LAPPEENRANNAN-LAHDEN TEKNILLINEN YLIOPISTO LUT

LUT School of engineering science

Sähkötekniikka

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Electrical drive system for plywood industry lay-up tablet

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TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto LUT
LUT School of engineering science
Sähkötekniikka

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Sähkökäyttöjärjestelmä vaneriteollisuuden ladontatabletille
Diplomityö
2020
69 sivua, 23 kuvaa ja 6 taulukkoa
Tarkastajat: Professori Juha Pyrhönen
TkT Pia Lindh.

Hakusanat: Oikosulkumoottori, servomoottori, dynaaminen jarrutus

Energian kulutus lisääntyy maailmassa vääjäämättä. Tämän takia on tärkeää koko ajan kehitellä uusia tapoja, jolla energian kulutusta voitaisiin pitää kurissa ja jopa vähentää.

Tässä tutkimuksessa oli tarkoituksena selvittää teollisuusoikosulkumoottoreiden ja servomoottoreiden eroja, mutta myös sitä, kumpi niistä soveltuisi ladontalaitteen moottorivalinnaksi parhaiten. Teollisuusoikosulkumoottorit ja servomoottorit ovat samankaltaisia. Niiden pääeroavaisuus on se, että teollisuusoikosulkumoottorissa ei ole valmiina roottorin asentoanturia, jonka avulla voidaan säätää tarkasti moottorin toimintaa kuorman tilan mukaan. Servomoottoreille tyypillistä on se, että niissä on sisäänrakennettuna tällainen anturi. Oikosulkumoottoriin voi kuitenkin asentaa tällaisen anturin erikseen.

Työssä on pyritty keskittymään neljään moottorin jarrutustapaan. Yhteisen välipiirin tapauksessa monta taajuusmuuttajaa kytketään yhteen niiden DC välipiirin kautta. Tällä tavalla ainoastaan yhdelle taajuusmuuttajalle tarvitaan sähkönsyöttö. Muut taajuusmuuttajat saavat sähkön yhteisen välipiirin kautta. Näin ollen yhden moottorin jarruttaessa voidaan regeneroitava energia kuluttaa muissa moottoreissa.

Jarruvastuksia käytettäessä ne yhdistetään moottorin taajuusmuuttajan välipiiriin jarrukatkojan kautta. Moottorin jarruttaessa ja välipiirin jännitteen noustessa jarrukatkoja alkaa syöttää energiaa jarruvastuksiin, joissa se muutetaan lämmöksi.

Jarrukondensaattori toimii jarruvastuksen tavoin, mutta energiaa ei muuteta lämmöksi vaan se varastoidaan jarrukondensaattoriin ja kulutetaan taas moottorin kiihdytyksessä.

Moottorin regeneraatioenergian syöttäminen verkkoon tapahtuu sitten, kun välipiirin jännite nousee tarpeeksi suureksi ja aletaan sähköä syöttää erilaisten komponenttien kautta takaisin verkkoon. Tällöin kaikki muut sähköverkon laitteet voivat kuluttaa tämän

generoidun sähkön omiin käyttötarkoituksiinsa. Kyseisessä ladontalaitteessa parhaiten toimiva ratkaisu olisi moottorin regeneraatioenergian syöttö verkkoon.

ABSTRACT

Lappeenranta-Lahti University of Technology LUT

LUT School of engineering science

Electrical engineering

Jani Venemies

Electrical drive system for plywood industry lay-up tablet

Master's thesis

2020

69 pages, 23 figures and 6 tables

Examiners: Professor Juha Pyrhönen

TkT Pia Lindh.

Keywords: Induction motor, servomotor, dynamic braking

Global energy consumption is increasing inevitably. Because of this it is very important to develop new ways to make machines more energy efficient.

The purpose of this study was to compare the differences between industrial induction motors and servomotors, the purpose was also to find the best suited motor solution for plywood industry lay-up devices. Industrial induction motors and servomotors are very similar. Their main difference is that industrial induction motors do not have an embedded rotor position encoder, which is needed in motor control functions depending on the load's condition. Servomotors always have inbuild encoders. It is, however, possible to install a position encoder in an industrial induction motor as well, which in a way makes it a servomotor.

In this work four different motor braking methods were studied. In a common-intermediate-circuit system, many frequency converters are connected together via their DC intermediate circuit. This way only one frequency converter needs a network power supply. Other frequency converters get power through the common DC link. By using such an arrangement, the braking energy generated by a motor can be used by other drives connected to the common DC link.

When braking resistors are used, they are connected to intermediate circuit of the frequency converter through brake chopper, which is a controlled IGB-transistor. When a motor brakes and the voltage of the intermediate circuit rises high enough, the IGB-transistor starts to feed this extra energy to braking resistors, where it is converted into heat.

A brake capacitor works as a braking energy storage. Now energy is not converted into heat, but it is stored in a capacitor and used again when the motor accelerates.

Regenerative braking energy can be transferred to the power supply network through different electrical components, where its other devices can use this electricity for their own use. In a lay-up system, the best suited solution would be this solution.

The first words

This work was assignment for me by Raute Oyj. The job application process was easy and I was very well received.

I would like to thank Raute Oyj for giving me the opportunity to make this master’s thesis for them. Especially, I would like to thank Antti Pennanen who was my supervisor for this work and helped me a lot. Also, I would like to thank all my co-workers who also helped me a lot. I was also in contact with Solfox Oy employers, who also helped me very much, so big thanks for them as well. I have started to work for Raute Oyj and I am continuing towards the new challenges.

Lahti, 23.5.2020

Jani Venemies

Contents

ABBREVIATIONS AND SYMBOLS

AC	Alternating current
DC	Direct current
U	Voltage
I	Current
R	Resistance
n_s	Electrical speed of the stator
f	Frequency
p	Pole pair number
n_r	Mechanical speed of the motor
s	Slip of the motor
$\mathrm{d}Q$	Charge element
v	Speed
B	Flux density
E	Electrical field strength vector
β	Angle between v and B
A_s	Stator linear current density
B_{δ}	Air gap flux density
T_{us}	Slot pitch
K_{ws}	Winding factor
N_s	Number of coil turns in series per stator phase
$\Psi_{s\sigma}$	Leakage flux linkage
PM	Permanent magnet
PMAC	Permanent magnet AC servomotor
BLAC	Brushless AC servomotor
rpm	Rounds per minute
EGB	Electronic gearbox
IRT	Isochronous real-time

1 Introduction

Energy consumption is growing every year globally and the largest growth has been in the Middle East and in China. In these countries the growth has been close to 200 percent between 1990 to 2008. This annual growth in energy consumption has raised a lot of talk about emissions and how to reduce them. This has led to many agreements between several countries whose goal is to reduce emissions and try to use more renewable energy sources. Energy is converted from many sources and for many different applications. Worldwide, energy is used by residential houses, public buildings, industry and transportation mainly for heating and electricity, but also for some other uses. The biggest energy consumer of these is industry, which had about 50 percent of the annual amount in 2012. [1].

Electricity in one of the energy forms which is produced using many different sources and ways. It is used in many applications for different purposes and usage of electricity has increased at the fastest rate of all other energy forms. In 2017 electricity generation increased by about 3.1 percent worldwide. The total amount of electricity generated was about 25 570 TWh. Renewables, coal and gas were the sources, whose usage increased most. Things that have increased the usage of renewable energy sources are governments support and technology development. Technology development has led to the decrease of system prices and made it possible that even ordinary consumer can afford their own renewable energy production systems. Most of these systems consist of photovoltaic systems, but also some small wind power production systems. As a whole, renewable energy sources consist mostly of wind, hydro and photovoltaic, but new ways have been developed continuously. Such examples are geothermal energy and wave energy. The largest of these renewable energy sources by far is hydropower. [2, 3].

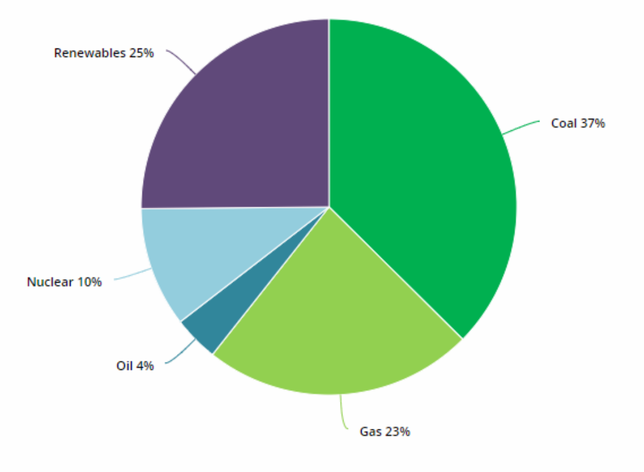


Figure 1. Primary energy in electricity generation in 2017 [3].

Electricity is partly converted into heat in transmission and in electrical appliances. In industry this has a big role because of the large electrical loads. Even a slight improvement here would provide considerable savings on a large scale. Most important appliances are frequency converters and motors, which are using large proportion of electricity in industry. Here proper sizing is very important, but also choosing the right type of motor for each case depending needs of the load. One of the largest places in industry where energy is wasted is dynamic braking, where motor changes to generator when it brakes, and this is usually being wasted in braking resistors as heat. There are many options in utilizing this wasted power and it is important to choose the most well-suited solution for each case.

1.1 The objective

Lay-up tablet is an application whose objective is to pile wooden veneer sheets on top of each other during plywood manufacturing. Here fast movement and accuracy are very important to provide a fast working application, which is a prerequisite for a well-functioning device.

The main objective of this thesis is to develop Lay-up tablet functions and at the same time, study related things. This includes proper frequency converter and motor sizing, and examination of different braking energy harvesting methods and doing some research for them. In this work the functioning of induction motors under dynamic load has been studied. The main movement of the lay-up tablet itself is linear. Servomotors have also been studied and at the same time a proper definition for it has been sought. It is done mainly by comparison to the induction motor. At the moment, induction motor is used to move the tablets. Based on the initial data, this function can be improved a lot by changing an industrial induction motor to a servomotor. There are some properties, which separate the induction motor and the servomotor from each other, but their main structure and working principle are the same.

There are many ways how electricity, which is generated in dynamic braking, can be used and in this thesis regeneration system, common DC bus and supercapacitor solutions have been studied. There is also information about braking resistor working principles. The main idea of these solutions is that in regeneration systems and in common DC bus solutions, this generated electricity would be used by some other application, while in supercapacitors case it would be stored for later use. Braking resistor wastes all this generated energy as heat.

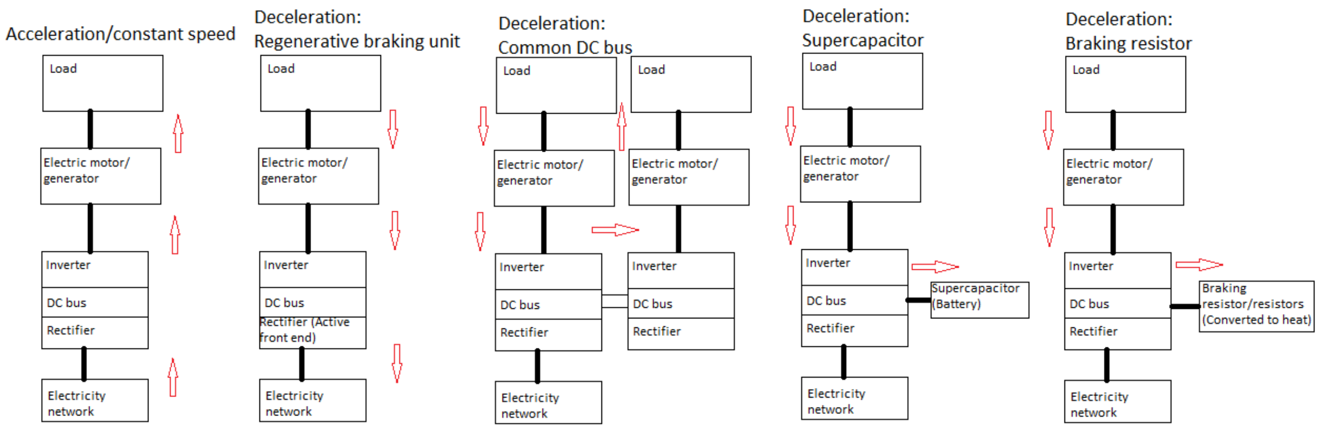


Figure 2. Working principles of normal variable-speed drive, different regenerative braking systems with either active front end, common DC bus or supercapacitor and braking resistor system.

1.2 Outline of the thesis

The second chapter explains the working principles of lay-up tablet.

The third chapter discusses induction motors and servomotors. There is lot of information about both motor types and frequency converters working principles and structures. Different motor controlling methods are being told and analysed.

In chapter four there is information regarding the dynamic braking methods. This section contains information about braking resistors, regenerative braking unit, common DC bus and supercapacitor.

Chapter five includes the results of the work.

In the last chapter the conclusions of this thesis are given. It explains which motor type was chosen and what braking power harvesting method would be best suited for this case. Also, conclusion for servomotors definition is discussed.

2 Lay-up tablet

The lay-up tablet is part of a lay-up line in plywood production. The mission of the lay-up line is to transfer a veneer sheet in a right orientation to the lay-up tablet, which stacks them on top of each other. After that, the stack is transferred to a pre-press where it begins to transform to plywood.

2.1 Working principle of a lay-up tablet

The lay-up tablet was invented to replace human operators. Its movements are powered by two motors. The first motor moves the tablet forwards and backwards, and the second motor rotates the conveyor belt on the lay-up tablet. The idea of the conveyor belt is to bring a veneer sheet on to the lay-up tablet and drop it off, when the table is at its front position.

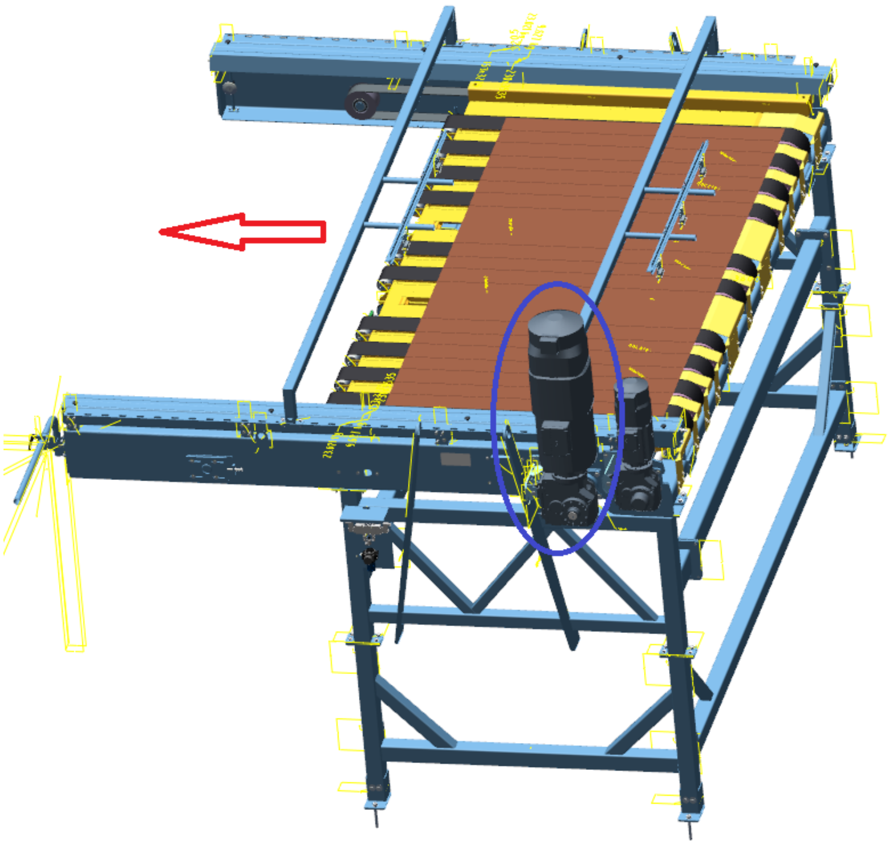


Figure 3. Lay-up tablet. The red arrow shows in which direction the yellow table part is moving in. In the figure, it is at its home position. The blue circle shows which motor moves this tablet. The brown plate presents a veneer sheet, which has just arrived on the lay-up tablet.

