C. adjustable speed

3) type of control

A. manual
B. motor driven

4) types of electromotor

A. direct current
    a. externally excited
    b. serial
    c. parallel
    d. compound
    e. with permanent magnets

Direct current electromotors are powered by DC power supply. Important piece of motor is commutator, which is mechanical rotational switch, which changes the direction of current to rotor coils. We use it to power coil when it is under active pole and achieve highest possible efficiency. These motors have easy control – we can control them by excitation voltage change. They also have linear relation between speed of motor and excitation voltage. Disadvantage of them is use of commutator. With it we create additional losses and have to maintain it. [4]

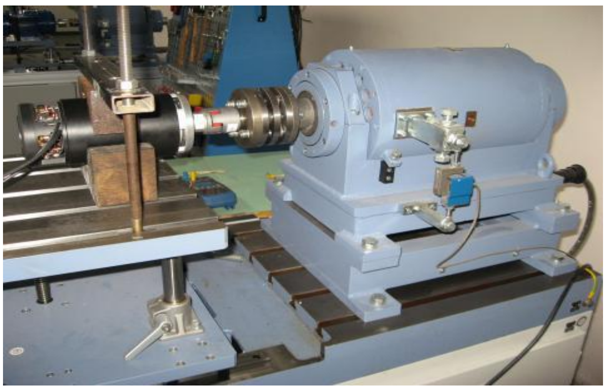

Image 2.5- DC motor [17]

Excitation winding can be connected to rotor in different ways or we can use permanent magnets. Each type of connection has its unique properties and use. If we use external excitation we power keeper winding from different power supply than stator winding. These motors are used in automobile industry and they are also used in drives of cameras, ventilators, pumps and heavy machinery. [13]

If we use series connection between rotor and excitation winding, we have only one current in keeper and mechanical characteristic becomes soft. These motors are used in traction, they have high torque in low speeds. Important is that they cannot be operated unloaded, because no-load current is very high and motor speed could become theoretically infinite. Recuperation of energy in these motors is more complicated than in external excitation. [4]

Parallel connection between windings is used in appliances where large scale of speed regulation is needed and we can also use this connection when we need easy braking. [19]

Compound connection has two excitation windings. One is connected to series with keeper and second is connected parallel. It combines properties of both types. Series winding increases magnetic flux that decreases speed and increases torque of motor. Parallel winding is limiting no-load speed. It is used for drives with hard start and in traction vehicles. [19]

B. alternating current
    a. asynchronous
    b. synchronous
    c. with permanent magnets
    d. reluctant
    e. stepper
    f. special

Asynchronous motors are largest group of electromotors. It has wide range of powers where it can be used. Flow of energy is realised on the basis of electromagnetic induction. It has high reliability and easy construction. It is usually connected directly to the network. Most common is three phased motor. With the use of frequency convertors in drive it can be operated in wide range of speeds. Speed of rotor and speed of magnetic field of stator is not the same that is why it is called asynchronous. [10]

Image 2.6 - Asynchronous motor [18]

Synchronous motors are used rarely. Their operation has many disadvantages. They must be phased into operation, we need to get them to operation speed with external machine and if it loses synchronization with rotating field, its power will drop quickly and motor will stop. [19]

AC motors with permanent magnets have many advantages over normal induction motors. They have higher efficiency, which leads to save of energy. This is caused by absence of rotor winding losses. The problem is usually with control of speed. We must use special encoders of real speed [16]

Reluctant electromotor are based on principle of reluctance which is magnetic resistance. It can have high power and is economically convenient. But it is very noisy due to significant fluctuations of twisting torque during low speeds. [19]

Stepper is special type of electromotor with many poles. It has synchronous speed and is used in applications where we need to control not only the speed but position of rotor too. For example in regulation technology and robotics. [19]

e) way of mechanical energy transfer

a. without transmission
b. with transmission

f) type of driven load

a. permanent load (S1)
b. short operation (S2)
c. discontinuous operation (S3)
d. discontinuous operation with start (S4)
e. discontinuous operation with electrical braking (S5)
f. discontinuous load (S6)
g. discontinuous regular load with electrical braking (S7)
h. discontinuous regular load with speed changes (S8)
i. irregular load with speed changes (S9)
j. discontinuous constant loads (S10)

S1 is permanent load when drive will achieve steady temperature rise in certain amount of time. S2 is short operation when drive will not achieve steady temperature rise and is shut down for time efficient enough to cool down to temperature of surrounding space. S3 is discontinuous operation when drive will not get to steady temperature rise but will not be shut off for significant amount of time to cool down to ambient temperature. Starting current has not great effect on temperature rise. S4 is type of load where starting current has great effect on rise of temperature. S5 is type of load which has electrical braking. S6 is type of load with sequence of different loads, but with no disconnect time. S7 is used when discontinuous load with electrical braking is regular. We use S8 when we regularly have different speeds of motor with different loads. In S9 load is changing irregularly but within certain range. S10 includes load characteristic with maximum of four discontinuous values. [15]

2.2.1 Speed – Torque (ω-M) diagram

The best way to see relation between torque of motor and its speed is to use ω-M diagram. We have 4 quadrants divided by horizontal axis on which we assign torque and vertical axis on which we assign angle velocity. The multiplication result of torque and angle velocity is performance of engine. If the performance is positive (Ist or IIIrd Q), then the drive is acting like motor, if the performance is negative (IInd or IVth Q), then the drive is acting like brake. From that we can assume that in first and third quadrant drive acts like motor and in second and fourth it acts like brake. Whole situation is clearly visible on image 2.7. [11]

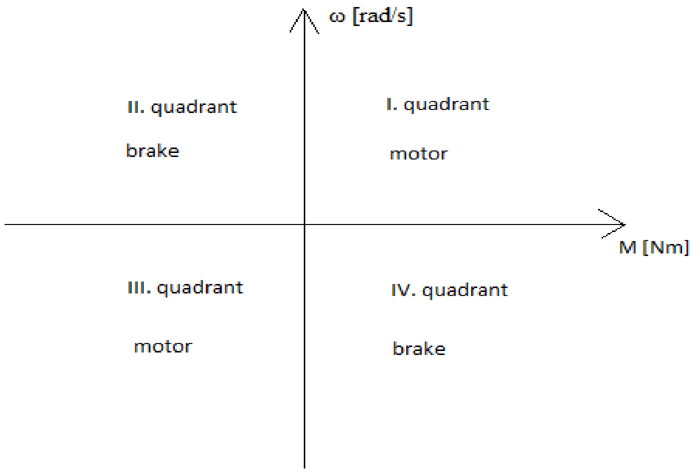

Image 2.7- Speed – Torque (ω-M) diagram [3]

Based on this characteristic we can divide electrical drives to three groups. First are one-quadrant – these drives can have operation point only in first quadrant and can only rotate in one way and cannot break electrically. Two quadrant drives can either change way of rotation with constant torque or they can change torque while way of rotation remains the same. Third group are four quadrant drives which can change sense of rotation and sense of torque. Operating point can be anywhere on ω-M diagram. [4]

2.2.2 Mechanics of electrical drive

Mechanics of drives is concerned with mutual interaction of electromotor and driven load. Parameters of motor are rated based on needs of driven load. We must solve mechanical system motor-load to determine if there is a possibility of mechanical oscillations and dynamical stress.

If we want to observe behaviour of mechanical system in time, we can find out that system can be in one of these states:

a) stop – system is not moving, angle speed is zero
b) start – system is increasing its either rotational or linear speed, angle acceleration is greater than zero and torque of motor is greater than torque of load
c) operation – system speed is constant, angle acceleration is zero and torque of motor is same as torque of load
d) braking – system speed is decreasing, angle acceleration is lower than zero and torque of motor is lesser than torque of load
e) counter-rotating – running system will stop first and then start again with opposite sense of rotation [4]

If we want to describe behaviour of rotational mechanical system we can use d'Alembert principle that states: *„Object rotating around its axis is in dynamical balance if resultant of all torques affecting object equals zero“.* [3]

Mathematically:

$$\sum_{i=1}^{n} M_i + M_d = 0 \qquad \text{eq. 2.1}$$

where M_i [Nm] – are driving and driven torques

M_d [Nm] – is dynamical torque

Mechanical performance is product of motor performance and its torque on shaft. We can write equation:

$$P = M_{mech} \cdot \omega \qquad \text{eq. 2.2}$$

where P [W] – is motor performance

M_{mech} [Nm] – is torque on shaft

ω [rad/s] – angle velocity

In further text we will always consider consumed performance as positive and supplied performance as negative. Angle velocity has constant sign for all parts of drive that means we can say sign convention applies to torques too, based on eq. 2.2. For simpler systems with one electromotor and one load we can rewrite motion equation 2.1 as follows:

$$M - M_z = M_d \qquad \text{eq. 2.3}$$

where M [Nm] – is torque of motor (torque on shaft)

M_z [Nm] – is torque of driven load

We can analogically say that torque in rotational motion is force in linear motion and angle velocity in rotational motion is velocity in linear.

$$\sum_{i=1}^{n} F_i + F_d = 0 \qquad \text{eq. 2.4}$$

$$P = F \cdot v \qquad \text{eq. 2.5}$$

We have several basic principles from uniform circle motion that we need to consider and use in rotational motors. Angle of shaft φ [rad] is angle track that motion vector completes in time. It is analogical to length of path being product of velocity and time. For rotational move we can write:

$$\varphi = \omega \cdot t \qquad \text{eq. 2.6}$$

But not all moves are uniform or direct. For more complicated moves we will use relation between position, velocity and acceleration. It is known that velocity describes how fast is change of position in time, in other words it is derivative of position in time. Acceleration shows how fast is speed changing in time so it is derivative of speed in time. Some principle applies to rotational moves but our variables will be different. Instead of position we use angle, instead of velocity we use angle velocity and instead of acceleration we use angle acceleration. We can say:

$$\omega = \frac{d\varphi}{dt} \quad and \quad \varepsilon = \frac{d\omega}{dt} \qquad \text{eq. 2.7}$$

Where φ [rad] – is angle

ε [rad/s^2] – is angle acceleration

We sometimes do not need angle velocity but we need circuit velocity. Relation between them is shown in eq. 2.8

$$v = \omega \cdot r \qquad \text{eq. 2.8}$$

Where r [m] – is circle radius

We can now define how we will calculate dynamical torque. Eq. 2.9 shows basic relation, inference of this equation is not purpose of this thesis, but you can look where formula came from for example in [12].

$$M_d = J \cdot \frac{d\omega}{dt} = J \cdot \varepsilon \qquad \text{eq. 2.9}$$

Where J [kgm^2] is moment of inertia

Torque is usually defined as product of force affecting a stiff object and its radius, causing the object to rotate. Torque in rotational motion is analogical to force in linear motion. Moment of inertia is describes distribution of mass in stiff object and we use it in rotational motion equations. In linear motion we simply use mass.