The data buses of the frequency converters of the tablet and the conveyor belt are connected to each other by using Ethernet and Profinet. Ethernet connection enables usage of electronic gearbox output, which works similarly to a mechanical gear between a motor and a load, but in this case between motors. In the EGB we choose the speed conversion ratio between two or more motors, which makes it possible to drive different motors from the same application at the same time and by using the same line speed. This controlling method is used to drop veneer sheet from the lay-up tablet. In this system Isochronous Real-Time Profinet is also used. IRT-Profinet enables cycle time below one millisecond, between applications. This can be used to speed up the communication, which makes this process more accurate.

2.2 Induction motor lay-up tablet

Induction motor is used to drive tablets movement. Table 1 shows averages of three different lay-up tablet cases, where we have e.g. moving times and other information as well. There is also dwell, which depends on how quickly we can bring a new veneer sheet on to the lay-up tablet after the movement. Moving time shows how much time it takes for the lay-up tablet to make its whole movement. Cycle time is a combination of these two. Table 1 also shows inverter continuous power, continuous regen power, peak power and peak current.

Table 1. Different tablets movement information which has been obtained by using CTScope program. All tablets are equipped with an induction motor drive system

	1. Mass = 570kg and moving distance = 2000mm	2. Mass = 340kg and moving distance = 1700mm (Starting of the line was still in progress)	3. Mass = 150kg and moving distance = 1700mm
Dwell (s)	0.67	0.87	0.4
Moving time (s)	3.34	2.26	2.35
Cycle time (s)	4.01	3.13	2.35
Inverter continuous power (kW)	4.32	4.39	3.58
Inverter continuous regen power (kW)	1.96	2.35	2.02
Inverter peak power (kW)	19.33	20.7	18.34
Inverter peak current (A)	31.46	38.51	31.19

2.3 Desired outcome

In this application, a low cycle time is the most important factor and we want to archive at least the same result as the current system would be able to provide, but it would be desirable to achieve even lower cycle times. Conveyor belt on the lay-up tablet has been kept the same, but it would not be a problem when we are trying to increase the cycle time of the lay-up tablet. Lowering of the continuous regen power would be also desirable or to try to find the best way to use it.

3 Motors, motor control and frequency converters

In this chapter we are telling about induction motors and servomotor. The section also looks at motor control methods, which could be used.

3.1 Induction motor

Induction motor is still one of the most used motor types in industry, even though competition has grown a lot as a result of the latest development in the field of electrical drives. Induction motor can also be called asynchronous motor, and there are single-phase-supplied and three-phase induction motors. Three-phase induction motors can be divided in to two groups, which are squirrel cage and slip ring motors. Single-phase-supplied induction motors are not usually used in industrial appliances, because they are more suitable for running small loads and there are no frequency converters dedicated for them. They are widely used in low-power household appliances. In this section we are focusing on three-phase induction motor, which is used in the studied system. The working principles of the synchronous AC motor is also explained briefly. There are also DC motor types, but they are not discussed in this section.

Induction motor is AC machine, and it is formed from active and passive parts. Active parts contain stator winding and stator plate package, which form a stationary part and rotor winding and rotor plate package, which form a rotating part. The meaning of passive parts is to keep active parts in place and transfer rotating movement into a load machine or in some cases from a power machine to a generator and lead electricity to a machine or away from it. As the name asynchronous motor states, in motoring rotor is rotating in a lower speed than the rotating magnetic field of the machine. Induction motor also has good overloading and fair field weakening characteristics, which can be utilized. In these cases, the motor needs some extra cooling system to operate without overheating.

Motor can also be changed to work as induction generator, where the rotor is also rotating in different speed than the rotating magnetic field, but in this case, it rotates faster. Induction generators can be divided into two groups, which are grid and capacitor magnetized induction generators.

3.2 Rotor

Rotor is often a motor’s inner part and the main differences between motor types can be seen mostly here. Rotor is the moving part and there are squirrel-cage rotor and wound rotor types. Both are used in industry, but as a result of the development of frequency converters today squirrel-cage rotor type is much more commonly used. In very few cases a motor with wound rotor might be used today. In this thesis induction motors are assumed to have squirrel-cage rotor.

3.2.1 Squirrel-cage induction motor

Squirrel-cage induction motor is the most commonly used motor type in industrial machines and it has squirrel cage shaped rotor winding, where its name comes from. This rotor type does not need any external power source to work. This is because when the stator is connected to an AC power source, it produces a rotating magnetic field, which induces currents into an asynchronously rotating rotor. This induced current produces rotor’s own magnetic field and interaction between these two magnetic fields produces torque. Sometimes in synchronous motors a squirrel-cage winding can be embedded into the rotor to operate as a damper. This can be used to increase direct-on-line starting torque, which on the other hand would lead to a decrease in acceleration time. [40]

Squirrel-cage induction motor is a short-circuited squirrel cage arrangement of winding conductors and it has usually two end rings. Conductor bars can be made of aluminium or copper or even their alloys. Conductor bars are arranged parallel to each other, but they are usually given slight skew. By doing this it reduces magnetic hum of the motor and makes it much quieter. This also increases resistance of the rotor and the slip for a given torque. Other squirrel-cage rotors pros are that same rotor can be used with many different pole pair numbers. [20]

End rings of the squirrel-cage rotor can be connected to the rotor conducting bars by welding, electrical bracing or bolting. When we have shorted end rings, we cannot use external resistance to increase the starting torque of the motor, which in case of this rotor type is quite low in direct on line starting. By increasing the rotor resistance, we can also affect the direct-on-line starting current, which would be smaller because of higher resistance in the rotor. However, when the rotor's resistance is kept small, motor has a very good efficiency during normal running operation, which is also very important when we are designing efficient induction motors. One way to fix this is to add two independent cages. The outer cage would be made from high resistance metal and inner cage would be made from low resistance material like copper. This leads to that the outer cage has a low reactance to resistance ratio and the inner cage has a high reactance to resistance ratio. Starting torque would be created by using outer cage and with right slip value, inner cage would provide the torque. [21].

3.2.2 Wound rotor induction motor

Slip ring induction motor uses wound rotor model and with it we can produce high direct-on-line starting torque. This motor can be used when with a squirrel cage motor the starting current would be too high and when a high starting torque is needed. A slip ring motor is suitable solution when we are using high-inertia loads, which have a long acceleration time. [24]

Rotor is provided with a three-phase winding and each of these windings is connected to separate slip rings. In a wound rotor motor there are also brushes, which provide a connection to a secondary circuit. When we are staring the motor, we can connect an external resistance in series with the rotor windings. This results in a high direct-on-line starting torque, low starting current and a better power factor. In a wound rotor motor, more voltage is induced in the rotor windings and the speed can be controlled quite easily, by using very simple methods. Because of the development of the frequency converters, wound rotor motors are very rarely used in industry, because of their disadvantages, where wearing of the brushes is the largest of them. [41] This machine type is, however, very popular as a wind turbine generator. In such applications it is called doubly fed induction generator.

3.3 Stator

Usually the AC power is supplied to the stator and with it we can produce a rotating magnetic field. Stator is usually the outer part of the motor and its structure is almost the same in every motor type. Basic layout is kept the same, but mainly only the windings on the stator may vary. In a stator when using a three-phase system, windings are placed on the slots of laminated core forming stator coils. They are also electrically spaced 120 degrees apart from each other and they can be connected to star or delta. There is also insulation required between these windings and it is usually made by coating them with varnish or oxide. [21]

3.4 Magnetic field

Stator and rotor currents create a common magnetic field. The interaction between this common magnetic field and the currents produces forces, which cause the rotational movement of the output shaft. The magnetic field component created by the rotor can be produced by using different methods. In case of induction motors, induced currents produce the magnetic field component of the rotor.

3.4.1 Induction motors magnetic field

Induction motors need to create rotating magnetic field. This is achieved by using symmetric three-phase windings and symmetric three-phase currents. Because of these two properties, there is no need for any additional devices to start or run the induction motors.

In three phase induction motor, the air-gap flux induces currents into the rotor and these currents create a magnetic field in the rotor, which together with the stator rotating magnetic field creates the common magnetic field. The rotor tries to oppose the change in rotor-winging currents and starts to rotate. For this to happen, the rotor needs to rotate physically slower than the common rotating magnetic field. This slip between these two causes the induction in the rotor and as a result of this rotor currents run and with the Lorentz force principle create torque. Increase of the slip increases the rotation rate of the magnetic field in the rotor. As a result, more voltage and therefore current is induced in the windings and more torque is produced. If the magnetic field and the rotor would be rotating at the same speed, no electromotive force would be forming in the rotor and there would be no torque. Usually the rated slip varies from 0.5 percent to 5.0 percent.

Magnetic field’s rotational speed can be calculated, by using formula

$$n_s = \frac{60f}{p} \tag{3.1}$$

where f is frequency and p is pole pair number.

Per-unit slip of the motor can be calculated by using formula

$$s = \frac{n_s - n_r}{n_s} \quad (3.2)$$

where n_s is the electrical speed of the stator and n_r is mechanical speed of the rotor.

There are two terminals for each phase and when U2, V2 and W2 for a star point and U1, V1 and W1 are connected to a three-phase supply, where symmetric three phase current starts to move through it and the motor starts.

There is magnetic reluctance always affecting the motor. This consists of the permeability of iron and air gap. If we would presume that $\mu_{rFe} \approx \infty$, the reluctance would only consist of the air gap and this would make it independent from the motor's magnetic flux, making it constant.

In the air gap there are magnetic flux ϕ_m and magnetic flux density B_m affecting in it. These two depend on the motor's magnetising current.

3.4.2 Torque production

The Lorentz force explains the torque production in rotating and linearly moving machines. The equation for Lorentz force is,

$$\mathrm{d}\boldsymbol{F} = \mathrm{d}Q(\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B}) \quad (3.3)$$

Where $\mathrm{d}Q$ (As) is the charge element, which is moving at speed $\boldsymbol{v}$ (m/s), $\boldsymbol{B}$ is flux density and $\boldsymbol{E}$ is the electric field strength (V/m) vector.

Magnetic field causes the force effect. We can get its absolute value in equations,

$$\mathrm{d}F = \mathrm{d}QvB\sin\beta \quad (3.4)$$

where β is the angle between $\boldsymbol{v}$ and $\boldsymbol{B}$.

Interaction between the air gap magnetic field and current, which is running through the windings, produces torque in traditional electric machines. When we have current-carrying conductor, we can form equation for at speed v moving charge element $\mathrm{d}Q$,

$$\mathrm{d}Qv = \mathrm{d}Q\frac{\mathrm{d}l}{\mathrm{d}t} = \frac{\mathrm{d}Q}{\mathrm{d}t}\mathrm{d}l = i\mathrm{d}l \tag{3.5}$$

This can be rewritten to the Lorentz force equation,

$$\mathrm{d}F = i\mathrm{d}lB \tag{3.6}$$

Maximum force can be produced when $\mathrm{d}l$ and B are perpendicular. Force drops in the ratio of $\sin\beta$ and with parallel current and flux density, until force reaches zero value. Therefore, perpendicularity between current i and flux density B is tried to be maintained to provide proper operation of the machine.

In squirrel-cage motor the stator both magnetizes the machine and carries currents, which produce torque. This produces conditions, where the spatial distribution of the stator currents is out of phase with the spatial distribution of the air-gap flux. Synchronous motors do not have this problem, because this can be controlled by applying the correct rotor excitation. By doing this complete air-gap flux density vector and stator current density vector perpendicularity can be achieved.

In squirrel cage rotors the Lorentz force is manifesting on the rotor and stator surfaces when the flux ϕ penetrates the rotor from the air gap of the electrical machine and intersects the rotor copper bar elements, which are carrying the currents. Total force for a single bar can be calculated by integrating it over the length of the bar.

When a current-carrying conductor is placed in a magnetic field it experiences a force. In the stator and rotor opposite forces are produced, which results in the production of the opposite torques.

3.5 Induction generator

As all electrical machines, also regular induction motor can also work as a generator without any internal modification. In this operation the rotor is rotating faster than the synchronous speed of the motor, so it has negative slip. Air gap flux linkage needs to be created in some way and it can be done by using two different methods. First way is to use grid magnetized method, where it draws reactive power from the electric grid. Second way is to use capacitor banks, which are connected to the machine and it gets reactive power using them. Second option can be used in places, where grid connection is not possible. Both magnetising ways are shown in the figure below.

When we are using induction motor in generation mode, typically slip absolute value in regenerative mode is the same as when motor is used at full-load motoring mode, but negative. Negative slip is obtained, by accelerating motor's rotational speed, which changes motor in generator mode. This generated energy can be supplied back to the supply network or it can be used by some other motor by using common DC bus or it can be stored for later use.

3.6 Field weakening

When we are operating an electrical motor at a higher speed than its rated speed is, we need field weakening, which is commonly used in many motor drive applications. In vector control, motor model is available, so the behaviour of a motor can be predicted, and overload situation can be avoided much more easily. If we are using an induction motor, field weakening can be achieved automatically, but for example in permanent magnet motors case there might be some difficulties to go into field weakening. This is because permanent magnets cannot be controlled and field weakening need to be done by demagnetizing the stator current.

In field weakening, motor voltage has reached its rated value and it cannot be increased any further along with rotational speed. If frequency is increased further while voltage is kept the same, the U/f ratio would decrease, and flux linkage would diminish. This means that there is a break down torque, which is reached in asynchronous motors when the angle Υ between the stator and the rotor flux linkage reaches about 45 degrees value. is. Motors might reach higher than its rated value voltage value in regenerative mode, which might happen when motor brakes and it is operating field weakening area.

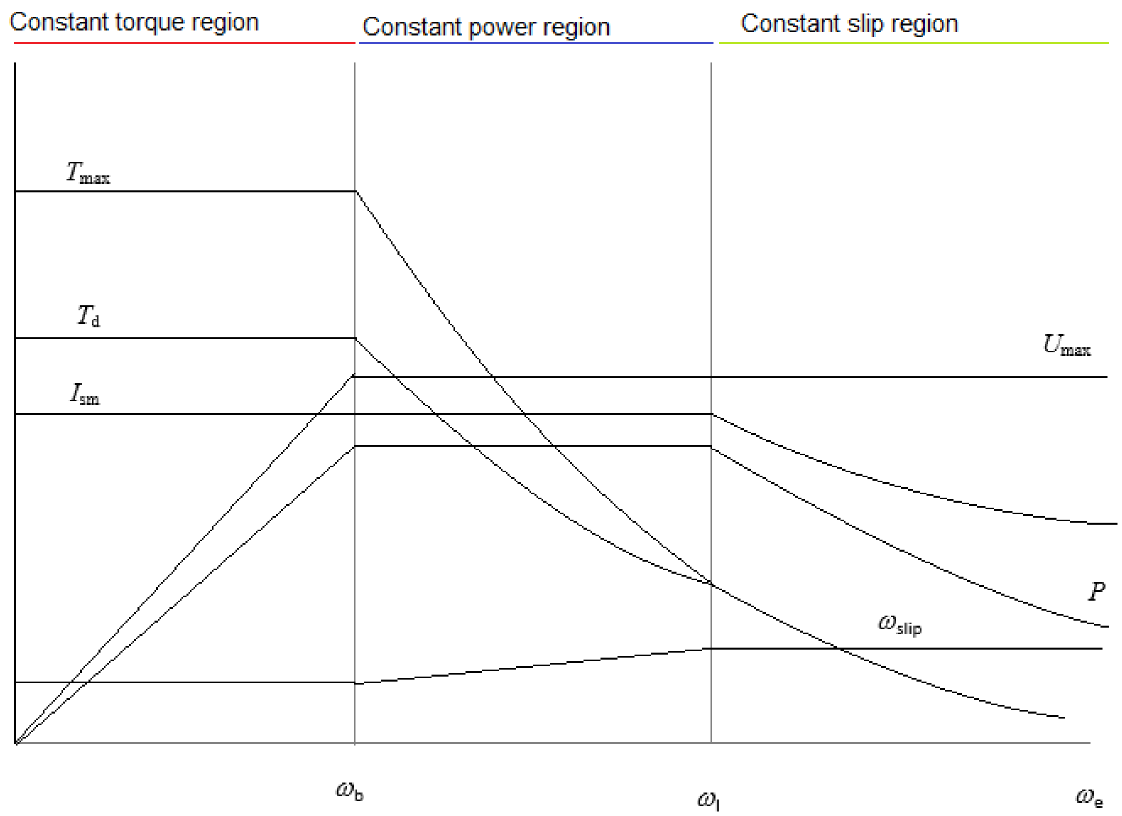


Figure 4. Field weakening regions. We can see how different variables are changing when we are moving religion for another. T_d and T_{max} are torque, I_{sm} is the maximum current magnitude, U_{max} is the maximum phase voltage, P the is power of the machine and ω_{slip} is the slip of the machine.

In Figure 4 we can see that at angular velocity ω_b is the speed where the field weakening starts. The region before this can be called constant torque region, where the voltage has not yet reached its rated value. The air-gap flux linkage is held constant and we can provide a constant torque with the constant slip frequency ω_{slip}. Next region is constant power region where voltage cannot be increased any higher, because it has reached its rated value. Usually there is some voltage saved in reserve, which can be used to provide extra torque in load changes. In this region current must be at the rated value and power stays at constant value. Flux linkage also decreases, which affects motor slip. In field weakening regions, torque needs to be decreased as speed increases, with this we can avoid breakdown situations. When we go deeper into the field weakening region, we enter the constant slip region. Power and current start to decrease in this region, and motor slip cannot be raised any further because it would cause a breakdown situation.

3.7 Synchronous AC motor

In this motor type the rotor revolves at the synchronous speed. Just like induction motor, synchronous motor also works by using three-phase AC currents. Its stator windings and magnetic circuit are very much the same. The main structural differences are found on the rotor side. The rotor might have an excitation winding or permanent magnets.

In case of permanent magnet rotor there is no need for rotor windings. Permanent magnets can be rotor surface-mounted or embedded. In a field winding rotor, there is DC current supplied to the rotor by an external source via sliprings. The currents and the winding produce the rotor current linkage and the rotor flux component. Synchronous AC motor will be discussed more in the servomotor chapter because they are usually equated with servomotors.

3.8 Servo motor

Servomotors have become more common as a result of their price reduction and their good dynamic load performance. Earlier servo motors have been much more expensive than industrial induction motors, but the price gap has reduced a lot during recent years. Servomotor is a linear or rotary actuator, which has precise control of angular or linear position. Therefore, closed-loop control system needs to be used. A servomotor fits, in principle, well in many applications like automated manufacturing systems, robotics, CNC machines and machine tools. [14, 13]

3.8.1 AC servo motors

There are one and three phase AC servomotors. Single-phase servomotors are used for a household application and three-phase servomotors are used for industry. Rotor and stator structure depend on what type of servomotor is in question. There are synchronous and asynchronous servomotors.

3.8.2 Synchronous AC servomotor

In these AC servomotors, the rotor is rotating at synchronous speed with the rotating magnetic field. There are two types of synchronous AC servomotors and they both have permanent magnet rotors, which are very commonly used today in servomotors. These motor types are permanent magnet AC(PMAC) servomotor and brushless AC(BLAC) servomotor. Their structures are very similar to each other and the rotor carries permanent magnets, whose shape and connection ways may vary. Permanent magnets limit overload and field weakening characteristics in these motor types.

Permanent magnets can be rotor surface-mounted or buried. When permanent magnets are rotor surface mounted, they are not so sensitive for parameter changes, this is because reluctance torque is not absent. When permanent magnets are buried the rotor, magnetic anisotropy produces reluctance torque. When this reluctance torque is absent, motor is very sensitive for parameter changes, which may be caused by temperature changes. The total torque of the motor increases with the reluctance torque. It is possible with proper design to increase the total torque, when buried permanent magnets are used. [51]

Usually differences between PMAC servomotors and BLAC servomotors are found in stator windings. Typically, BLAC servomotors have concentrated winding and PMAC servomotors have distributed winding, but both of these winding types can be used in either servomotor type. Stator coils can be wound to produce trapezoidal or sinusoidal current linkages. If the stator coils are trapezoidally wound they produce a trapezoidal back-EMF waveform, which produces audible noise. This also produces torque ripple, because commutation is active every 60 degrees. If stator coils are sinusoidally wound, it produces a sinusoidal back-EMF waveform. This eliminates audible noise and reduces torque ripple effect. In this case, rotor position feedback information is required for all times for proper operation. To produce a steady torque for each case, when you are using PMAC servomotor, typically production of the sinusoidal stator currents is desirable and when you are using BLAC servomotor, it is typically desirable to produce rectangular-shaped stator currents. Fully sinusoidal or rectangular shaped currents however cannot be produced, because of the inverter PWM. This produces small current ripples, which creates small torque ripple. This is usually filtered at high speeds because of the rotor inertia. Inductance resists rapid current changes and in BLAC servomotors case this makes it impossible to produce rectangular-shaped stator currents, so currents have trapezoidal shape. BLAC servomotors have commutation ripple, which depends on the speed of the motor. This makes PMAC servomotors more suitable for high-performance position applications. PMAC servomotors are also more suitable for higher speed ranges when same parameter variables are used. This is because BLAC servomotors has higher current flow restriction, when the back-EMF equals the dc bus voltage.

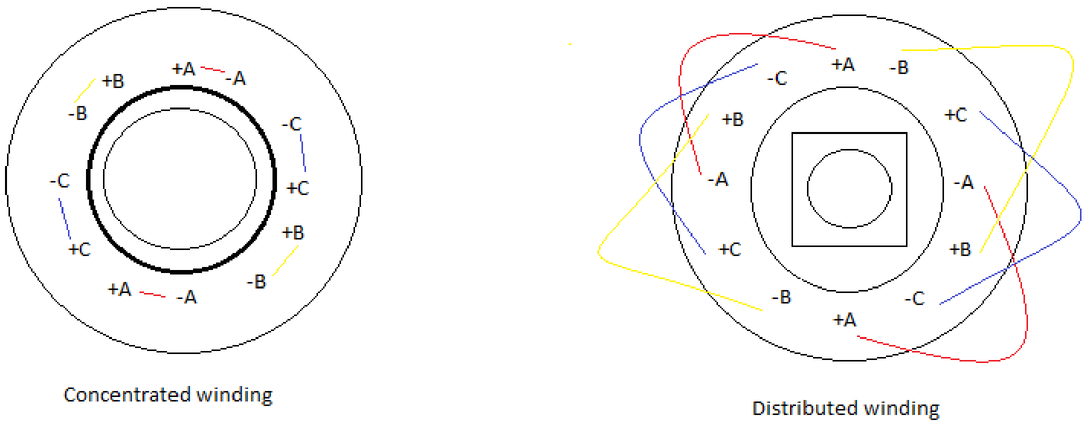


Figure 5. Left side – concentrated non-overlapping winding (BLAC) and right side – distributed winding (PMAC).

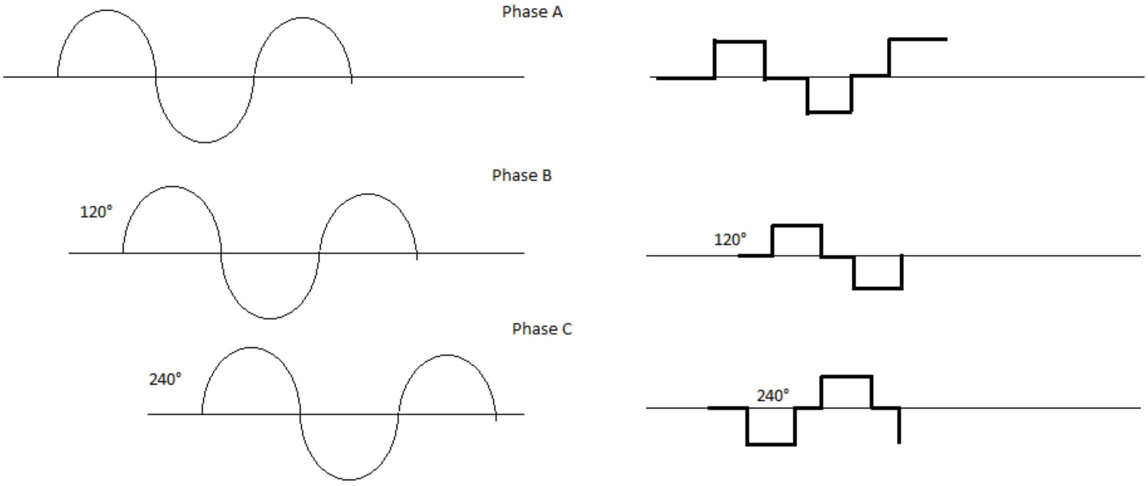


Figure 6. Left side illustrates distributed winding current waveforms (PMAC) and on the right side are concentrated winding current wave forms (BLAC).

In these permanent magnet servomotors, the losses consist of copper and core losses. Copper losses can be easily calculated by using stator resistance and stator current magnitude and its shape. Core losses are hard to calculate, and they can be divided into hysteresis and eddy current losses. These core losses are usually much higher in BLAC servomotors due to the higher harmonics, which contribution is much higher.

Permanent magnet motors always have some cogging torque affecting their operation. This happens when rotor's permanent magnets align at minimum opposition to reluctance or magnetic flux. This cogging can be reduced by skewing the rotor's magnets or stator slots. When this is done by one slot pitch, it reduces cogging. Usually there is no significant differences in cogging torque between the BLAC and the PMAC servomotors. [20]

These servomotor types are well suited options for the tablet's motor drive. Unidrive M700 series has RFC-S mode available, which is suited for running BLAC servomotors. So, in these two permanent magnet servomotors, BLAC servomotor was chosen to be a better suited solution in this case. This is because of the compatibility with the Unidrive M700 and because of its other favourable properties.

3.8.3 Asynchronous AC servomotor

Asynchronous AC servomotor works quite similarly to an induction motor. In my opinion an induction motor can be called asynchronous AC servomotor if a rotor position feedback device is installed to it.

Asynchronous servomotor's rotor is rotating in a different speed than the airgap rotating magnetic field. This changing magnetic flux produces current in the rotor windings. There are conducting bars, which are buried in the rotor and they are short circuited at both ends. This makes it possible to create wanted magnetic field. Asynchronous motor structure also removes permanent magnets maximum power restriction but requires accurate angle position measuring.

3.9 Control methods

In case of an induction motor we can control its function by using open loop control or closed loop control. Each of these methods has their pros and cons. Which one of these is used to control the motor depends on the needs of the application.

3.9.1 Open loop control

Open-loop controller does not give any feedback information about the motor and it is most suitable for systems where there is no need for any operational adjustments. However, adjustments can be made manually for the system. Induction motors are usually controlled by using this method, because there are no basic functions to get any feedback information from them. Disturbances and changes in system do not change the output values of the open loop system. This provides a reliable and sustainable system, which is important in the industry.

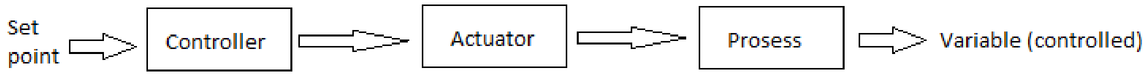


Figure 7. Open loop control process.

This open loop control system is also simple, and it is very easy to create and implement in any system if only the prerequisites – such as high enough torque producing capability without accurate control – can be fulfilled. Systems cost is also low, and this control method is best suited for systems where there is no need for very precise speed accuracy. Such applications are for example cooling systems.

3.9.2 Closed loop control

Closed loop control method is much more complex than open loop control but offers also a much better performance. Closed loop controller collects feedback information and adjusts control variables by using this information. Induction motors can also be used with closed loop control, but it needs some extra devices to do so, such as rotor position resolver or encoder. Feedback information can be collected by using encoders or resolvers, which allow measuring the speed and the position information of the motor.

Figure 6 shows an example of a closed loop system. This system uses position, speed and current information to adjust controllable variables. This controlling method works well with dynamic load.

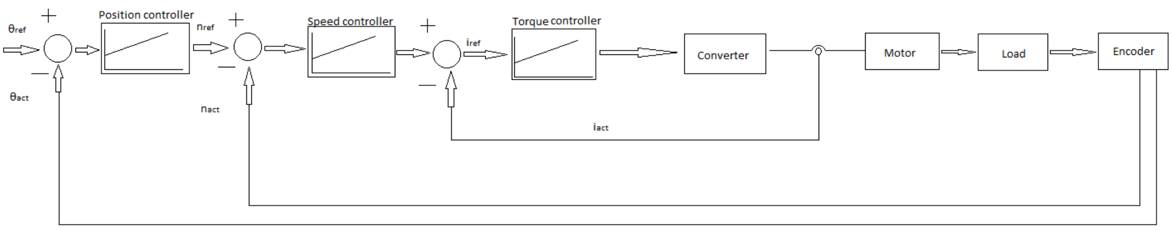


Figure 8. Example for closed loop system with position, speed and torque control.

3.10 Feedback system

In closed loop system we need one or more feedback sensors. We can use absolute encoders, incremental encoders or resolvers. There are also some other devices that can be used such as hall effect sensors, but encoders and resolvers are commonly used in modern motion control systems. Conditions and needs determine which one is best suited for each system and sometimes even both might be used.

3.10.1 Resolver

Resolvers are very durable, and they can work in harsh conditions and because of that they have been commonly used in military applications to provide robustness. Resolver can measure the degree of the rotation. It has digital counterpart such as the digital resolver, which changes a resolver’s analogue signal to digital. A traditional resolver creates analogue signals by using three windings, where one works as an excitation winding, which is the rotor part. Typical excitation frequency is 10 kHz. Two other windings work as secondary windings, which are the stator parts. These two secondary windings are 90 degrees apart from each other. Both secondary windings create their own signals, which are called sine and cosine signals. These signals are fed to a resolver-to-digital converter, where these cosine and sine signals can be changed to a digital signal. Using this digital signal information, we can tell the motor’s shaft position.