Moment of inertia is constant for most of mechanical systems that’s why we can reproach it before derivation and formula becomes simpler. Thanks to eq. 2.7 we can rewrite eq. 2.9 in three ways, using either angle of shaft, angle velocity or angle acceleration. We usually use formula with shaft angle for immediate position and we use formula 2.9 for tasks that require immediate speed. The mostly used formula in electrical drives is eq. 2.9. We can have more complicated mechanical systems where solving with these formulas could be very long. That’s why we use special methods to make our work easier. We will describe two most used ones. [4]

A) release method – we will divide complicated mechanical system into several parts and release them from their position. In releasing place we will substitute effect of mutual relations with newly created reaction force and torque. Each part will be described with motion equation and then we will solve system of equations. This method respects all influences and can be used in any mechanical system but solution of large system of equations can be long.

B) reduction of forces and masses method – we will substitute all system with one fictional object. This object will be affected by all forces and torques of system. We can then rewrite eq. 2.3 to this form:

$$M - M_{zred} = J_{red} \cdot \varepsilon = J_{red} \cdot \frac{d\omega}{dt} = J_{red} \cdot \frac{d^2\varphi}{dt^2}$$ eq. 2.10

Where M_{zred} [Nm] – reduced torque

J_{red} [kgm^2] – reduced moment of inertia

Mechanical parts of system is connected transmission and gears. It allows us to change speed of motor for needed speed for driven load. It is ratio of input and output speed of drive system. In other words:

$$i = \frac{\omega_1}{\omega_2} = \frac{z_2}{z_1}$$ eq. 2.11

where z_1 [-] – number of teeth of first gear

z_2 [-] – number of teeth of second gear

We can figure out how to calculate reduced torque from power equality. Total power input on shaft of motor minus losses in system must equal power output at load.

$$P_1 \cdot \eta = M_{red} \cdot \omega \cdot \eta = F \cdot v$$ eq. 2.12

If we will now use eq. 2.8 and eq. 2.11 and combine them with eq. 2.12, we can express formula for reduced torque. We will index formula for general use.

$$M_{ired} = F_i \cdot r_i \cdot \frac{1}{i_i} \cdot \frac{1}{\eta_i} = M_i \cdot \frac{1}{i_i} \cdot \frac{1}{\eta_i}$$ eq. 2.13

where η_i [-] is efficiency of transfer path

For reduced moment of inertia formula we need to use eq. 2.9 for dynamical torque. Dynamical torque of unreduced system must be equal to dynamical torque of reduced system.

$$M_{1ired} \cdot \omega_1 \cdot \eta_{1i} = J_{1ired} \cdot \frac{d\omega_1}{dt} \cdot \omega_1 \cdot \eta_{1i} = M_{di} \cdot \omega_i = J_i \cdot \frac{d\omega_i}{dt} \cdot \omega_i$$ eq. 2.14

And from that we get a formula for reduced moment of inertia

$$J_{ired} = J_i \cdot \frac{1}{i_i^2} \cdot \frac{1}{\eta_i}$$ eq. 2.15

We will be using equations 2.13 and 2.15 for optimalisation of drive later. [4]

2.2.3 Torque of motor

Each motor has different torque behaviour. We usually observe this behaviour in relation with motor speed because these output parameters are important for everyone. It determines which motor is good for which purpose and load. We can see how torque of motor is changing with increasing or decreasing speed on image 2.8.

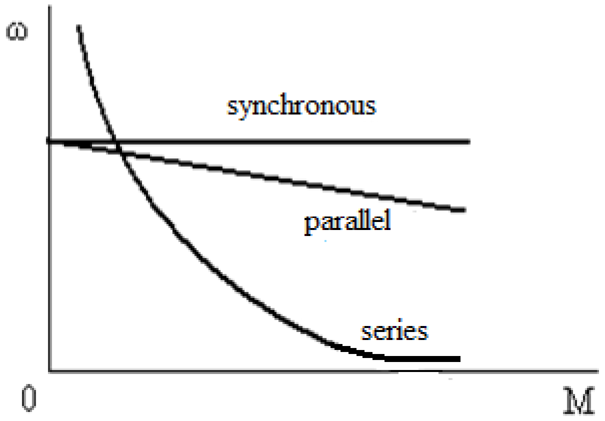

Image 2.8 - Characteristics of drive torque [9]

If angle velocity is independent on torque of motor we speak of synchronous motor. This machine is connected to power network and its speed is proportional to frequency of network and is not changing with load. We call it hard characteristic.

If angle velocity is slightly decreasing then we speak of derivative motor. Process is linear.

If angle velocity is decreasing faster with logarithmic curve we speak of series motor. That is soft characteristic. Speed of motor is proportional to load. Bigger the load, lesser the speed. [3]

We call this characteristic inversional mechanical characteristic. It is widely used in power engineering and electrical drives. Instead of torque we can sometimes need power $\omega=f(P)$. In theory of electrical machines however, we use torque characteristic $M=f(\omega)$ and power characteristic $P=f(\omega)$. [3]

2.2.4 Torque of load

This characteristic indicates behaviour and reactions of driven mechanism (load) to torque of motor and its speed. We use these characteristics to determine which motor do we need and what value of torque and speed is optimal for operation of our mechanism. Mechanical energy is usually changed in load to different type of energy. If we can get supplied energy back from mechanism, it is active torque of load. If we cannot it is passive torque of load. Situation is shown on image 2.9 [3]

2.2.5 Electromechanical transient states

Transient is behaviour of drive in time between two stable states. It is also understandable as response to change of control signal or drive parameter. That means every time we change voltage of source the drive enters a transient state for certain amount of time before it stabilizes on needed value. This response to change of parameters is very important when designing drive. There are three basic transient states that must be considered:

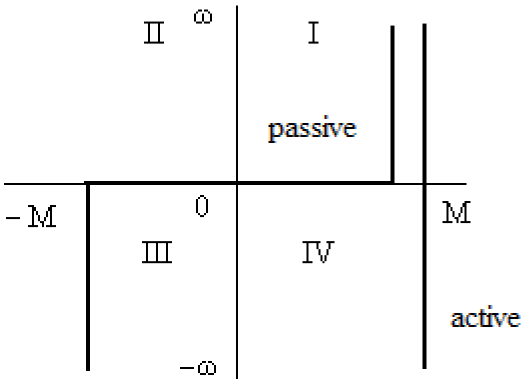

Image 2.9 – Torque of load [9]

1. electromagnetic transients – electrical and magnetic energies of magnetic circuit of motor are changing into one another. This state usually lasts from tens to hundreds of milliseconds before stabilizing. We can measure electromagnetic time constant on oscilloscope from current graph.

2. electromechanical transients – electromagnetic torque and angle velocity of motor are changing into one another. This transient stabilizes in hundreds of milliseconds or tens of seconds. We can measure electromechanical time constant on oscilloscope from speed graph.

3. thermal transients – temperature rise of winding and magnetic circuit of motor is changing in time and it lasts from milliseconds to tens of minutes.

Generally for electromechanical calculations we can assume constant electromagnetic torque because electromagnetic transient is over before the electromechanical transient finishes. Similar when determining temperature rise of motor we do not have to consider electromechanical influence because it is usually already ended.

2.2.6 Losses of drive

In every machine or device used for conversion of energy part of that energy is lose in useless form (thermal, friction, ventilation). Loss energy is difference between input energy from supply and output useful energy of machine. It is important to know what kind of losses designed machine have and find a way how to lower them and increase final efficiency of drive.