Resolver is a kind of an electrical machine and can resist heat and vibration as well as electrical machines usually, and it is a well-suited solution in places where feedback device might experience both of these. Resolver, however, lacks similar accuracy which encoder can provide.

Present-day resolvers, however, do not have a rotating excitation winding but the excitation winding is wound on the stationary part. The rotor has saliency that modulates the output. The stator winding system then includes cos- and sin-windings to provide similar output as the traditional resolver.

3.10.2 Rotary encoder

There are two types of rotary encoders, which are absolute encoder and incremental encoder. Encoders are more accurate than resolvers, but they need a good environment to work properly.

Absolute encoder can maintain its position information even if power is cut off from it and is able to provide it again when power is turned on. This is possible because of the multiple code rings. Absolute encoders commonly use mechanical, optical or magnetic absolute encoder types.

In a mechanical absolute encoder, there is a metal disc, which has a cam and it is connected to a shaft. There are also sliding contacts, which each are at the different distance from the shaft. When the shaft is rotating these contacts are wiping against parts of the metal disc where there is no cam in it. Each of these contacts has a separate electrical sensor, which creates a binary code when the contact is on a cam. The metal disc is designed so that, every possible position of the shaft gives a unique binary code.

In an optical absolute encoder, there is also a disc, which in this case is made of glass or plastic. A light source is used to create an optical pattern, with which the position of the shaft can be determined. The controlling device needs to be able to read the code. This controlling device can be a microprocessor or a microcontroller. When we are using a magnetic absolute encoder, there are two or more magnetic poles, which are installed in series. By using a magnetic sensor, we can create magnetic pole position codes. This code can be read by using a microprocessor or a microcontroller. Magnetic absolute encoders are good in conditions, where they may experience vibration, minor misalignment or shocks, because they are relatively insensitive to them.

Encoding can be done by using either binary coding or Gray coding method, where there are several parallel contacts, which each have “on” and “off” state. Code is built by using contact state information and by increasing the number of contacts, we can obtain a more accurate shaft angle information. The problem in standard binary encoding is that, when the angle is changed to the next sector, it causes more than one state change in the contacts. This leads to that while changing state, code shows many different angle sectors before it moves to the correct one. This can be fixed by perfectly aligned contacts. The easiest way to fix this problem is to use Gray coding, where each contact is organized the way that only one state changes when we are moving to the next sector, see Table 2.

Table 2. Standard binary encoding by using three contacts. Three contacts result in eight different sectors (2^3) during one rotation. For example, when going from sector 3 to 4 every contact state change when the binary system is used.

Sector	Contact 1	Contact 2	Contact 3	Angle
0	OFF	OFF	OFF	0-45°
1	OFF	OFF	ON	45-90°
2	OFF	ON	OFF	90-135°
3	OFF	ON	ON	135-180°
4	ON	OFF	OFF	180-225°
5	ON	OFF	ON	225-270°
6	ON	ON	OFF	270-315°
7	ON	ON	ON	315-360°

Incremental encoder is used to just recognize a change in position. This is a very useful feature in some applications, but we cannot tell what the shaft's absolute position is. This can be done by using incremental encoder interface, which receives signals from an incremental encoder and uses them to produce absolute position information. Incremental encoder uses mechanical, optical or magnetic sensors, which can recognise rotational position changes. Incremental encoder uses two output signals to create two square waves, whose frequency can indicate what is the rotational speed of the shaft. Signals phase relationship tells in which direction rotation is happening. There can also be extra output signal, which can be used to keep track on certain angle. When passing through that angle it creates a pulse.

Table 3. Typical specifications for encoders and resolvers [33].

	Resolvers	Encoders
Maxim speed (Counts per revolution)	500 000	2 448 000
Typical accuracy (Arc-minutes)	15.0	1.5
Typical tracking response time	15 ms	<1 ms
Standard resolution (Counts per revolution)	16 384	32 640
Tolerable shock-caused acceleration level	$50 \times g$	$5 \times g$
Temperature range of the operation	-55-175℃	0-100℃

3.11 Scalar control, vector control and direct current control (DTC)

We need a certain speed and torque defined by the application. This can be achieved by using scalar control, vector control or direct torque control. Motor speed can be controlled by changing supplied voltage magnitude and frequency.

3.11.1 Scalar control

Scalar control is one of the simplest motor speed controlling methods. In scalar control there are two values, which are varied at the same time. These two are supply frequency and supply voltage. When supply frequency is controlled, it also affects motor impedance, which again affects current. This can be avoided by controlling also the supply voltage. If only the frequency would be decreased, or the voltage would be increased, it could cause saturation of the iron parts and therefore excessive current. When just voltage and frequency are controlled, and it is hoped that the motor will operate accordingly it is called open-loop scalar control. There is no need for feedback signals from speed or rotor position, so the system cost stays low. It is also very simple and feedback signal errors cannot affect it.

Closed-loop scalar control is a much more precise way to control the speed of the motor. When closed-loop scalar control is used, feedback signal of the motor's speed is needed.

This control method makes it somewhat possible to control the torque of the motor and because torque is controlled, load torque changes do not affect the speed of the motor. Slip control loop is needed in the closed-loop control, because the slip is proportional to the torque. Real speed value is compared to the desired speed value and the difference between these values is corrected by using a PI controller. Usually current is not controlled, because it makes the system more complex. This creates a magnetic flux that cannot be controlled.

3.11.2 Vector control

In this chapter we focus on field-oriented control (FOC), which can provide smooth operation over the full speed range, full torque at zero speed and good dynamic performance. This control method is commonly used for brushless motors. Field oriented control can be used to control induction motors and AC synchronous motors.

Field-oriented control is said to be able to generate full torque at zero speed, although this is not entirely true, because it can produce full torque down to 1Hz or less. This controlling method is also able to execute fast accelerations and decelerations, which are required when seeking a high dynamic performance. Vector control is becoming more common because of moderate cost and possibility in reduced power consumption. Motor size can be kept smaller with field-oriented control. [50]

In field-oriented control, typically motor-phase currents i_{U} and i_{V} are measured, which makes it possible to assume that $i_{\mathrm{W}} = -(i_{\mathrm{U}} + i_{\mathrm{V}})$. With these measured values, we can obtain values for torque current (i_{sT}) and flux current ($i_{\mathrm{s\Psi}}$).

$$T_{\mathrm{e}} = \frac{3}{2} p \frac{L_{\mathrm{m}}}{L_{\mathrm{r}}} \Psi_{\mathrm{r\Psi}} i_{\mathrm{sT}} \tag{3.7}$$

Where p is pole pair number, L_{m} is magnetizing inductance, L_{r} is rotor inductance and i_{sT} is the torque current.

This can be done by knowing the angular position of the rotor in real time. Vector control includes model of the motor and by using motor model, we can predict its action in different situations.

3.11.3 Direct torque control (DTC)

Direct torque control is one type of vector control and It was originally developed for the induction motors. In direct torque control the torque and the flux can be controlled. It is also a very accurate control method, but it requires high computation capability but only limited knowledge of the motor parameters to work. Direct torque control can reach accuracy of up to 0.5% in speed and 2% in torque.

Adaptive rotor model, optimal switching logic and, torque and stator flux linkage hysteresis control are the most important elements of direct torque control.

3.12 The frequency converter

We need to reduce the stress of the power supply, and the mechanical stress on the motor and shaft when we are starting the motor. This leads to much longer lifetime for the motor. This can be achieved by using a frequency converter.

The frequency converters are used to supply controlled power to electrical motors, which makes it possible to control the motor operation. There are two main parts in frequency converter, which are rectifier part and inverter part. There is also always an intermediate circuit, but it can be external if we are using separated rectifier and inverter. Rectifier part converts AC to DC. This can be achieved by using a diode or a thyristor bridge. Rectifier might cause losses and interferences to the supply network. This might cause problems to the supply network when we have many frequency converters connected to it. This makes it important that a frequency converter input filter in used and the cable lengths are kept short.

Produced DC is supplied to an intermediate circuit and it is called DC bus circuit. Here DC needs to be filtered, because when AC is rectified to DC, it causes ripple voltage to the circuit. The voltage can be filtered by using an inductor and capacitors before it enters the inverter part. There might also be filters, which impede harmonic distortion off. This harmonic distortion may cause problems in the power source, which is powering the frequency converter.

After DC is filtered, it is supplied to the inverter part. In this part there are switches, which can be power transistors or power thyristors. Thyristor resembles a diode, but it can be controlled. Thyristor lets current flow only in one direction, this is done by using anode and cathode. Current can only move in from an anode (A) to a cathode (K). Thyristor can be controlled through a gate (G), where we need to give positive control current pulse that makes current flow through to the thyristor. When current flows through to the thyristor and it changes its direction, thyristor goes back to non-conductive state. In an IGB-transistor, current flows from the collector (C) to the emitter (E). It can be fully controlled by changing control voltage between gate (G) and emitter. GTO-thyristor can also be fully controlled through the gate, but the power needed to control its function is much higher and its switching frequency is also lower than with IGB-transistors. GTO-thyristor is commonly used in high power inverters, because power which can be controlled by using it can rise up to several megawatts.

IGB-transistor is a much more suitable choice than a GTO-thyristor. Power that is needed to control an IGB-transistor is very low and it has also fast switching frequency, even up to about 20kHz. It is also suitable for high power applications which use power electronics for directional devices. By using PWM we can regulate frequency and voltage. With these we can create false AC voltage by using DC, which emulates all three phases of the AC sine wave. The switching frequency of the inverter must be adjusted correctly, because when choosing the correct switching frequency, we can reduce the noise, losses and vibration of the motor. In figure 9 the voltage waveforms of a voltage-source frequency converter are schematically is explained.

Figure 9. Principle waveforms of a voltage-source frequency converter: DC bus filtering creates almost smooth DC voltage. Output pulses of the inverter are formed with many pulses per half period.

Rectifier, the intermediate circuit and inverter are constructed from different parts, which have different operational purposes. These are explained below,
Rectifier:

1. Before AC is converted to DC, there is an input filter. Input filtering can be arranged by using an inductor. Its main objective is to filter voltage spikes from the electric network.
2. Six-pulse rectifier bridge, which changes AC to DC, Fig. 10

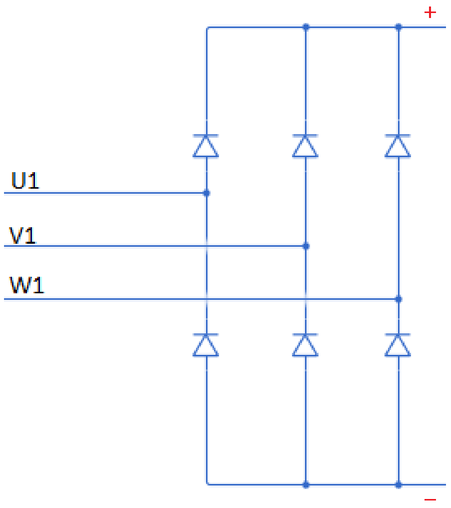


Figure 10. Six-pulse diode rectifier bridge

An intermediate circuit:

1. Coil, which works as a filter in an intermediate circuit. Resists the change in the current and filters current spikes.
2. An intermediate circuit control thyristor. When the voltage in the intermediate circuit during start up rises high enough, frequency converter's electronics get current and thyristor goes into a conducting state
3. Charge resistor. In the starting situation charger resistor charges intermediate circuit's capacitors close to the rated voltage. This is done to lower starting current.
4. The discharge resistor, Fig. 11 Discharges intermediate circuit's voltage, so that when maintenance is performed the worker cannot get electric shock.
5. Intermediate circuit capacitors work as frequency converters current spike bank. So, they work also as a filter. We can provide "fast current" to the load.

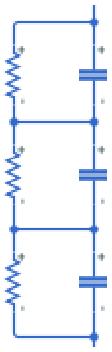


Figure 11. The discharge resistor and intermediate circuit capacitors

6. IGBT, Insulated gate bipolar transistor. PWM (Pulse-width modulation) usually controls extra power to the braking resistors (external). This happens when intermediate circuits voltage rises too high and braking resistors IGBT-terminal starts to lead the current to it. By using this we can avoid high voltage in an intermediate circuit, which would cause problems in the frequency converter.
7. Current sensor measures intermediate circuit's current and power ($P(t) = U(t)I(t)$). Current can be measured by using shunt resistor, which is a small resistor. Current is led through it and the received voltage can be measured. Current value is obtained by using Ohm's law.

Inverter (in Fig. 12):

1. IGBT-terminals (V4, V5 and V6). Produces sinusoidal three-phase voltage kind of PWM. PWM clock pulse frequency is commonly between 4kHz and 20kHz (carrier).

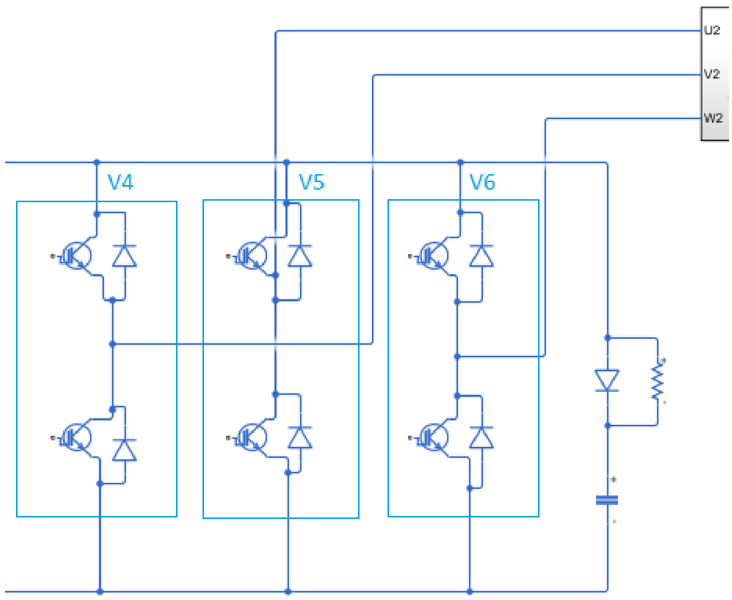


Figure 12. Inverter part. Upper transistors create positive voltage and lower transistors create negative voltage. When they are both non-conducting, we have zero voltage. By switching between these, we can produce pulse pattern whose fundamental is the sine wave AC voltage the motor is supplied with.

There are also two important parts, which are earth fault transformer and heat sink temperature sensor. Earth fault transformer can identify possible earth fault. When a fault situation happens, current is conducted to the frame. Heat sink temperature sensor measures heatsinks temperature, where frequency converter terminals and semiconductors are connected. Errors here might happen because of broken fan or dusting.

There are many different variations of frequency converters, but the main properties are the same. Some frequency converters have active front end. In this case rectifier diodes are replaced by IGBTs. This makes it possible that it can work both in motoring mode and regeneration mode, where it allows regenerated power to be fed back to the supply network. IGBTs also reduce harmonics, but an LCL filter is needed to reduce higher order of harmonics, which are caused by IGBTs switching frequency. The LCL filter consist of two equally sized coils, which are connected in series and between them there is a parallel connected capacitor. Active front end makes the frequency converter power factor much better. Frequency converter power factor tells how efficiently the electrical power is used. Power factor is obtained in equation,

$$PF = \frac{\cos\theta}{\sqrt{1+THD^2}} \tag{3.8}$$

Where θ is phase or displacement angle, between the applied voltage and resulting current, which is kept close to unity in case of active front end. This is because an active front end reduces THD, which also improves the power factor. Because of these properties, power factor is much higher than in the frequency converter, which does not have an active front end. With active front end we do not need large braking resistors, where the regenerated energy would be wasted. [42]

3.12.1 Unidrive M700 series

The system studied employs control techniques Unidrive M700 series frequency converter. There are three different operational modes, which can be used to drive motors. They are open loop mode and closed loop modes RFC-A and RFC-S. These frequency converters can be used to drive induction motors and permanent magnet brushless motors.

In open loop mode there are three different drive options, which are open loop vector mode, fixed *U/f* mode and quadratic *U/f* mode. In open loop vector mode, voltage which is applied to the motor is proportional to the frequency. Only when motor runs at low speeds, its parameters are used to apply the correct voltage. By doing so, we can ensure that the flux is kept constant under varying load conditions. Maximum torque can be produced down to

1 Hz for a 50 Hz motor. Fixed *U/f* mode works very similarly to open loop vector mode, but voltage boost at low speeds is set by the user. Maximum torque can be produced down to 4 Hz for a 50 Hz motor. In quadratic *U/f* mode, voltage, which is applied to the motor is proportional to the square of the frequency. Voltage boost at low speed is set by user in this mode as well. This mode is not suitable for application which needs a high starting torque.

RFC-A mode is a rotor flux-oriented control for induction motors. It encompasses closed loop vector control and it can work with or without position feedback device. When feedback device is used, speed is monitored to ensure that demanded speed is achieved and by controlling motor flux, full torque can be provided even down to a zero speed. Current, voltages and key motor parameters can be used to estimate the motors speed, when position feedback device is not used.

RFC-S mode is also rotor flux control, but it is used for permanent magnet brushless motors. RFC-S mode uses closed loop control method with or without feedback device. Feedback device is used to control the speed of the motor to be what is demanded and to get absolute position information. Rotor is self-excited by the permanent magnets and because of this flux control is not required, but it is still possible to adjust it. Output voltage needs to be accurately matched to the back EMF of the motor, which can be done by using absolute position information. RFC-S mode can be used without feedback device.

Unidrive M700 also has active front end control mode, which enables that regeneration energy can be transported back onto the power line. Active front end control mode also enables power factor control, which can be used for power quality management and reduce power harmonics.

3.13 Gear

In the lay-up tablet there was a helical-worm gear unit, whose gear ratio was 1:7.24. The aim of the work was also to think about which type of gear would work the best in the new system. Mounting and supporting the motor and gearbox also caused difficulties in the old system. Gears are used in many applications to provide high enough torque, while also keeping motors reasonable sized. In some cases, speed might even be increased or decreased by using gears. So, gears can reduce or increase the output speed, which is provided to the load. There are many gear options at hand and each of them has different features, which makes them suitable for different motor types and conditions. In case of servomotors planetary gear option is most commonly used because of its high efficiency. [44]

Planetary gear consists of a sun gear, planet gears and a ring gear. Planet gears are transmitting torque and are located between the sun ring and the ring gear. The sun gear is in the centre of the gear and the ring gear is the outer ring. Because torque is shared with many planet gears, it can handle large torques. [46]

The inertia of the gear needs to be added to the load's inertia, but on the other hand it also reduces the load's total inertia by its conversion ratio, so all inertias after gear is been reduced. This reduced load inertia can be calculated by using formula,

$$J_{\mathrm{red}} = \frac{J_{\mathrm{load}}}{i^2} \quad (3.9)$$

Where J_{load} is inertia of the load and i is gear conversion ratio.

Total inertia can be calculated by formula,

$$J_{\mathrm{Total}} = J_{\mathrm{red}} + J_{\mathrm{mot}} \quad (3.10)$$

Where J_{mot} is the inertia of the motor.

3.14 Important sizing equations

Inverter continuous current is the current which inverter can produce constantly. It can be called also RMS current. This RMS current can be calculated by using formula,

$$I_{\mathrm{RMS}} = \sqrt{\frac{I_1^2 t_1 + I_2^2 t_2 + I_3^2 t_3 + I_{\mathrm{Dwell}}^2 t_{\mathrm{Dwell}}}{t_1 + t_2 + t_3 + t_{\mathrm{Dwell}}}} \quad (3.11)$$

Where I_1 is current in period t_1, which is acceleration period, I_2 is current in period t_2, which is steady speed period, I_3 is current in period t_3, which is deceleration period and I_{Dwell} is current in period t_{Dwell}, which is pause time after the movement.

The RMS torque need to be considered when we are dimensioning the motor. The RMS torque is the thermal equivalent compared to the continuous thermal limit of the engine. This RMS torque can be calculated by using formula,

$$T_{\mathrm{RMS}} = \sqrt{\frac{T_1^2 t_1 + T_2^2 t_2 + T_3^2 t_3 + T_{\mathrm{Dwell}}^2 t_{\mathrm{Dwell}}}{t_1 + t_2 + t_3 + t_{\mathrm{Dwell}}}} \quad (3.12)$$

where T_1 is torque in period t_1, which is acceleration period, T_2 is torque in period t_2, which is steady speed period, T_3 is torque in period t_3, which is deceleration period and T_{Dwell} is torque in period t_{Dwell}, which is pause time after the movement. This formula is simplified version of the actual calculation. In reality, acceleration and deceleration torque ramps are divided into many samples, which gives a more precise RMS torque calculation.

Nominal output torque is calculated by using the formula,

$$T_{\mathrm{M}} = \sqrt[3]{\frac{\frac{n}{2} t_1 T_1^3 + n t_2 T_2^3 + \frac{n}{2} t_3 T_3^3}{\frac{n}{2} t_1 + n t_2 + \frac{n}{2} t_3}} \quad (3.13)$$

Where n is speed of the motor at steady speed period, t_1 is acceleration period, t_2 is steady speed period, t_3 is deceleration period and t_{Dwell} is pause time after the movement.

Mean input speed is calculated by using formula,

$$n_{\mathrm{m}} = \frac{\frac{n}{2} t_1 + n + t_2 + \frac{n}{2} t_3}{t_1 + t_2 + t_3 + t_{\mathrm{Dwell}}} \quad (3.14)$$

Where n is speed of the motor at steady speed period, t_1 is acceleration period, t_2 is steady speed period, t_3 is deceleration period and t_{Dwell} is pause time after the movement.

When we are braking by using induction motor or servomotor, braking produces energy. We can calculate this storable energy by using the formula,

$$E = \frac{C(U_2^2 - U_1^2)}{2} \tag{3.15}$$

Where C is capacitance, U_1 is minimum voltage and U_2 is maximum voltage.

Annular cylinder equation, inertia:

$$I = \frac{1}{2} m(r_2^2 - r_1^2) \tag{3.16}$$

Where m is the mass of the cylinder, r_1 is the inner radius of the cylinder and r_2 is the outer radius of the cylinder.

Solid cylinder equation, inertia:

$$I = \frac{1}{2} mr^2 \tag{3.17}$$

Where m is the mass of the cylinder and r is the radius of the cylinder.

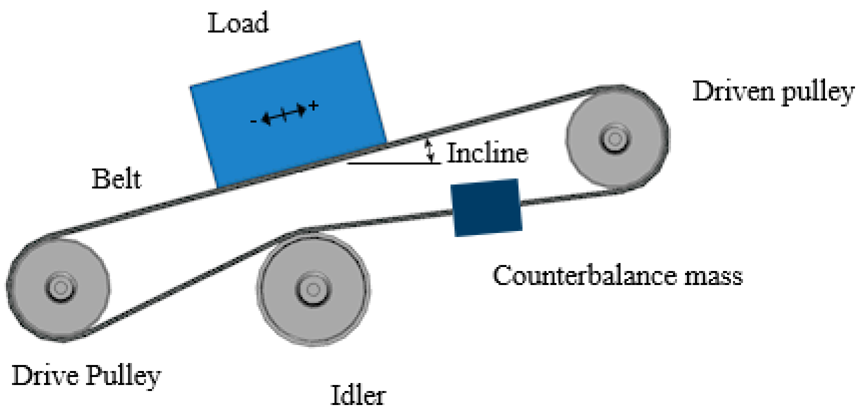


Figure 13 The drive mechanics of the lay-up tablet. The load is the lay-up tablet.

In figure 13 we can see driving mechanics of the lay-up tablet. Drive pulley part is connected to the motor via the gear unit. Inertia of the lay-up tablets driving mechanism J_{DM} can be calculated by using these formulas,

$$J_1 = (m_{\mathrm{load}} + m_{\mathrm{CB}} + m_{\mathrm{Belt}}) r_{DP}^2 + J_{\mathrm{IP}} \left(\frac{r_{\mathrm{DP}}}{r_{\mathrm{IP}}}\right)^2 + J_{\mathrm{DnP}} \left(\frac{r_{\mathrm{DP}}}{r_{\mathrm{DnP}}}\right)^2 \quad (3.18)$$

$$J_{\mathrm{DM}} = J_{\mathrm{DP}} + J_1 \quad (3.19)$$

Where m_{load} is mass of load, m_{CB} is mass of counterbalance, which in this case we don´t have, m_{Belt} is mass of belt, r_{DP} is radius of drive pulley, J_{IP} is inertia of idler pulley, r_{IP} is radius of idler pulley, J_{DnP} is inertia of driven pulley, r_{DnP} is radius of driven pulley and J_{DP} is inertia of drive pulley.

There are many inertia equations for different shapes, but in equations 3.16 and 3.17 we can see annular and solid cylinder equations. By using these equations and equation 3.19, we can calculate inertia of the driving mechanics. In addition to inertia value there are also friction and air resistance as well, which resist movement.

Inertia mismatch can be calculated by using formula,

$$IM = \frac{J_{\mathrm{L}}}{J_{\mathrm{M}}} \quad (3.20)$$

Where J_{L} is the load inertia and J_{M} is the inertia of the motor.

4 Dynamic braking

In industrial applications lots of power is wasted in dynamic braking, where regenerated power of the motor, which is produced by braking of the motor is transformed into heat. This is done by using braking resistor or resistors. Dynamic braking increases electrical motor’s deceleration rate and enables motor’s quick stop. There are some limitations how fast the motor’s deceleration can be done, but usually this provides a braking method, which is fast enough. In this part of thesis, we are researching different solution to use or storage this otherwise wasted energy. Dynamic braking is one part in the development of the lay-up tablet functions in the better direction. By choosing a suitable method, it might also be financially beneficial.

4.1 Braking resistor

Tablet's dynamic braking is typically done by using braking resistors. Because of their low price and simplicity braking resistors are very commonly used to perform dynamic braking. It is very important that the braking resistors are sized properly, because if it is not done correctly it may cause some problems in the frequency converter and in the resistor itself. When we are sizing a braking resistor for an application, the most important things, which we need to know about the operation are braking power, peak braking power and operation conditions.

Braking action happens when motor starts to decelerate. When this happens, it goes into a regenerative mode, which causes the intermediate circuit voltage to rise. When an intermediate circuit voltage rises to a preselected value, it triggers the braking IGBT. It is used as an electronic switch, which enables power supply to the braking resistor. This power is transformed into heat in the resistor. Every frequency converter has a recommended resistance value for the braking resistor, which can be found in the manual. If the value of the resistor is too small, it causes problems in the frequency converter's braking circuit. If the produced braking power is too big, it causes unnecessary warming of the resistor. At the right resistance value braking of the motor is most effective. High resistance value might lead to that braking period of the motor rises too high.

Lay-up line's tablet is an application for plywood and LVL (Laminated veneer lumber) industry, where all appliances need to be well protected, so that the risk of fire can be kept to a minimum. There is lots of wood dust and moisture in the air, which might cause some risk factors. Therefore, a braking resistor is not the best suited solution in the tablet's dynamic braking. Application's ambient temperature is usually also quite high, which weakens the performance of the resistor. Cycle time is usually between 3 and 4 seconds, and deceleration times are very fast. This makes continuous braking power quite high and because of these it needs high braking power capacity. Braking resistors can also be provided some extra cooling, which reduces the temperature of the resistor.

BLAC servomotor is well suited motor type for the tablet and because of its low inertia we can reduce otherwise wasted power. This makes it possible to reduce the braking resistor power and make them better suited solutions for this motor drive.

4.2 Regenerative braking unit

When an electrical motor is decelerated it works as a generator. Different manufacturers have different solutions how to supply this power back to the network. One way is to supply this generated electricity back to the network by using a frequency converter, which has this feature in it. It would work as motoring drive and regenerating drive as well, without using any extra equipment. This is, however, more expensive than one way working frequency converter, which can only work in a motoring drive.

We can use two four-quadrant converters back to back enabling active network bridge operation and full four-quadrant operation of the motor itself. These two would be connected to each other by a cable via DC bus and the frequency converter, which would work as active network bridge and supply either to motor with power or supply possible regenerated power back to the supply network. This however needs some equipment between the active bridge and the supply network. This is because the voltage needs to be filtered and controlled to the right level, which in most cases is 400 volts. Fig. 13 illustrates a four-quadrant drive system converter arrangement.

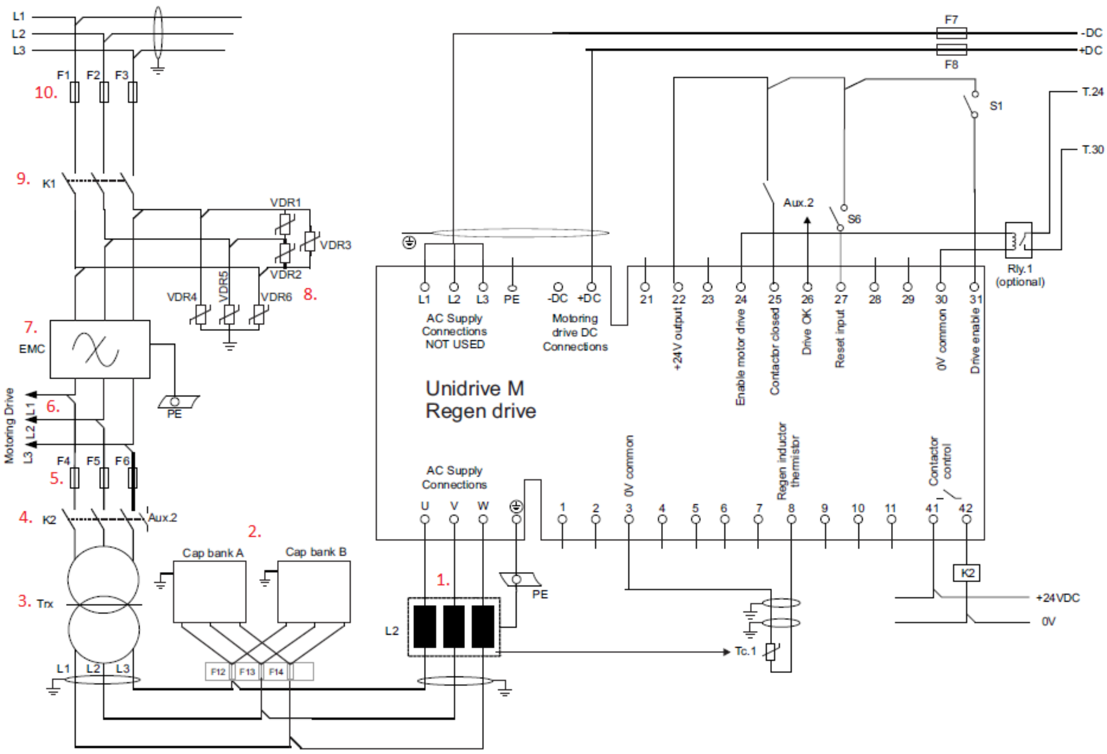


Figure 14. Control techniques. Active network bridge connections.