Efficiency is quotient of output and input energy or work. But sometimes we need to compare amounts of energy in time. So we can express efficiency as ratio between output power and input power. Sum of output power and losses in drive must give input power.

$$\eta = \frac{P_2}{P_1} = \frac{P_2}{P_2 + \Delta P} = \frac{P_1 - \Delta P}{P_1} \qquad \text{eq. 2.16}$$

a) losses in rotor and stator windings – in rotational machines 35 – 60% of all losses happen in windings, in transformers it is even more, about 70 – 78%. They are proportional to current in winding squared. They are created when the current is going through windings. Current increases temperature of windings and loses energy in form of the useless heat. We can measure them when motor is shorted. [4]

b) losses in excitation winding – in DC machines with series excitation we add them to losses in keeper. In synchronous and other machines they are taken as constant. [4]

c) losses on commutator and slippery rings – they are important in asynchronous ring, synchronous and DC machines. They are proportional to current. Loss of energy is caused again by current which heats the slip rings and commutator and leaves machine in form of heat. [4]

d) losses in magnetic circuit – they are divided into two groups. Hysteresis losses are caused by magnetic hysteresis in cyclic magnetization of ferromagnetic materials. Some of the magnetic energy dissipates in form of heat and the losses are proportional to magnetic induction squared and frequency of supply voltage. Eddy current losses in magnetic circuit are caused by eddy currents, which are result of electrical conductivity of ferromagnetic materials. In order to decrease losses from eddy currents created from magnetic energy we construct machines with isolated sheets, because eddy currents are proportional to area. These losses are also proportional to magnetic induction and frequency of supply voltage both squared. When we add these losses together we have total losses in magnetic circuit or total losses in iron as they are called. We can measure these losses when the machine is working with no load. [3]

e) Losses in mechanical parts – they can be either frictional or from ventilation. Friction losses are created when rotating parts create friction together and part of mechanical energy is converting to heat which leaves machine. They are proportional to speed of machine. Ventilation losses are created in ventilators of machine which serves for cooling motor and removal of unneeded heat. [4]

f) Losses in convertors – they are sum of all losses in convertor such as losses in current circuits, in semiconductor materials, cooling systems, supports systems, control systems etc.

2.2.7 Controlling of electrical drives

When improving technological processes we can distinguish two development stages.

Mechanization – is process designed for reducing hard psychical labour of workers

Automation – is process to substitute need for human control of different technologies. Objective of this is to increase speed and quality of technological process.

Regulation is most common type of control. Regulation system evaluates immediate values of physical quantities and maintains their values in acceptable radius based on criteria. In electrical drives we need high speed of regulation intervention. Various semiconductor convertors are used as regulators in drives. For example frequency convertor in asynchronous motor for regulation of speed. Sometimes we also need rectifiers, inverters and other types of convertors in drive. [4]

2.2.8 Connection of electrical drive and switching device

The drive moves and controls contacts of switching device, that means it controls switching device on and off. In this case, our demands on drive parameters are derived from kinematic and dynamic parameters that we require. For example speed and character of contact movement, angle of shafts, frictional and resistance forces, stroke of contacts, effective time, weight of all parts and other.

For switching devices we use direct or indirect drives. Indirect drives contain one special part called freewheel. Its purpose is to transfer torque of drive to movable contacts and to separate mechanism of switching on and off. Direct drive is usually used in arcless switching devices.

Both options can be either manual or machinal. Manual are again used mainly with arcless or simple devices while machinal are used widely everywhere else. It can use different types of energy. Some drives have both manual and machinal option, while manual serves usually when machinal does not work or there is some work on the drive. [2]

2.3 DC machines

The main use of DC machines is in regulation and traction, although use of asynchronous motors or other type of motor with semiconductor regulation is becoming more and more popular.

Magnetic circuit of DC machine is composed of metal sheets. On poles of stator we can find excitation winding or permanent magnets. There are two kinds of poles on stator – main poles and commutation poles which serves for improving commutation and compensation of keeper reaction. In grooves of main poles there is also compensation winding. This winding also serves for compensation of keeper reaction. Keeper winding leads to commutator and through brushes to terminal. [13]

Advantages - Series DC motors have soft motor characteristic as is shown on image 2.8, which is why we use them in traction – torque is high on low velocities. Other types of excitation also have high torque on low velocities but their relation is linear. All DC motors have easy way to control their speed with either keeper voltage or excitation current change (this change is not usable in DC motor with permanent magnets where excitation is constant). Operation characteristics can be adjusted to needs of load with excitation changes. DC motors have large range of speeds and powers where they can be used and direction of rotation can be easily changed. One of options is to switch polarity of keeper voltage. [4]

Disadvantages – The presence of a complex commutator which is difficult to operate and maintain and which also produces additional losses of motor. Maximal speed and thus also maximal power is limited by commutation. [4]

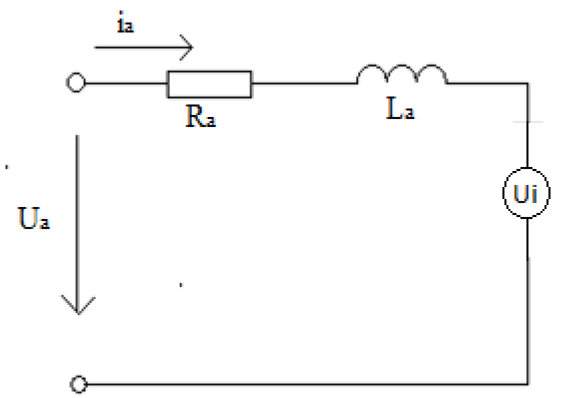

Image 2.10 – DC machine circuit model

The circuit model for DC series machine is shown on image 2.7. There are resistance, inductance and induced voltage of keeper. Excitation winding can be in series with keeper. It can also be parallel to keeper or both (this option is called compound). Some DC motors use external excitation of stator winding or permanent magnets. In DC series motor there is only one current, which means excitation current is the same one as keeper current. We usually add together resistance of winding and keeper. Ballast resistance is also used for regulation in DC motors. Keeper in DC machines is rotor winding with brushes. [4][14]

For our purposes we will simplify mathematical model of DC machines with following assumptions:

- the influence of eddy currents is disregarded,

- the influence of voltage drop at the brushes is disregarded,
- the influence of keeper reaction is disregarded,
- the influence of the transformation coupling between windings is disregarded,
- the disperse magnetic flux of the excitation winding is disregarded, [14]

With these simplifications, mathematical equation of circuit would be:

$$u = R_a \cdot i_a + L_a \cdot \frac{di_a}{dt} + u_i \qquad \text{eq. 2.17}$$

where R_a [Ω] – is resistance of keeper winding

i_a [A] – is immediate value of keeper current

L_a [H] – is induction of keeper

u_i [V] – is immediate value of induced voltage

During optimalisation we will be relying on two basic equations for torque and induced voltage of DC machine. Derivation of these formulas is not part of this thesis and can be found for example in [13].

$$M = C_{ss} \cdot \phi \cdot i_a \qquad \text{eq. 2.18}$$

$$u_i = C_{ss} \cdot \phi \cdot \omega_m \qquad \text{eq. 2.19}$$

where C_{ss} [V/Wb · min^{-1}] – is constant of machine

Φ [Wb] – is magnetic flux

ω_m [rad/s] – angle velocity of motor

We can determine constant C_{ss} from construction quantities of motor.

$$C_{ss} = \frac{1}{\pi} \cdot \frac{p}{a} \cdot N \qquad \text{eq. 2.20}$$

where p [-] – is number of pole pairs

a [-] – is constant determining type of winding

N [-] – is number of keeper threads

It is useful to know relation between mechanical velocity of motor and induced voltage. We will use circuit equation 2.17 in steady state where time derivations will be zero and equation 2.18 and put them together:

$$U = R_a \cdot I_a + U_i = \\ = R_a \cdot \frac{M}{C_{ss} \cdot \phi} + C_{ss} \cdot \phi \cdot \omega_m \qquad \text{eq. 2.21}$$

Now we can separate angle velocity on one side of equation and determinate relation between angle velocity and supply voltage.

$$\omega_m = \frac{U}{C_{ss} \cdot \phi} - \frac{R_a \cdot M}{(C_{ss} \cdot \phi)^2} \qquad \text{eq. 2.22}$$

First fraction is no-load speed because when motor works unloaded its torque is zero which eliminates second fraction. Second fraction represents speed drop due to load torque and it determines hardness of speed-torque characteristic.

Later in optimalisation we will be comparing DC series motor and DC motor with permanent magnets. We must know what parameters these motors have and what theoretical differences they have.

Speed-torque characteristic of DC motor with permanent magnets is linear curve. Speed is decreasing with torque. We can achieve higher speed with keeper voltage change. From equation 2.22 we can derive another option for regulation of speed. If excitation current will be lower we can achieve higher speed. Magnetic flux is proportional to excitation current. Last option is to change resistance in keeper. We can use ballast resistance and adjust shape of speed-torque characteristic. These motors are used in automobiles, cameras and in drives of electromobiles, submarines, boats etc.

Curve that describes behaviour of series DC motor speed with changing load is called polytrope. It is shown on image 2.6. From its shape we see that when motor has no-load speed we can theoretically achieve infinity, the curve is asymptotically approaching angle velocity axis. In real machines however it is not possible because of non-zero loses. But still it is important to know that we cannot operate series motor unloaded because we could destroy the motor. This characteristic is called soft that means torque is rapidly decreasing with speed. When we want to use a drive with DC series motor we must consider that it has high torque in low speeds. These motors are mainly used in traction.