Raute Oyj uses Control Techniques frequency converters. An active network bridge and a motor control converter belong in the setup. A DC bus connection between the active network bridge the motor converter, needs DC fusing (fuses F7 and F8 in Fig. 14) if the active network bridge is smaller than the motor converter. All other equipment, which is needed are placed between the active network bridge and the supply network as shown in figure 14.

1. First there needs to be an inductor. Its purpose is to filter current and act as a buck-boost energy storage depending on the converter operation.
2. Switching frequency filter capacitors, which stabilize the voltage and power flow.
3. Isolating transformer, which transforms the voltage to 400 volts.
4. Active network bridge main contactor which enables disconnection from the electrical circuit.
5. Active network bridge fusing, which disconnects the system from the electrical circuit in case of fault.
6. Motor converter connection. Here is the input for a motor converter.
7. EMC filter, which limits electromagnetic interference.
8. Varistor network line-to-line 550 Vac + Varistor network line-to-ground 680 Vac. These work as overvoltage protection.
9. Main supply switch or contactor is where the whole output can be turned off.
10. Main active network bridge supply fuses, where the whole output is turned off in case of fault.

With this equipment it is created a system, whose impact on the supply network is minimal. Active network bridge’s power factor is close to unity, which makes them very efficient. Active network bridge also produces clean power, which is a consequence of the low total harmonic distortion. System price however rises quite high, because of its complexity. [47]

4.3 Common DC bus

Common DC bus solution is one of the ways to benefit from motor braking energy. Its total cost is also low and if it is done right, all braking energy can be used in the other frequency converter drives. In this solution as its name states, several motor converters are connected to the common DC bus. This makes it possible that while one or more motor drives are braking, other drives can use that energy for their own operation. Common DC bus can be built in many ways. In figure 15 a solution is shown where a rectifier supplies power to the inverters. This usually lowers the systems total cost.

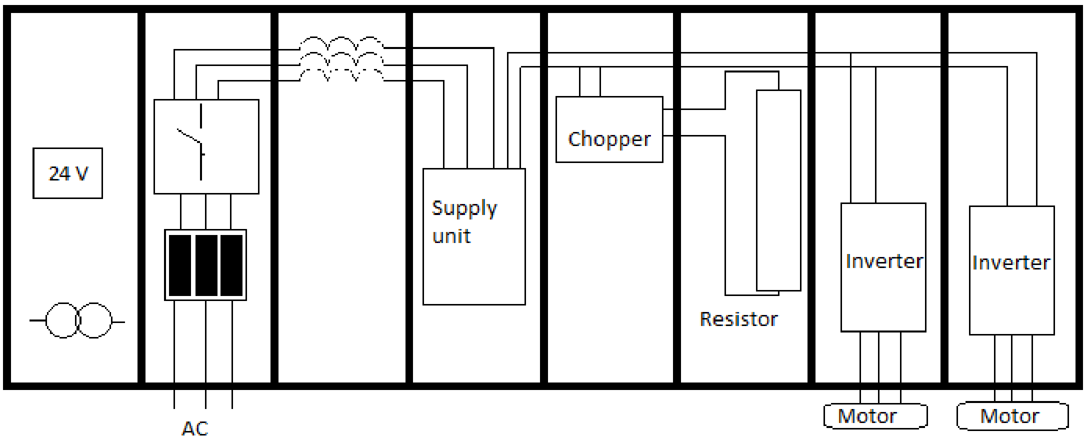


Figure 15. Common DC bus solution. Rectifier supplies power to the inverters, by using a common DC bus. The common DC bus also includes a braking chopper and a resistor.

There are many different variations of this system. It mostly depends on what manufacturers have to offer. Some manufacturers do not offer inverters or rectifiers separately. Usually price differences between a whole frequency converter and only the inverter part is quite low. When manufactures do not have separate inverters and rectifiers, we can just use frequency converters to do the same thing. In this case the network converter is selected to be large enough to supply all frequency converters trough the common DC bus and to drive its own motor at the same time. Fuses are usually required to protect the system. Every time when a motor brakes in a common DC bus system, it allows other frequency converters to use this generated power for their own needs. The largest frequency converter usually also has a braking chopper and a resistor, where the rest of the energy can be wasted. Some manufacturers have a frame block option to connect frequency converters together. In this case fuses are only needed for supplier frequency converter and frame block first frequency converter.

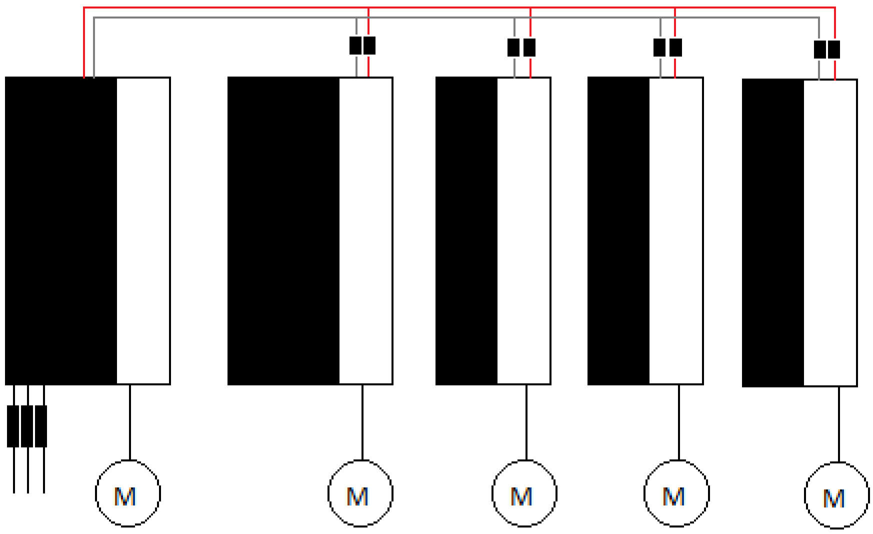


Figure 16. Large frequency converter supplies other frequency converters without supplemental fuses, which would be located close to supplier frequency converter.

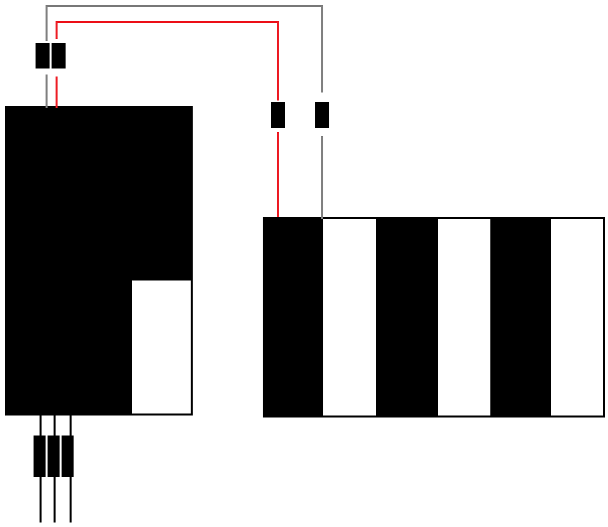


Figure 17. Large frequency converter supplies other frequency converters. Other frequency converters are connected to the same frame block. Fuses need to be installed between frame block's largest frequency converter and supply frequency converter.

Above figures 16 and 17 show two common DC bus systems solutions when we are using Control Techniques frequency converters.

Table 4 reports a system where we have six frequency converters in parallel and each of these have their own capacitance values. Every drive also has maximum group capacitance and if total capacitance value exceeds the smallest drives maximum group capacitance value, it needs DC fuse protection. Common DC bus system can also be created by using many frame blocks. By doing so we do not need DC fusing between every drive, but only between different frame blocks.

Table 4. Sizing information for a common DC bus solution by using paralleling design.

								700 VDC fuse	
			The frequency converter type/size	Motor size	Action	Capacitance (uf)	Max group Capacitance	max rating	min rating
1	Input / converter		M700-074 01000A, 45 kW	10.43 kW	Tablet transfer back and forth	2340		125A dc	125A dc
2		Frame block	M700-05400270A, 11 kW	9.2 kW	Conveyor belt drive	780	4680	125A dc	40A dc
3		Frame block	M700-04400172A, 7.5 kW	5.5 kW	Conveyor belt drive	660	4140	100A dc	30A dc
4		Frame block	M700-04400172A, 7.5 kW	5.5 kW	Conveyor belt drive	660	4140	100A dc	30A dc
5		Frame block	M700-04400172A, 7.5 kW	5.5 kW	Conveyor belt drive	660	4140	100A dc	30A dc
6		Frame block	M700-04400150A, 5.5 kW	4 kW	Tablet transfer back and forth	660	4140	100A dc	25A dc
7		Frame block	M700-04400150A, 5.5 kW	4 kW	Conveyor belt drive	660	4140	100A dc	25A dc
	Fuces between 1 and 2								
					Total capacitance:	4080			

Common DC bus and regenerative drive systems can be combined as well. We can have a common DC bus and an active front end rectifier, which would supply power to the inverters and supply extra braking power to the network. In this case there would not be any need for a braking chopper and a braking resistor.

4.4 Supercapacitor (DES)

In this solution when the motor is decelerating, energy which is produced in dynamic braking is transferred to a supercapacitor, which can be called dynamic energy storage (DES). The main problem with these systems is their price, which can be more than double compared to the other options. Therefore, this option is usually ignored in business world. If common DC bus or regenerative braking unit or braking resistor solution cannot be used or not wanted to be used, we can use DES to store and use energy. These systems are independent of the main system and they can usually work with converters, whose DC link continuous voltage will not rise over 800 VDC, which is the DES unit maximum continuous DC link voltage value in this case. Usually frequency converters have regenerative mode, which helps them to adapt to changing DC-voltage. This also enables some limit value parameters, which provides protection for the frequency converter.

The DES is separated from supply network and that is why it does not affect it at all. It has its own power electronics and control unit enabling clever storing and utilization of the stored energy. In event of braking, it is energised and charged, and in event of accelerating it returns stored energy back to the DC link. This is made possible by defining the maximum and minimum DC link voltage values. After that the DES controls its own functions with these two values. When the DC link reaches its predefined maximum value, the DES starts to absorb energy from it. After braking action, DC link voltage starts to decrease and when it reaches defined minimum value, the DES starts to return the stored energy back to the DC link. This happens when the motor starts to accelerate. The DES stops supplying energy after it reaches certain charging level or minimum voltage level and waits the next braking event. These systems usually have self-learning features, which make it possible that they can be easily connected in parallel. Connection to the frequency converter is achieved easily by using four connections. These connections are:

1. Negative terminal of the DC link,
2. Braking transistor,
3. Positive terminal of the DC link,
4. Some interface, for example RS422 interface.

These connections can be found commonly in modern systems. The DES units usually also have a small braking resistor built in them to absorb voltage spikes.

The DES produces energy savings during acceleration. When motor start to accelerate at first it uses stored energy. When all stored energy has been used, it starts to use electricity network in its acceleration. This first period of acceleration, which is done by stored energy can bring significant saving in the long run.

When we are starting to dimension the DES unit, we need to know the applications driving cycle time, peak power, generated maximum energy and braking time. By using these values, we can choose a suitable unit for each system by using the graphs. In table 5 there are some example values.

Table 5. Example values for sizing DES units.

Driving cycle	1.2 (s)
Peak power	15 (kW)
Max energy	5 (kWs)
Braking period	0.6 (s)

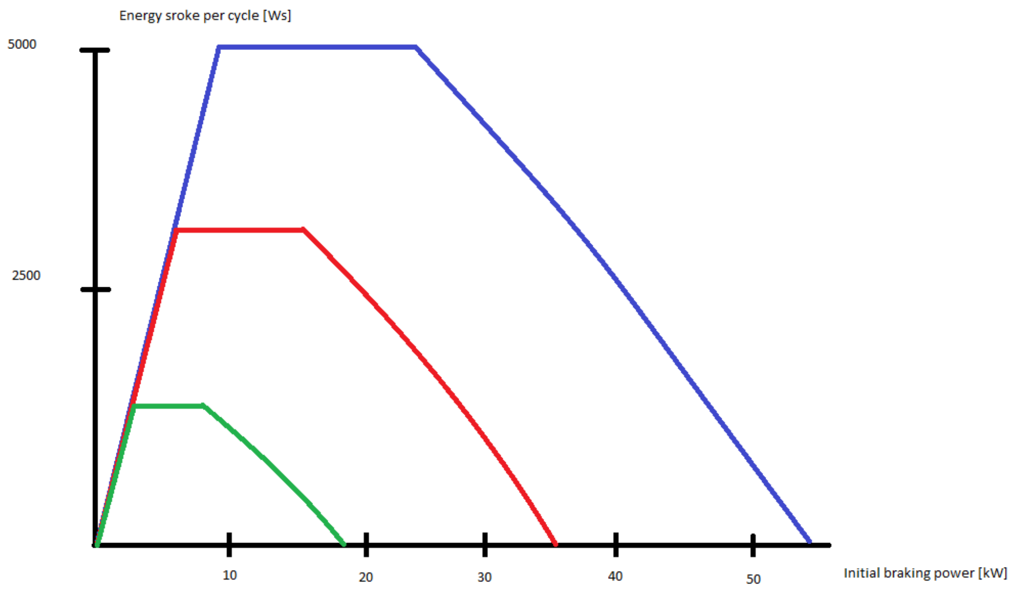


Figure 18. DES maximum energy stroke/Initial braking power with parallel connection. Green has one DES 3.0F 2s-cycle device, red has two DES 3.0F 2s-cycle devices and blue has three DES 3.0F 2s-cycle devices.

In figure 18 we can see that three DES 3.0F 2s-cycle devices have offer storing capacity of 5000 Ws, which is high enough. This capacity can be harnessed at power up to 25 kW. This makes this solution suitable for this use.

5 Solutions

In this selection we review the results and conclusions, which were obtained.

5.1 Measurements

CTScope was used to take measurements on the drive. In these measurements we can see a lot of information about how induction motor works, when it is used to move a linear movement load. There was no need to use their scope meter equipment, because CTScope program did provide enough data.

5.1.1 CTScope

By using CTSope program, we can analyse induction or servomotor action. it was used to analyse the tablet's induction motors functions. CTScope is a software that is created by

Control Techniques and it is designed, to work on their own frequency converter families. It is a software oscilloscope where you can view drive values and analyse them. It is also very easy to use because its user interface is based on a traditional oscilloscope. You can view up to eight analogue channels and four digital channels at the same time, you can also adjust sample period down to 1 ms. It works with CT-RTU, CTNet, Ethernet (CT_TCP/IP), MD29MON and ANSI interfaces.

Measurements were taken in three different cases by using CTScope. In each of these cases an induction motor was used to move the tablets and their payloads were also different. First lay-up tablet was the lightest, the second one was heaviest and third one was in the middle. This did provide a wide area of data, which could be analysed. Induction motor's control method was closed loop vector control. By analysing different scoped variables and by following the tablet's movement, we could acquire good knowledge of the tablet's functions and understand how we could improve it. Optical absolute encoder did work as a feedback device for the induction motor rotor speed.