This thesis will now concentrate on DC motors with permanent magnets because this type of motor is used in drive. [4]

2.3.1 Starting drives with DC motors with permanent magnets

As stated before, when we connect motor with zero induced voltage and zero speed to network, the unloaded speed will be very high and dangerous for motor. Is it caused by fact that rotor current in this moment is limited only by low resistance of rotor winding. The current is critically high and can damage motor and cause high torque impacts. We must limit its amplitude. We can determine its value from eq. 2.23. This theory does not apply in smaller DC motors with permanent magnets, where voltage is low and resistance of keeper is high. [14]

$$I_{aK} = \frac{U}{R_a} \qquad \text{eq. 2.23}$$

a) starting by inserting ballast resistance

When we use additional resistance in series with rotor winding we can limit inrush current and torque. Curve of characteristic shifts to lower speed value based on sum of all resistances. More than one ballast resistance is usually used. All ballast resistances are gradually disconnected or shorted after limiting inrush current. In the end in operation mode all ballast resistances are disconnected because it would not be useful to limit current and motor power in operation. We only use them when the motor is starting. Disadvantages include: possible torque impacts during switching resistance stages and additional losses of energy in ballast resistances. Equation for lower inrush current:

$$I_{aK} = \frac{U}{R_a + \sum_{i=1}^{n} R_p} \qquad \text{eq. 2.24}$$

where R_p [Ω] – is ballast resistance

b) starting with reduced voltage

As is shown on eq. 2.23 another way to decreasing inrush current and torque is by limiting supply voltage. This method is energetically economical and if continuous supply voltage rise is ensured, there will be no torque impacts. It is also possible to use feedback loop and start motor with constant values of current and torque. When possible it is better to choose this way of starting. [4]

2.3.2 Braking of DC motors with permanent magnets

a) Regenerative braking

DC machine will be operating in generator mode, that means it will have negative torque and will be converting mechanical energy to electrical and return it to power supply. Machine can enter this mode by switching polarity of load torque, for example when car is going down the hill. The speed will be higher than no-load speed and it enters regenerative mode. This is the most energy efficient way of braking. We can use power from kinetic energy to charge accumulator in electromobile.

b) Resistance braking

Machine is disconnected from network and connected to series of resistors, while operating as dynamo. The braking torque is determined by braking current, which depends on induced voltage and braking resistance:

$$I_a = \frac{U_i}{R_a + R_B} \qquad \text{eq. 2.25}$$

where R_B [Ω] is braking resistance

Advantage of this method is simple use which is why it is still used in e.g. rail vehicles for braking. Disadvantage is again waste of energy in form of heat in braking resistor in case of simple inverter used without recuperation.

c) counter current braking

In order to enter this mode we must reverse polarity of no-load speed. It can be done in two ways – we can either change polarity of rotor or change polarity of winding. Counter current is higher than rotor current so ballast resistance must be inserted to the circuit to waste braked energy and energy from power supply. [4]

2.3.3 Controlling drives with DC motors with permanent magnets

a) controlling speed by inserting ballast resistance

Speed change depends on the magnitude of ballast resistance change and on course of mechanical characteristic of load. Again this method is wasteful but simple so it is still used in many rail systems.

$$I_a = \frac{U_a + U_i}{R_a + R_p} \qquad \text{eq. 2.26}$$

b) controlling speed by supply voltage change

From equation 2.21 we already know relation between motor speed and supply voltage. Because of hard mechanical characteristic speed change does not depend on course of mechanical characteristic of load. Increasing supply voltage leads to increase of speed. This is economical method. Continuous change of supply voltage is provided by semiconductor converter when it is set to maintain desired value of motor current. [4]

3 OPTIMALISATION

The most common parameter to be optimalised is purchase price of drive. Companies are always trying to save money where it is possible while retaining efficiency of technological process and quality of product. In my work I should try to decrease price of new motor and also price of operation costs. I will not numerically determine all parts but rather try to use generally cheaper ones or come up with new solution while retaining or even improving parameters of drive.

Image 3.1 - Hypoid gearbox

Another useful optimalisation is decreasing consumption of energy and energy losses. This is best used with machines and devices that are in constant operation where decreasing energy consumption can lead to saving a lot of money for company. But our solution includes shorting device which will only be used several times a month and for a short amount of time. Therefore optimalisation on energy would not be so effective and is important only for system with limited amount of energy (energy harvesting systems).

We can also change dimensions of drive to make it smaller and save space. Or we can make it lighter. But these solutions are not always needed in stationary machines and devices and could distinctly increase price of drive. Our drive is located in high voltage switchboard and is not needed to be smaller.

There are lots of other ways to optimalise machine or device, for example increasing output power, increasing speed, increasing torque or we can improve control unit of drive and increase reliability.

If the drive is overrated it will have bigger weight, dimensions and price. Overrating will also decrease efficiency and dynamical torque during transients can be higher which leads to greater mechanical stress which decreases service life of drive.

If the drive is underrated it leads to decreasing of useful power and if overloaded it leads to higher temperature rise of motor components which mainly affects isolation that has lowest point of melting. This leads to decreased service life of drive isolation. Costs of repairs then increase operation costs. [4]

3.1 Analysis of current drive solution

The purpose of electromotor is to drive shorting device located in high voltage switchboard. Shorting device is not compulsory part of switchboard and is used only several times a month when doing maintenance on switchboard. Its drive can be manual or machinal, but some

Image 3.2 - Current drive

customers want to control the switching device from far away so they choose this electric drive. Current solution is shown on image 3.2

Electric drive is composed of DC electromotor Groschopp No. 11686106 type PM1 48-55 with permanent magnets (image 3.4), frontal gearbox Renolit SO-GFB type SG 80, hypoid gearbox composed of two front cogwheels and one hypoid cogwheel which is shown on image 3.1, mechanical stop (image 3.5), camshaft, control unit (image 3.5) and terminal (image 3.3). Hypoid gearbox is in aluminium pressure-casted frame. There is sheet piece for attachment of drive to switching device.

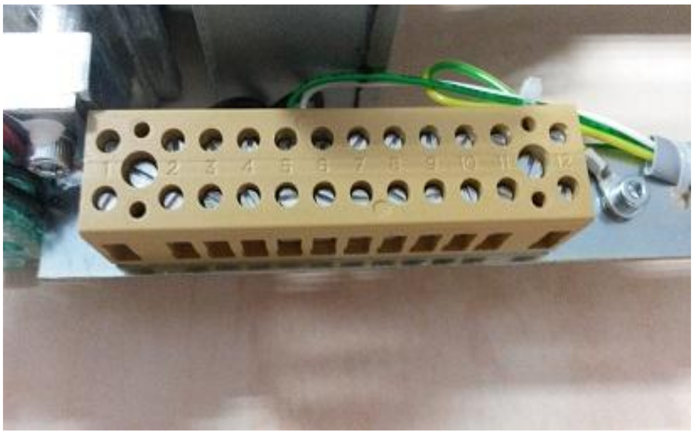

Image 3.3 - Terminal

Torque of motor is only 4,77 Ncm but drive has two gearboxes. Output from frontal gearbox with transmission ratio 149 leads to hypoid gearbox. Hypoid gearbox is self-locking which means when shorting current occurs it cannot distort the shaft. Mechanical stop prevents operation of motor in extreme positions to prevent damage of shorting device.

a) Nameplate parameters of DC motor PM1 48-55:

U_n = 220 V

I_n = 0,26 A

P_n = 40 W

n_0 = 8000 min^{-1}

Isolation class: B

Ingress protection: IP44

b) Nameplate parameters of frontal gearbox type SG 80:

M_{dmax} = 800 Ncm

i = 149

where U_n [V] – is rated voltage of drive

I_n [A] – is rated current of drive

P_n [W] – is rated power of drive

n_0 [min^{-1}] – is unloaded speed of drive

M_{dmax} [Ncm] – is maximal dynamical torque

i [-] – is transmission constant of drive

Isolation class informs us which materials are used for isolation of motor and what temperatures can it withstand.

Table 3.1 - Isolation classes of motors [20]

Isolation class	**A**	**E**	**B**	**F**	**H**
Ambient temperature [°C]	40	40	40	40	40
Permitted temperature rise [°C]	60	75	80	105	125
Temperature reserve [°C]	5	5	10	10	15
Final temperature [°C]	105	120	130	155	180

Our motor is class B. From table we can determine final temperature 130°C which must never be exceeded otherwise isolation would not endure. Ambient temperature depends on place where drive will be situated. Permitted temperature rise is determined by isolation material. Final temperature is sum of ambient temperature, permitted temperature rise and temperature reserve.

Image 3.4 - DC motor with permanent magnets

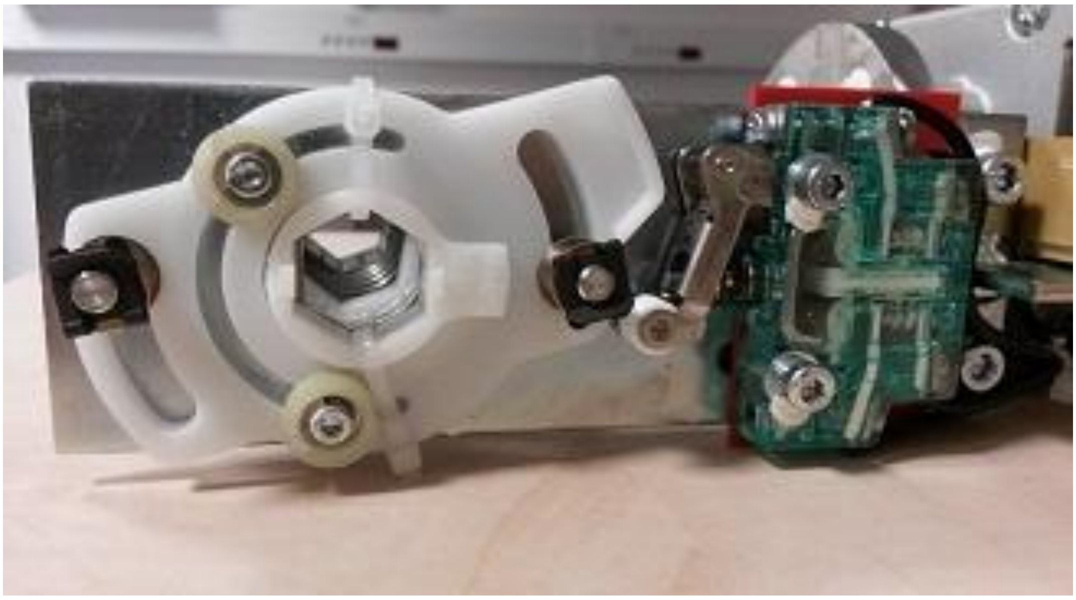

Image 3.5 - Control unit and mechanical stop

IP code otherwise known as ingress protection code is united international way of nameplating technical devices and appliances. Subject of nameplating is protection against intrusion of body parts, dust, water or accidental contact with mechanical casings and electrical enclosures. Exact information about nameplating can be found in standart IEC 60529. Generally first number indicates solid particle protection and is rated from zero to six where six is the highest protection. Our motor has rating of four, which means it is protected from all solid parts larger than 1 mm. Second number indicates protection against ingress of water. Our motor has rating of four, which means it is protected against water splashing from any direction.

The shorting device type EK6-1710-210 is three phased switching device located in high voltage switchboard. It is generally used when we need to do maintenance or repair work on switchboard. It is in operation only few times a month. Positions of shorting device and its design is shown on image 3.6.

3.2 Optimalisation options

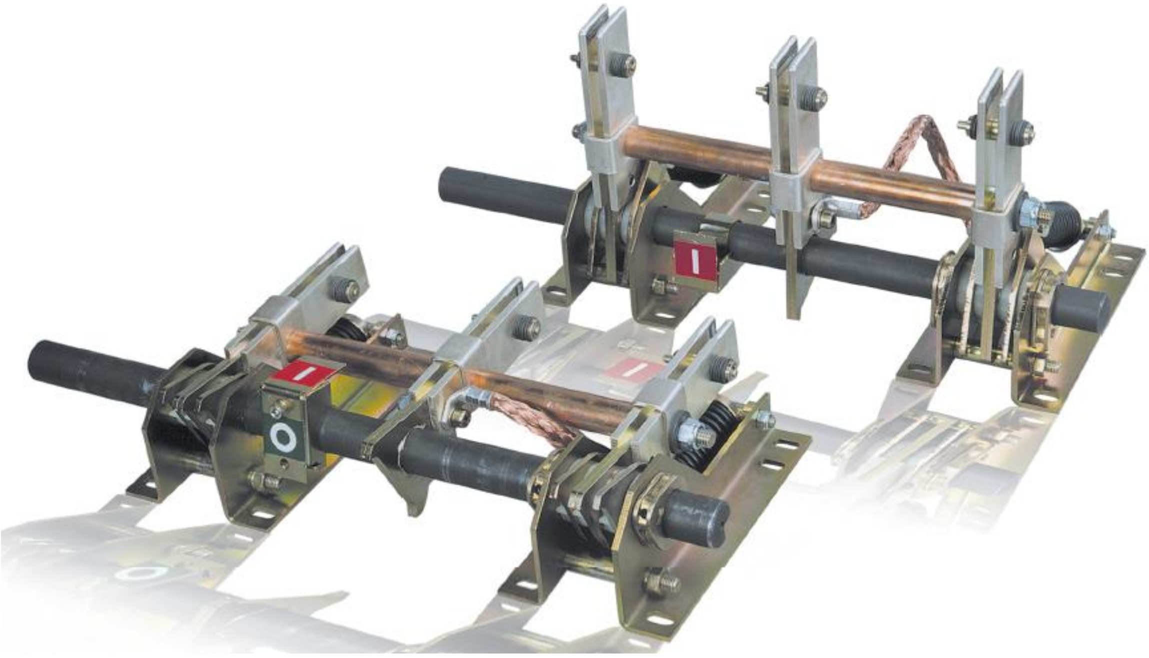

Image 3.6 - Shorting device positions – opened and closed

I will present two or more different solutions of current shorting device drive. There are some problems with drive which should be resolved. It consumes a lot of energy, drive itself is rather expensive. Reason for this is use of two gearboxes which increase dimensions, weight and price. Also DC motor with permanent magnets in high torques with high currents is spontaneously becoming less excitated which leads to further increase of current, overheating problems with isolation and of course problems with breakers of drive which disconnect drive due to high current.

First I will try to use different motor. From all motors and characteristic the most convenient one is DC series motor. It has high torque in low speeds and soft mechanical characteristic. This would remove problems with breakers and overheating because this motor would not become spontaneously less excited. The excitation current which is same as keeper current is regulated by supply voltage change. It will probably be a little more expensive solution because excitation winding from copper is more expensive than permanent magnets but we could achieve far better operation parameters.

Solution on energy consumption will not be included, because this optimalisation is better for devices and appliances that have permanent operation where sum of all saved energy would be great. Shorting device is in operation only few times a month so sum of energy saved in one year will be far lesser.

Lastly, I will try to solve problems with gearboxes. Use of only one gearbox will save place and will also make drive lighter. It should decrease price of drive too. We need to find gearbox of parameters at least equal to sum of these two current gearboxes or better. I will try to calculate and use special impact gearbox in drive.

3.3 Measuring and description of current solution

3.3.1 Test of shorting device

Before writing this thesis we have conducted an operation test of shorting device in ABB s.r.o. where we determined needed torque for switching shorting device on and off as well as other useful operation parameters which we can use in optimalisation.

Measurement of torque has been done according to this block diagram:

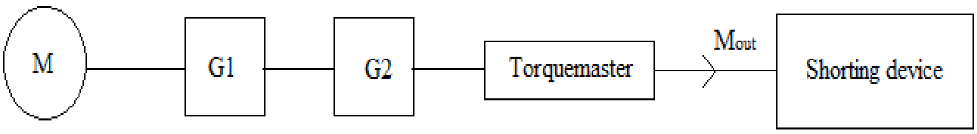

Image 3.7 - Block diagram of shorting device test

In this diagram M symbolizes DC motor with permanent magnets, G1 is frontal gearbox followed by G2 which is hypoid gearbox. On shaft we have torquemaster for determining torques of drive M_{out}. We used torquemaster 300 Nm. This measurement with connected shorting device will be later compared with measurement without shorting device (from this measurement we will be able to calculate consumption of drive itself).

Results of shorting device measurement:

a) type parameters

Table 3.2 - Type parameters of shorting device

U_n [kV]	f_n [Hz]	I_{sn} [kA]	I_{nk} [kA]	U_{sw} [kV]	U_{wi} [kV]	p_p [mm]	n_s [-]	l_k [mm]	l_s [mm]
17,5	50	40	100	38	95	210	3	210	655

where U_n is rated voltage, f_n is rated frequency, I_{sn} is rated short-lasting current (3 seconds), I_{nk} is rated switch-on short current, U_{sw} is short-lasting withstandable AC voltage, U_{wi} is withstandable voltage in atmospheric impact, p_p is pole pitch, n_s is number of springs, l_k s length of knife and l_s is length of shaft.

b) voltage drops (current 100 A)

Table 3.3 - Voltage drops of shorting device

	U	V	W
ΔU [mV]	1,5	1,7	1,9

c) mechanical parameters

Table 3.4 - Mechanical parameters of shorting device

v [m/s]	a [ms]	α [°]	β [°]	M_{on} [Nm]	M_{off} [Nm]
6,4	0,8	88,6	15,3	151	203

where v is velocity, a is asynchronism, α is switching angle, β is insertion angle, M_{on} is maximal torque when switching on, M_{off} is maximal torque when switching off.

This operation test has been performed 50 times and shorting device cleared all requirements of operation test. Now we have parameters of shorting device which we can use in optimalisation.

On image 3.8 there is torque behaviour of shorting device when switching on and off. There is quick rise in torque after 0,5 seconds and then continuous decrease. We can determine maximal torque from graph and length of switching.

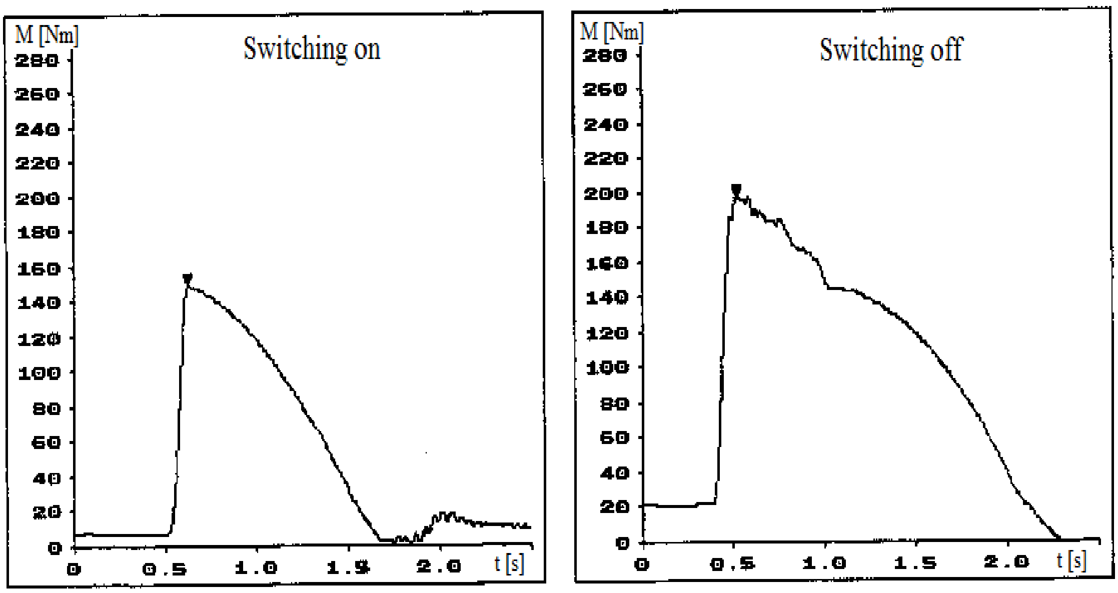

Image 3.8 - Torque behaviour of shorting device in time for switching on and off

3.3.2 Gearbox calculation

From nameplate parameters we know rated power and speed of motor. We can calculate torque of motor M_1 using equation 2.2.