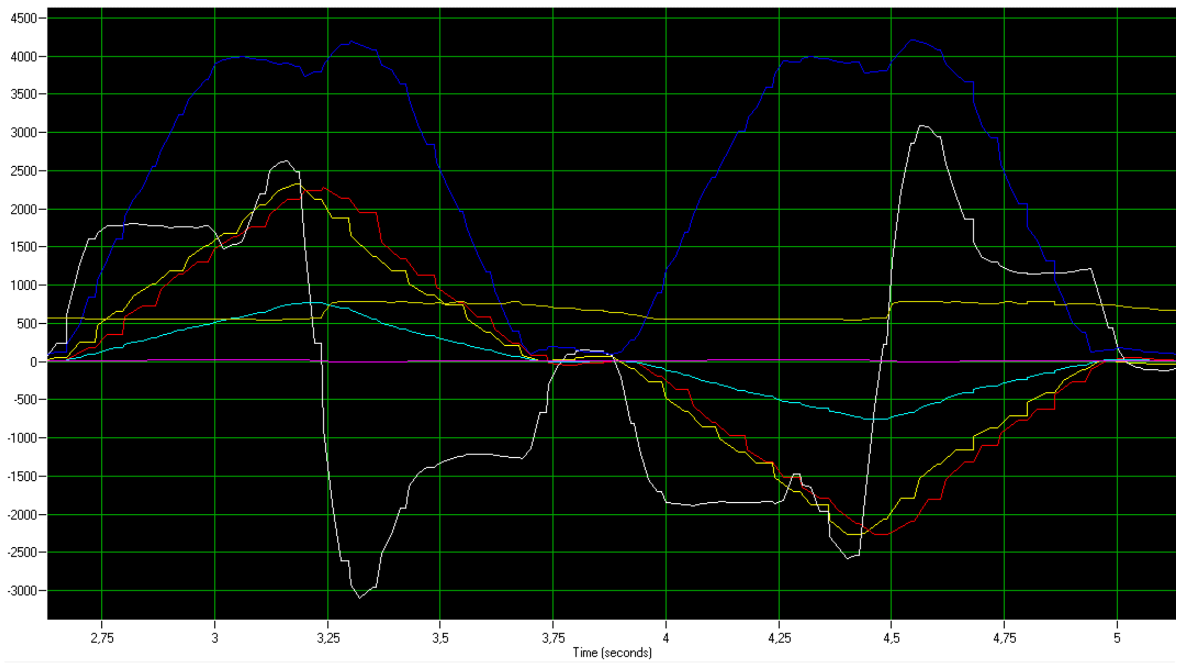


Figure 19. CTSope measurements in case 1. Yellow line is final speed reference of the motor (RPM), red line is the actual speed of the motor (RPM), brown is DC bus voltage, white is torque producing current (scaled 100 times the actual value), purple is output power, light blue is output frequency (scaled to 10 times the actual value) and blue is output voltage (Scaled to 10 times the actual value).

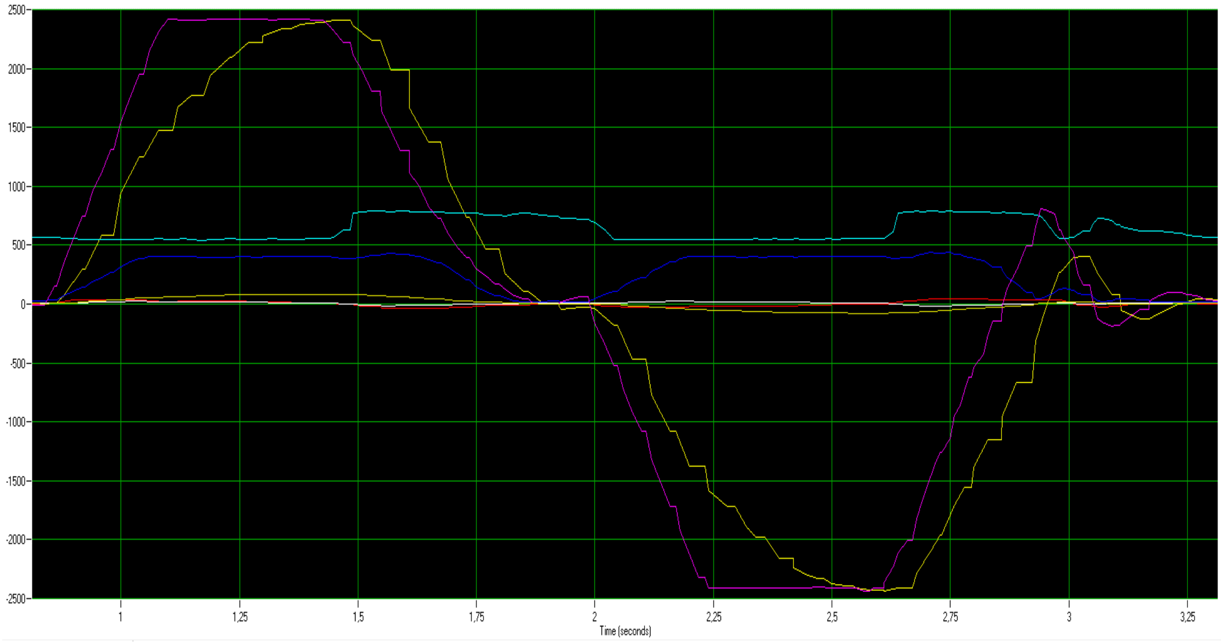


Figure 20. CTSope measurements in case 2. Yellow is speed feedback, purple is final speed reference, red is torque producing current, white is output power, light blue is DC bus voltage, blue is output voltage and brown is output frequency.

Cycle time varies depending on the tablet’s moving distance and its payload, but the cycle time varies in these cases between 2.4 second and 3.5 seconds if we are not counting dwell, which can vary on each cycle. When we are comparing the effects of the tablet mass, we can compare the scoped measurements in figure 19 and in figure 20. Tablets are of the same size, and their moving distance is also the same, but masses of the tablets however are different. In figure 16 the tablet mass is about half of the mass of the tablet in figure 17. It needs to be noted that the tablet in figure 17 has not been adjusted to full capacity yet, because of the braking resistor capacity problems.

5.2 Results

In figure 16 and 17 we can see scoped values in two cases. By analysing each scope measurements, we can compare them with each other and see how the mass of the tablet affects the induction motor’s function. In this chapter some problems in tablet operation are pointed out and some ways to improve it are listed, but mainly the solutions of improving this operation are handled later in this thesis.

By analysing the speed of the motor, we can see that it cannot keep up with the reference speed. This is because of the industrial induction motor’s high inertia, which makes it impossible to follow the reference speed precisely, but the difference is so small that it does not affect the system function. One another factor is that we cannot use high enough starting torque. This is because it would start to cause overheating in the motor at least in high ambient temperature. In plywood and LVL factories the ambient temperature close to the lay-up tablet can easily rise to 60℃, because of the neighbouring hot presses. Overheating issues usually occur during summertime, but a lay-up tablet must work properly both in summer and winter times. There have been cases, where it has been possible to decrease a lay-up tablet cycle time by increasing the ramp values and speed values in the wintertime, but in the summertime the motor has overheated. Because we cannot use high enough starting torque speed lags and makes it impossible to catch up to the reference speed. Another one of the high inertias effects is that it shoots over the set positions. This effect can be seen when the tablet’s movement speed is increased high enough. In figure 20 the movement of the tablet is still quite slow and therefore this effect is not seen in it.

By lowering the inertia of the motor, we would be able to increase the dynamic load performance. This is a very important factor in the tablet’s movement because it is fast, and its load is dynamic. Inertia’s effects to the dynamic performance can be tested, by using a motor sizing program. When the total inertia value is decreased required maximum torque value and RMS torque value are decreased. Lower total inertia value also reduces inverter peak and continuous current. Regenerated peak and continuous power values also decrease.

The induction motor’s nominal speed is 1500 rpm. In figure 19 we can see field weakening effect at about 1500 rpm, when its torque producing current increases considerably. This can take place because the motor load is clearly lower than its maximum torque in the field weakening at the speeds seen in the chart. When we are starting to brake the induction motor while being in the field weakening, it causes braking current to reach a very high negative value. The torque-producing current decreases slightly after the motor reaches its nominal flux linkage level at the rated speed. From this we can conclude that field weakening has an increasing effect to the braking power. We can also see that the brake ramp is very steep, so it also makes braking power to rise, because more braking torque is required to stop the induction motor movement. This is because of its higher inertia value, which resists the change in speed more. These factors cause the braking power of this operation to be quite high and because of all this power is wasted in the braking resistors, we need much braking capacity.

Frequency of the motor reaches the maximum value of 76.4 Hz in case of figure 20 and the point where the output voltage reaches its rated value 400 volts, the output frequency is 57.3 Hz. In these tablet's scoped measurements, we can see that the output frequency is about 50 Hz at the rated voltage.

Continuous and peak output power can be decreased by lowering the mass of the tablet, but the effect of that stays quite low. This is mainly because of the induction motor's high inertia, which is 0.0817 $\mathrm{kgm^2}$, but also because a gear is used, which also lowers the effect. We can calculate the referred load inertia of the lay-up tablet, by using formula (3.9). Let us assume that the lay-up tablet mass is 300 kg. In this case our load inertia J_{load} would be 2.48 $\mathrm{kgm^2}$ and our gear ratio i is 9.

$$J_{\mathrm{red}} = \frac{2.48\ \mathrm{kgm^2}}{9^2} = 0.0306\ \mathrm{kgm^2}$$

From this calculation, we can see the reduction effect of the gear on the inertia of the load. The load inertia value drops to 1.2% of the original value.

The high inertia of the induction motor causes the drive to use most of its output power in the acceleration or deceleration of the induction motor. The load torque effect in case of the induction motor drive is quite low. For example, when we have an application and we can choose between two motors, where only motor inertia separates them from each other. The inertia of the bigger motor is 45% greater than the inertia of the other motor. The higher-inertia motor has about 9% greater continuous and peak power. Inertia mismatch, however, is better with a larger inertia motor. So, by altering the load mass a little, we cannot affect much the induction motor function in this operation.

Tablet's acceleration and deceleration vary in all three cases. In all cases the acceleration and deceleration is tried to be made as fast as possible, however, acceleration cannot exceed 7.5 $\frac{\mathrm{m}}{\mathrm{s^2}}$. This is because the veneer sheet cannot stay on the tablet at any higher acceleration rates. Acceleration and deceleration rates do not have any restrictions after the veneer sheet has been transported to its endpoint, which is when the tablet is moving back to home station. Restriction when the veneer sheet is on tablet could be eliminated, by installing a suction cup system on the tablet, but this would be challenging to implement.

Table 1 on page nine shows some values of two cases where tablet movement has been brought close to the maximum in cases one and three. If in these situations the speed of the operation is further increased, it causes over heating of the motor and braking resistors. One of the causes of this is the ambient temperature, which is quite high in the plywood factory.

5.3 Motor comparison

Servo motor does not have any common definition. Structure of the servomotor is very similar to other industrial motor types. You can call original induction motor asynchronous AC servomotor, if it has a precise feedback sensor embedded. It depends on the manufacturer and the application which motors are called servo motors.

Induction motor main parts are the stator and the rotor, there is also rotors end rings. When the rotor is rotating, it rotates the shaft, which is used to transfer mechanical power to the load. There are also bearings, which reduce friction of the rotating shaft. Wearing of the bearings is one of the most common cause for the faults of the induction motor. Sometimes induction motor might have a fan build in them, which would provide self-cooling effect. This part is usually left out of motors which are rotating at high speeds, because it would create disturbing noise and significant losses.

PM servomotor structure is very similar to the induction motor structure. The differences are that the absolute encoder is built inside of the motor, on the back side of the shaft and the rotor is usually build by using permanent magnet material. Permanent magnet material is rare earth material, which helps in producing a high torque.

All main differences of these motors are caused by PM, which enables these changes. Encoder is also inbuild in a PM servomotor, but it can be installed on an induction motor shaft as well. Usually it is placed on the non-drive end of the shaft outside of the motor. Usually motors have feedback mounting adapter, where feedback device can be installed.

Differences between other motor types and servomotors are in the most cases that, the servomotors are much lighter because of PM excitation. Because of inbuild feedback device, it is very accurate and efficient, when rotating or moving linearly. Servomotors and other motor types control methods are similar. Usually servomotors control method differs a little from other motor types control. There are also motors with PM, which are not classified as servomotors. Usually servomotors have much lower inertia This smaller inertia is mainly caused size differences in rotor. This is a very useful feature while moving dynamic loads. Servomotors as all electric motor types can work both in motoring and regenerative mode.

In my opinion there are three things which make a servomotor:

1. Servomotors are low inertia machines, whose inertia can sometimes be even just one tenth compared to the inertia of a same speed and power industrial motor. This low inertia is acquired with a PM rotor.
2. Servomotors are machines, whose functioning is brought as close to the maximum as possible, because of the feedback device.
3. Servomotors always have a rotor position feedback device embedded in them.

These definitions however do not always apply. Because of similarities to the other motor types and servomotor’s structure, it is impossible to find one proper definition for it. The best explanation for the servomotor is as mentioned earlier that, a servomotor is a linear or rotary actuator, which has precise control of angular or linear position.

5.4 Dimensioning

Motors are usually used to rotate conveyors or move loads. Often gears are needed to provide correct rotational speed and torque. In case of the tablet variations in mass and moving distance make motor and drive sizing quite challenging.

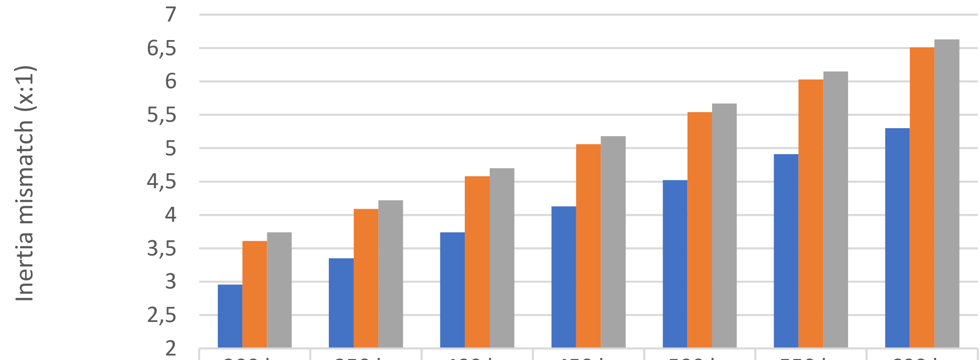
5.4.1 Moment of inertia

Inertia is very important when we are sizing the motor, because it is the property which resists its rotational speed change or directional change. So, inertia works like inductance. Other factors that affect rotational speed are friction caused by the moving parts and the air resistance. Conclusion is that lower inertia value provides better dynamic performance.

Motor and the load have their own inertias. This ratio cannot be bigger than 1:10 in case of servomotors. If this value would be exceeded, it would resolve in a very unstable motor operation.

5.4.2 Gear selection

In lay-up tablet we chose to use planetary gear, which would be able to handle large torques. It is also small, and light compared to the common gear solution. Selected conversional ratio was 1:9. With this conversional ratio our inertia mismatch is kept at good value and output speed of the gear would be sufficient.