$$M_1 = \frac{P_n}{\omega} = \frac{P_n}{(2\pi \cdot n)/60} = \frac{40}{(2\pi \cdot 8000)/60} = 0{,}0477\ Nm \qquad \text{eq. 3.1}$$

As it was stated the transmission ratio of frontal gearbox i_1 is 149. With this information we will determine torque between both gearboxes M_2. It is transmission into slower speed and higher torque.

$$M_2 = M_1 \cdot i_1 = 0{,}0477 \cdot 149 = 7{,}11\ Nm \qquad \text{eq. 3.2}$$

To find out output torque M_3 which is used for switching shorting device we must first determine transmission ratio of second gearbox. However we do not have nameplate parameters for this gearbox. We must calculate number of teeth on each gear and then combine all of them together using eq. 2.11. From test of shorting device we know that outer torque should be somewhere between 120 and 230 Nm. It is shown on image 3.1 that hypoid gearbox has 6 gears. That means three transmissions. Number of teeth from first to sixth gear:

$z_1 = 4$

$z_2 = 20$

$z_3 = 15$

$z_4 = 35$

$z_5 = 16$

$z_6 = 27$

By combining all three transmission ratios we will get final transmission ratio of whole gearbox. We are using eq. 2.11.

$$i_2 = \frac{z_2}{z_1} \cdot \frac{z_4}{z_3} \cdot \frac{z_6}{z_5} = \frac{20}{4} \cdot \frac{35}{15} \cdot \frac{27}{16} = 19{,}69 \qquad \text{eq. 3.3}$$

Transmission of hypoid gearbox is approximately 19,69. We can now calculate outer torque M_3.

$$M_3 = M_2 \cdot i_2 = 7{,}11 \cdot 19{,}69 = 140\ Nm \qquad \text{eq. 3.4}$$

3.3.3 Preparations for measurement

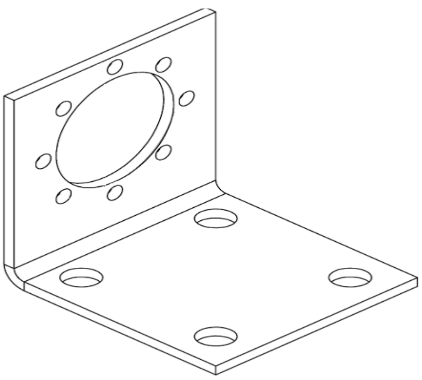

Image 3.9 - layout of universal holder

First we wanted to measure speed and current characteristics of motor alone. That would mean we have to put torquemaster between motor and frontal gearbox. After disassembling the motor we realised that it is not possible to get between motor and gearbox because it was permanently sealed. We then decided to take apart hypoid gearbox and rest of drive from motor and frontal gearbox and measure them together. There will be small inaccuracy because of additional losses of gearbox and other measurement faults but we have to count with them.

Now we need to design and prepare measure equipment. Whole measuring system will be fixed on frame based on FM system profile 40x80mm. To fix the motor we must design universal holder which will be made from bended metal sheet. Thickness 3 millimetres should be sufficient. Lower part of sheet which will be used for fixation on frame will have 4 holes for M8 bolts. Vertical distance between them is given by diameter of frame which is 40mm. Horizontal distance is arbitrary, but we do not want to waste material. Upper part of sheet will be fixated on motor. We are going to use bolts from motor. That determines four holes in upper sheet. Big hole in the middle is again determined by motor parameters and serves for fixing the sheet on motor. Whole situation is shown on layout on image 3.9.

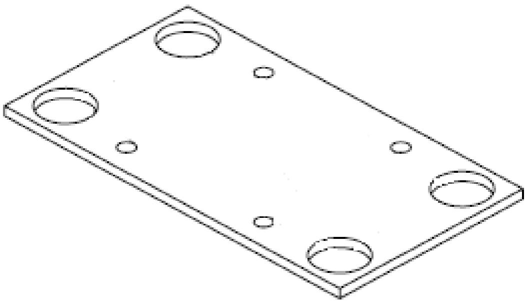

Image 3.10 - layout of TQM holder

Torquemaster is a device designed for measurement of torque. Torque between our gearboxes is 7,11 Nm. Next higher standardized value of torque that we have available is 20 Nm. We are going to use Torquemaster TM 304 with rated torque 20 Nm. Motor shaft has diameter 10 mm which is same as torque shaft. They will be connected with 10-10 conjunction. Axes of shafts obviously need to be in same height. In order to accomplish this, we must underlay the torquemaster with another 3 mm metal sheet. Outer holes for M8 bolts will be used again for fixation on frame with same parameters. Inner four holes will be used for fixation of torquemaster to the sheet. Distances between them are given by torquemaster dimension parameters. Layout of this sheet will be called underlay for torquemaster and is shown on image 3.10.

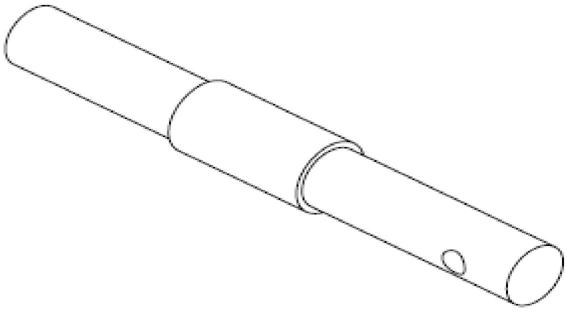

Image 3.11 - layout of shaft

Next there will be bearing in bearing housing and another shaft connected with torquemaster with second conjunction. We will use same bearing which is used in motor and that is bearing SFK 6001 2Rs. Dimensions are given and layout is shown on image 3.11. Bearing housing inner edge of hole must have diameter of bearing to fit correctly. Outer edge must fit into metal part of drive. There must be 4 screw threads on each side of housing for assembly. Screw threads on one side must be shifted by 45 degrees to avoid collision with screw threads on the other side. Layout of mentioned shaft is on image 3.11 and drawing of bearing housing is on image 3.12. For fixation on frame we will use the same universal holder with one difference. This one will have eight holes. Four holes will be shifted by 45 degrees. Bearing will fit into bearing housing and there will be a shaft, which will be connected to torquemaster on one side and to rest of drive on the

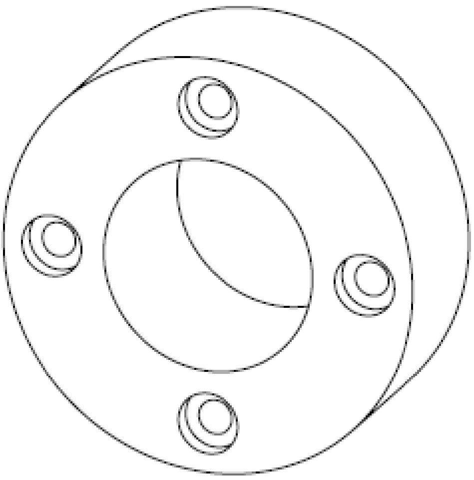

Image 3.12 - layout of bear housing

other side. The shaft length is given. On the side of torquemaster we need about 20-30 mm for conjunction. Then another 22 millimetres for bearing which will have 12 millimetres because of bearing size and another 58,5 mm for drive fixation. It must be similar to shaft of motor for which it is made for. Also the hole for pin must be in same distance from end of shaft. With these informations we can design equipment which will be used in drive measurement. Detailed layout of all parts as well as completed and assembled equipment created in Solidworks are available in attachments.

3.3.4 Measurement of unloaded drive

For our measurement we are going to use DC power source from laboratory table which consists of three phase autotransformer, rectifier and capacitor. Any other external or internal power source can be used. We will be measuring unloaded speed, torque and current of motor for three different voltage levels – 110 V, 150 V, 220 V. Last voltage level is rated. Voltage will be adjusted with autotransformer. Amperemeter and voltmeter are going to be measuring current and voltage for us and will be connected after power source. Electrical drawing of this circuit is shown on image 3.13.

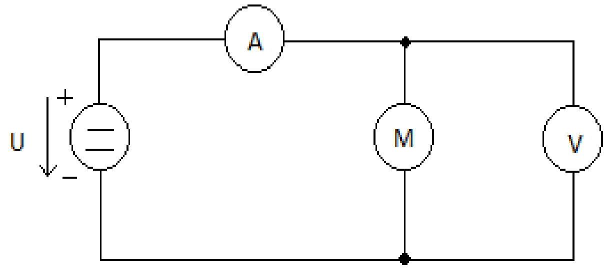

Image 3.13 – Electrical drawing of power source connection

Torque and speed are measured with torquemaster 20 Nm as stated before. We will measure only three values for each voltage level so it will not be enough points for graph. Results of are measurement of unloaded state are written in table 3.5.

Table 3.5 - Measurement results

	n [1/min]	M [Nm]	I [mA]
U1	26,2	0,95	38,06
U2	36,5	1,06	42,32
U3	57,7	1,1	52,18

Where U_1 = 110 V, U_2 = 150 V and $U_3 = U_n$ = 220 V. This measurement tells us about loses of second gearbox. Torquemaster was connected between gearboxes. Motor was loaded only with second gearbox so torque 1,1 Nm is equivalent to losses of drive. Otherwise theoretically unloaded torque would be 0 Nm. Due to time restrictions the measurement of loaded state will not be conducted. Whole assembled measurement system ready for measuring is shown on image 3.14. It corresponds with Solidworks model, which is also part of this bachelor work and can be found in attachments.

Used devices:

- Power source from laboratory table
- Amperemeter: Multimeter Fluke 289, series number 97220164
- Voltmeter: Multimeter Hexagon 340A series number 122180522
- 2x 10-10 shaft connection
- PM motor Groschopp series number 11686106 with first gearbox
- Torquemaster TM 208HS 20 Nm, SAP: 000000315090-0000
- Display device MAGTROL 6400A series number 1K640057A
- Rest of shorting device drive with second gearbox
- Hexagonal shaft from structural steel OK 17

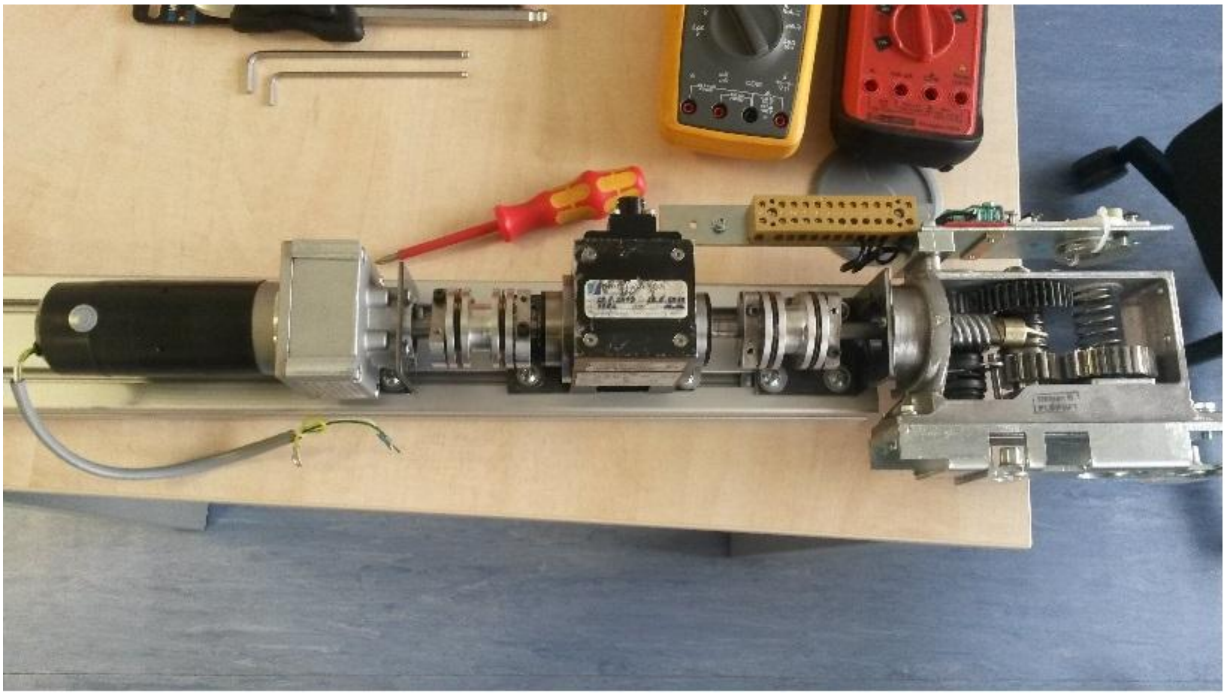

Image 3.14 - Measurement system

3.4 Gearbox optimalisation

3.4.1 Research for new solution

I did some research on companies producing various gearboxes and first company that offered interesting solution was Stromag Brno. They are offering frontal gearbox – Cyclo 6000. It has special epocyclic construction and can reduce speed very effectively using evolvent gears.

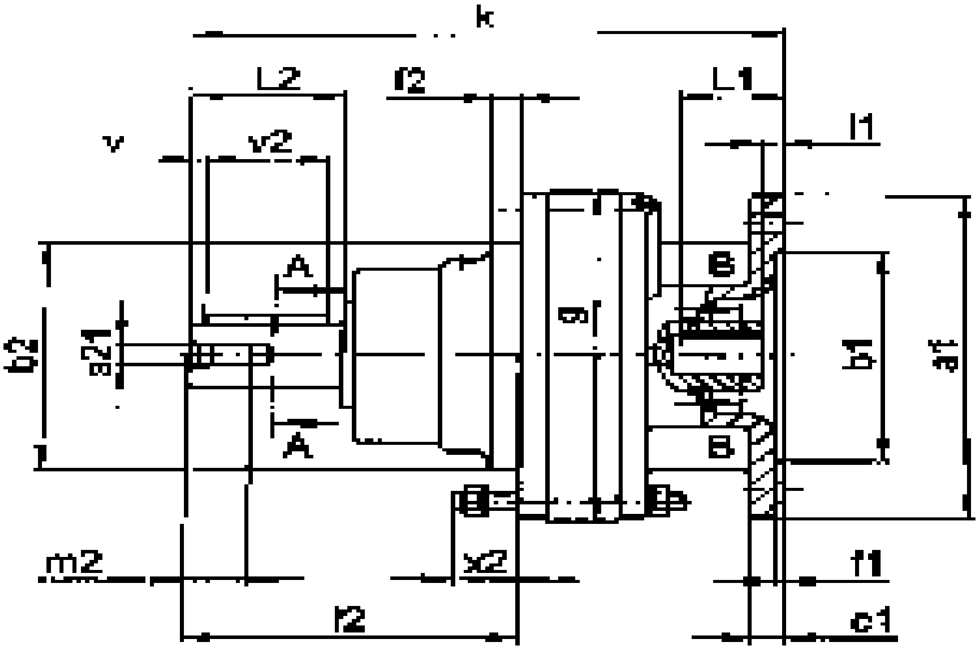

Image 3.15 - dimensions of gearbox

System Cyclo is designed to lower friction between contacting parts. Classic gear has limited amount of contact points. System Cyclo has one third of cycloid disc always in operation. Since the Cyclo system distributes the load to numerous cycloid teeth, it can withstand momentary intermittent shock overloads up to 500% of gearbox rated torque in extreme situations. At least 30% of Cyclo's unique disc profiles share the shock overload and the components are in compression. This means it cannot be sheared off and provides excellent efficiency even at high ratios, reliability and long service life usually longer than 50 000 operation hours. Due to the lower friction we have smaller temperature restrictions. The inertia of this gearbox is reduced to minimum, so it can respond quickly in applications with frequent starts, stops and severe reversing. The shear-free cycloid profile makes the unit ideal for those applications that quickly wear out competitor's gearboxes. In comparison to sliding tooth contacts in classic speed reducers, this option provides lower noise levels.

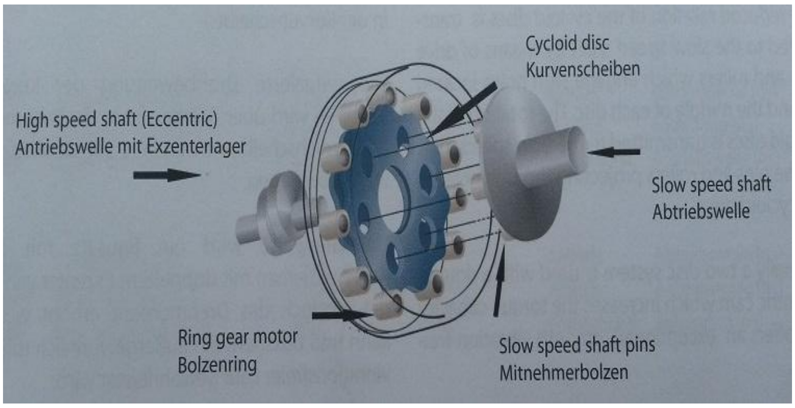

Image 3.16 - Cyclo 6000 principle

In our case its advantages are good transmission ratio and that every part is in same axis. It also greatly saves space. Because our transmission ratio of both current gearboxes is over 2000, if we were to use this gearbox it would have two stages.

We visited this company and talked about suitability of their gearboxes in our drive and then proceeded into finding the correct type. We need output torques around 200 Nm and output speed about 1,5 spins per minute. It is transmission into slower speed and higher torque. Currently two gearboxes are used. Total transmission ratio of both is about 3000. First option is to use Cyclo 6000 in complete drive type CNHM012-6125E-525/GF63S/4, size 6120DA with output speed of 1,92 spins per minute and torque 538 Nm. It has higher torque than current output, so it should be more effective. It is also smaller than current gearbox system. Layout of gearbox and its dimensions are shown on image 3.13, 3.15 and 3.16. Additional information can be found in Stromag Brno catalogue. [21]

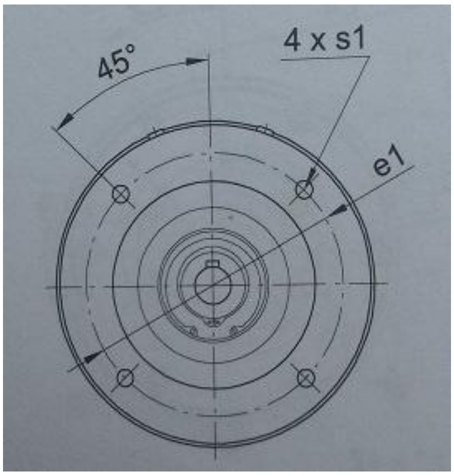

Image 3.17 - front view of gearbox solution

The big disadvantage of this gearbox solution is higher purchase price than current gearbox system. This means it has competitive initial cost, but of course its long service life, minimal need of maintenance give this gearbox superiority over many other classic gearboxes.

CNFX...	Slow speed shaft / Abtriebswelle									High speed shaft / Antriebswelle							
	Ø b2	Ø e2	f2	Ø g	l2	s2	x2	z2	AE2	Ø d2	L2	u2	t2	v	v2	s21	m2
6060E 6065E	80 g6	98	4	110	73	M6	21	6	0°	14 k6	30	5	16	2,5	25	M5	12
6070E 6075E	80 g6	98	4	110	84	M6	21	6	0°	20 k6	40	6	22,5	4	32	M6	15
6080E 6085E	95 g6	118	5	134	106	M8	27	8	22,5°	25 k6	50	8	28	3,5	40	M10	22
6090E 6095E	105 g6	134	6	150	129	M8	29	8	22,5°	25 k6	50	8	28	3,5	40	M10	22
6100E 6105E	105 g6	134	6	150	139	M8	28	8	22,5°	30 k6	60	8	34	3,5	50	M10	22
6110E 6115E	115 g6	146	6	162	143	M8	28	8	22,5°	35 k6	70	10	38	7	56	M12	28
6120E 6125E	140 g6	180	14	204	154	M10	30	6	0°	35 k6	70	10	38	7	56	M12	28

Image 3.18 - table with gearbox solution dimensions

Next we tried to look for gearbox system solution using impact gearbox. It would be great solution and it is possible, but independent impact gearbox is not being industrially produced anywhere. It could be separated from impact wrench but the process would be rather complicated. It has big advantage over other gearboxes – it has great overload options and high impact torque. Additional research would be needed. Impact gearbox has not been used in this industry branch yet but it should be very efficient.

Another option is to use plastic gears. Current metal ones could be unnecessary. Plastic ones could save space and make the drive lighter and greatly cheaper. Company Teatechnik produced plastic and metal gearboxes. From informations they gave me, we can assume that plastic gear are roughly five times cheaper than metal gear with same dimensions. Their specialist also told me that our solution with outer torque about 200 – 250 Nm could not be transferred with plastic gears without mechanical damage or severe shortening of service life.

3.5 Motor optimalisation

3.5.1 Research for new solution

We want to find a DC series motor with similar or better parameters than current PM motor. Motor should be cheaper or equal in price. First, we need to know when we compare these two motors with similar parameters, which one would be cheaper. In order to find out I contacted a specialist in marketing at company ATAS Náchod. This company produces electromotors of many kinds and other electrical appliances.

Table 3.6 - Price comparison of series and PM motor

Price comparison	Parameters	Number	1-5	6-25	26-50	51-250	251+
NK2G2A	40[W].8000[T].220[V].	30861	2348	1761	1526	1249	1228
P2RH479	40[W].5300[T].24[V].	50479	2821	2116	1834	1500	1475

Motor with PM for comparison has series number P2RH479 and series motor has NK2G2A. From table 3.1 we can see that these motors have similar parameters. Power is equal, speed of PM motor is lower, but that is not a problem. The biggest difference is in voltage level. It is implied that series motors are used usually at higher voltage levels. Also, the series motor is cca 20% cheaper than the one with PM. In our drive we need motor with voltage levels from 24 – 220V so in this case, using series motor will be not only more effective, but also cheaper which we can see in second part of table. Number implies number of motors purchased. Also motor with PM can lost its excitation and increase current abnormally which can cause a breaker to disconnect. Series motor has additional winding on stator and his excitation can be controlled. Also it has better parameters, for example it can greatly reduce speed which is exactly what is needed in shorting device drive. We need to change 8000 spins of unloaded motor into 1,5 spins per minute on load. My first suggestion is to use series motor NK2G2A. This series motor will be compared with other series motors of different companies.

Nameplate parameters:

Table 3.7 - Nameplate parameter of NK2G2A

	U_n [V]	P_n [W]	I_n [A]	n_n [min^{-1}]	Cover	Operation	m [kg]
NK2G2A	220	40	0,45	8000	IP 20	S1	1,6

Series motor NK2G2A has exact same power as currently used PM motor. It is similar in size and weight but it only has one voltage level option for 220 V. Also rated speed is higher so we would probably need bigger gearbox system which would increase cost and size of drive.

Second option is to use series DC motor NK2G7P. It is also produced by ATAS Náchod company. As we can see from table 3.7 voltage has again only one level and is higher than voltage level of previous series motor. Rated power is also higher, but speed is lower which is very convenient because we need to reduce speed to 1,5 min^{-1} anyway and lower rated speed and higher power imply higher rated torque of motor. This means we would not need current gearbox system and we could change it for smaller and lighter gearbox with lower transmission ratio. This implies that usage of this motor would bring cheaper shorting device drive solution.

Table 3.8 - Nameplate parameters of NK2G7P

	U_n [V]	P_n [W]	I_n [A]	n_n [min^{-1}]	Cover	Operation	m [kg]
NK2G7P	230	50	0,52	5000	IP 20	S1	1,6

Third option is to use motor from FK3K series. We did not found any specific motor but these series have the following range of nameplate parameters:

Table 3.9 - Nameplate parameters of FK3K series

	U_n [V]	P_n [W]	I_n [A]	n_n [min^{-1}]	Cover	Operation	m [kg]
FK3K	230	50 - 160	0,52	3000 - 8000	IP 20	S1	3,1

This option is variable one. Company can choose rated power and speed of motor which the need in shorting device drive and customize price and torque of drive as needed. Variability of this motor should be sufficient for any series motor that could be used in drive.

From these options after complex technical evaluation and comparison I would recommend substitution of current PM motor with DC series motor NK2G7P. All advantages and disadvantages of these options have been stated above.

In last part of motor optimalisation I will calculate transmission ratio for reduced gearbox when using motor NK2G7P to show how much cheaper and smaller gearbox would become.

Dimensions and technical documentation of all suggested motor solutions can be found in attachments.

3.5.2 Gearbox reduction calculation

First, we will determine rated torque of NK2G7P with using eq. 2.2. We are using nameplate parameters of this motor from table 3.7.

$$M_1 = \frac{P_n}{\omega} = \frac{P_n}{2\pi \cdot n_n/60} = \frac{50}{2\pi \cdot 5000/60} = 95{,}49\ mNm \qquad \text{eq. 3.5}$$

Rated torque of previous solution was 47,7 mNm. We will assume that frontal gearbox will remain the same. After this gearbox the torque will be:

$$M_2 = M_1 \cdot i_1 = 0{,}09549 \cdot 149 = 14{,}23\ Nm \qquad \text{eq. 3.6}$$

Torque between gearboxes was 7,11 Nm and now it is two times as high. We want output torque to be same – that is 140 Nm. From this information we can find out new transmission ratio of reduced hypoid gearbox.

$$M_3 = M_2 \cdot i_{2red} \Rightarrow i_{2red} = \frac{M_3}{M_2} = \frac{140}{14{,}23} = 9{,}838 \qquad \text{eq. 3.7}$$

Ratio of current solution has been calculated in chapter 3.3.2 equation 3.3. Result was 19,69. Transmission ratio of reduced gearbox is 9,838 approximately two times smaller. Now we will estimate which gears could be removed. Result closest to 9,838 was chosen:

$$i_2 = \frac{z_2}{z_1} \cdot \frac{z_4}{z_3} = \frac{20}{4} \cdot \frac{30}{15} = 10 \qquad \text{eq. 3.8}$$

As equation 3.3 implies, gear 5 and gear 6 from current solution can be completely removed and number of teeth of fourth gear can be reduced to 30. Many more options can be used to reduce gearbox. In this example it is shown that 2 gears can always be removed and you can customize number of teeth on other gears as you need.

Second option could be with use of direct hypoid gearbox that means only hypoid and one gear. We would have to change number of teeth in order to get transmission ratio around 10. For example z_2 = 30 and z_1 = 3.

$$i_2 = \frac{z_2}{z_1} = \frac{30}{3} = 10 \qquad \text{eq. 3.9}$$

These options will reduce price, dimensions and weight of gearbox system. This example was calculated for usage of motor NK2G7P, but similar process can be done with any DC motor.

4 CONCLUSION

This bachelor work contains informations about theory of switching devices without arc and chosen parts of electric drives theory which are needed for optimalisation. Work puts together theoretical part of drives and practical application. Whole chapter is dedicated to direct current motors which are widely used in the world.

In practical part there are results of shorting device test which was done to determine detailed informations about shorting device operation in order to design the best drive for it. Especially important are maximal switch-on and switch-off torques. These define what drive must we use that means which motor, which gearboxes and what parameters they all should have.

Next part contains informations and protocols about current drive solution. Here we see what parameters drive has and what could be improved from mechanical characteristics. Then I analyse gearbox system and in cooperation with industrial company design new gearbox. This option using Cyclo 6000 gearbox would prove much more effective and would also be smaller but it would be more expensive. Other option which could be later used is impact gearbox. This was not used before and it would be something new. Last option from gearbox optimalisation would be using plastic gears in hypoid gearbox. After discussion with representative of certain company we can conclude, that using plastic gears would be a very good solution and they would be able to lower production price of drive, its dimensions and weight. But they are not able to withstand torques of 200 Nm and more and therefore cannot be used in our solution.

Last part is about motor optimalisation. Three different series winding motors are introduced and compared. After complex evaluation I recommended one of them. It has many advantages over current PM motor. One of them is option to reduce gears in current gearbox system making whole drive cheaper and smaller.

All of presented solutions can be used and should improve current drive. Every optimalisation was discussed with technician in greater detail to avoid any greater mistakes. There is possibility of new options which were not mentioned and maybe they will be explained in master thesis that will be a continuation of this work.

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