	300 kg	350 kg	400 kg	450 kg	500 kg	550 kg	600 kg
1: Inertia mismatch i=10 (8ft)	2,955	3,35	3,74	4,13	4,52	4,91	5,3
2: Inertia mismatch i=9 (8ft)	3,61	4,09	4,58	5,06	5,54	6,03	6,51
3: Inertia mismatch i=9 (14ft)	3,74	4,22	4,7	5,18	5,67	6,15	6,63

Figure 21. Shows inertia mismatch ratio in different mass classes. Here we have used two different gear ratios, which are 1:10 (*i* = 10) and 1:9 conversion rations (*i* = 9). The first and the second row show the mismatch ratios for eight feet tablet and the third row shows it for the 14 feet tablet, which is the largest tablet size we have.

With a new servomotor we have motor inertia 0.00887 $\mathrm{kgm^2}$. Our total load inertia after gear is 0.03201 $\mathrm{kgm^2}$. This value includes the own inertia of the gear. Our lay-up tablets mass in this case is 300 kg and gear ratio is 1:9. With these values we get inertia mismatch value

$$IM = \frac{J_\mathrm{L}}{J_\mathrm{M}} = \frac{0.03201\ \mathrm{kgm^2}}{0.00887\ \mathrm{kgm^2}} = 3.61 \qquad (5.1)$$

Old induction motor inertia mismatch value can be calculated, by using the same tablet mass and the same load inertia. Induction motor inertia is 0.0817 $\mathrm{kgm^2}$. In this case we get value

$$IM = \frac{0.03201\ \mathrm{kgm^2}}{0.0817\ \mathrm{kgm^2}} = 0.39 \qquad (5.2)$$

With these calculations we can notice that the inertia mismatch value is much better (smaller) in case of the induction motor.

5.4.3 Equipment selection

When we have studied the tablet's function and decided, which motor type would be the best replacement for the industrial induction motor used earlier, then we can start the motor dimensioning. After the dimensioning is done, we can compare the old and new motor values with each other and check if we have been able to influence the planned points.

In Table 6, we have compared some induction motor values with the selected servomotor values. In servomotors case we have K_e value, which is the ratio between r.m.s line to line voltage produced by the motor and the speed in U/1000rpm. The speed of the servomotor can be calculated by using formula,

$$n = UK_{\mathrm{e}} \tag{5.1}$$

Where K_e is given in volts per 1000 rpm.

Table 6. Comparison of some tablet motor values.

	Induction motor (Old motor)	Servomotor (Selected)
Inertia	0.0817 kgm^2	0.00887 kgm^2
Mass (motor+gear)	115 kg	67 kg
Rated power	11.0 kW	10.43 kW
Rated current	21.0 A	20.75 A
Max current	153.3 A (starting current)	83.4 A
Rated torque	71 Nm	33.2 Nm
Rated speed	1480 rpm	(3165 rpm*)
Number of poles	4	8
Rated frequency	50 Hz	-
Volts per 1000rpm (K_e)	-	98
Max torque	184.6 Nm (starting torque) and 156.2 Nm (Acceleration torque)	133.5 Nm
Gear ratio	7.24	9

- calculated from the rated power and torque – not an official value

The inertia of the servomotor is just 12 % of the inertia of the industrial induction motor. This difference is mainly caused by the rotors size difference. The servomotor rotor diameter is much smaller than the rotor diameter of the IM. This makes its dynamic performance much better. The mass of the motor is decreased a lot, which makes connecting the motor to the tablet much easier. The gear ratio is increased so that we can have right output speed for the load shaft. Torque values decrease somewhat, but this can be compensated by the gear ratio change. In the sizing program there were two acceleration rules, which can be used. These rules are 1/2 and 1/3 rules. You can also create your own acceleration waveform model. In the 1/2 rule, we start to accelerate the speed of the motor and when it reaches the top speed, it starts to decelerate. This means that in this case the motor would not move at constant speed at any given point. In the 1/3 rule each action takes 1/3 of the total moving time. These actions are acceleration, constant speed and deceleration. By testing both acceleration waveforms creating ways, I noticed that in the second rule, we would be able to choose a smaller motor and a smaller frequency converter than in the first rule case. In the first rule all peak values are lower, but continuous values are higher. The first rule also requires a much higher maximum speed of the motor than the second rule. For comparison, by only changing the acceleration rule, in the case of the first rule the required maximum speed of the motor would be about 4000 rpm, but in the case of the second rule it would be about 3000 rpm. Based on this data we can assume that the 1/3 rule would be the best rule to use at least in this case. So, by using the 1/3 rule we can lower the motor’s RMS torque and maximum required speed value.

This study shows that the selected servomotor is a much better suited option to move the tablet than the industrial induction motor. Servomotor selection was done by using SERVOsoft program, which is very simple and easy to use. It is developed by the Control Techniques for servomotor selection. In the program you can create motion profiles and sequences. You can also view any profile, for example the current and the torque.

When you start to select a motor and frequency converter for a load, first you need to select the load’s drive mechanism. In this section the most important things are that you calculate load inertias and mark load masses. Axle diameters need also be put in the program so that the actual speed and the acceleration and the deceleration rates can be calculated. After this you create the desired sequence. There is also an option to choose coupling type if any. This can be a direct coupling, a geared coupling, a belt system or pulley. The most common of these is gear, which was used in this work as well.

After this, you can select your motor and frequency converter from the database. In this program you can size the frequency converter to the motor very precisely, but because of the many different weight classes we decided to choose one model bigger frequency converter in this case. This is because of the possible modernisation project where tablet mass may be much larger, and the selected frequency converter would not be able to provide high enough current to achieve the wanted cycle time. The price difference between these models was also negligible.

In the program we can examine the power and energy profiles. Some of these can be seen in figure 22.

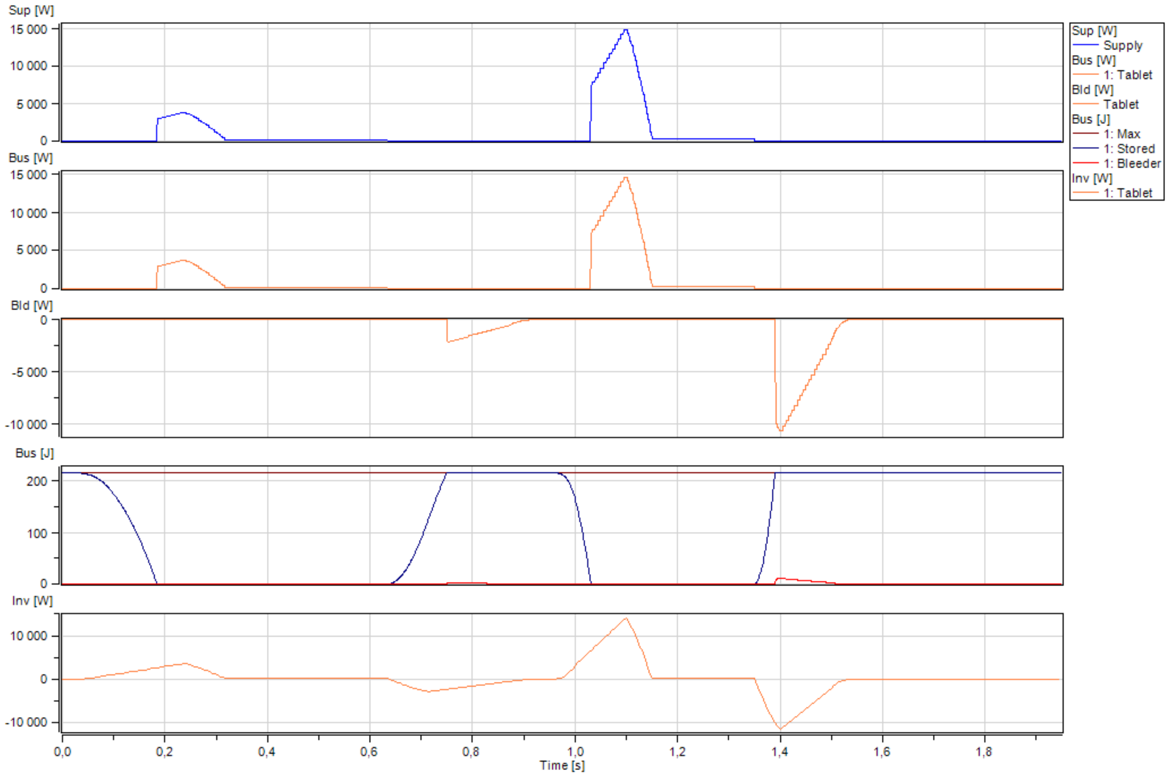


Figure 22. Power and energy profiles.

The first graph on top is the system supply power profile, the second one is bus power profile, the third one is bleeder power profile, which is power distributed to each enabled bleeder on the bus. Bleeder consist of a chopper and resistor. The fourth one is bus stored and bleeder energy profiles and the fifth one is the inverter power profile.

We are also able to examine the motor and inverter performance curves, which can be seen in figure 23. By using all these available curves and values, we can determine, which one of the motors and the frequency converters are best suited for this application.

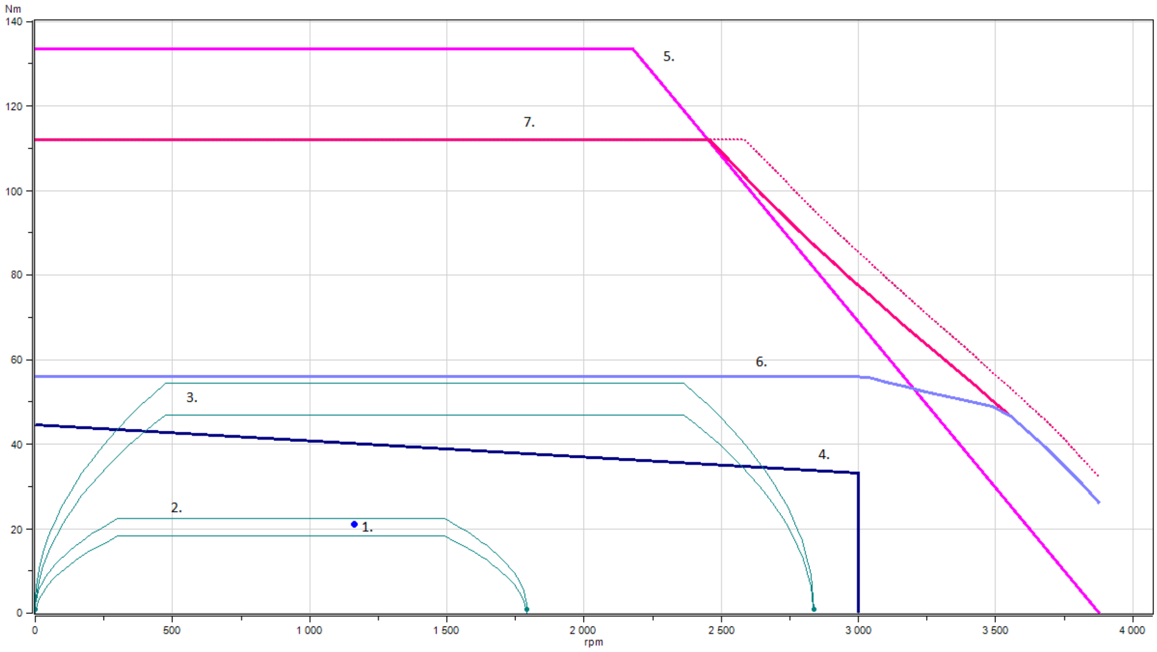


Figure 23. Motor and inverter performance in speed (rpm) torque (Nm) plane. 1. Application RMS torque, 2 and 3. Application profiles, 4. Motor rated continuous torque characteristic curve, 5. Motor rated peak torque characteristic curve, 6. Inverter rated continuous torque characteristic curve (based on the motor selected), which is linked to the selected electrical motor, 7. Inverter rated peak torque characteristic curve.

5.5 Braking system

For a lay-up tablet all these possible solutions have their pros and cons. In the existing system, we have been able to discover that the braking resistors are not offering a good solution for this case. This is because of overheating issues of the existing resistors. This might be fixed by selecting different resistor types and manufacturers, but working conditions need to be considered, too. Braking resistors are also wasting all this energy, which is not the case in other options. Braking resistors however offer very simple and usually quite cheap dynamic braking system.

A four-quadrant drive solution would provide reasonable price and a well working system in many situations. A four-quadrant system does not have any restrictions, which would leave it out of options. The only thing which might affect it, would be poor supply network, but this becomes a problem very rarely. In my opinion a four-quadrant system would provide the best solution for dynamic braking in tablet use, but it is still quite a costly system.

For the studied system common DC bus system would not be the best suited solution. This is because other motors should be able to use all of the power, which has been generated through dynamic braking. Other motors, however, are not rotating or accelerating at the right time or this happens very rarely. Every lay-up line is also different, so it is hard to try to implement a common DC bus solution for all lay-up lines of a factory. This problem can be fixed by using a braking resistor, which would use surplus energy. In my opinion this takes the purpose off from the system. In all common DC systems, there might be some moments of time when braking resistors are needed, but in this system a braking resistor would be in constant use. Because the cost of this system stays quite low, a common DC bus solution could still be used in lay-up lines to save some space in switchboard supplying motors and even reduce cabinets number. This would save some valuable floor space in a factory.

The DES is very simple to install, and it does not need any other equipment to work. However, price gap is too big compared to the other systems, so it eliminates this option off in this case. In the future, the DES applications prices might drop and after that it would provide a well-suited solution in many cases.

6 Conclusion

In this study our mission was to find ways to improve the lay-up tablet functions by studying different motor type options and different dynamic braking solutions. In the studies we tried to find a proper definition for the servomotor.

All motors have a stator and a rotor. Stator is stationary part and rotor is rotating part. They need to produce their common magnetic field, which is important in producing torque for rotational movement. Stator flux linkage is the integral of the voltage supplied to its terminals. Rotor magnetic performance depends on its construction. It may have a DC-winding, permanent magnets or in case of an IM the rotor currents are created by induction.

Induction motor is one of the most commonly used motor types. Its function is based on induction, where the airgap rotating magnetic field induces voltages to the rotor and produces current. For this to happen, the common magnetic field needs to be rotating faster that the rotor. If the rotor is rotating faster than the common magnetic field, induction motor goes into regenerative mode.

Industrial induction motor was used in tablet’s motoring drive. Industrial induction motors, however, have usually quite high inertia and large mass. Hight inertia reduces the dynamic load performance, which is important in this application. Induction motors have good overload capacity and they can go deep into the field weakening. In this application feedback device is needed to enable good dynamic performance. Best suited controlling method is vector control.

When we studied the induction motor action in tablet’s use, we were capable of noticing that a servomotor would be much more suitable motor type in this application. The high rated torque of the industrial induction motor cannot be used because of the factory high temperature, especially in summer. Introducing a servomotor helps in reducing the overheating issues of the motor and the braking resistors. The size and mass of the selected servomotor is also 40% less than the current induction motor, which makes it easier to attach it mechanically on the lay-up tablet. Motor’s inertia can also be reduced and through this, the motor’s dynamic load performance improved. Inertia mismatch needs to be considered. System inertia mismatch value cannot be more than 10, or it would resolve in unstable motor operation. If for some reason the inertia mismatch ratio would be close to the maximum value or even over it, we would need a high-resolution encoder. This would allow us to get as much information about the motor from encoder while it is running. This enables much better motor control, which means that speed controller can be adjusted with much greater accuracy. This enables better control of inertia. We were also able to achieve the same cycle times than with an induction motor and with some tablet sizes even better cycle times. One other possible solution for the motor selection would have been to use smaller 230/400V induction motor connected in delta in which case nominal speed of the motor would have increased. In this case, a higher gear ratio could have been used. This would have been a little cheaper solution compared to a servomotor.

Electrical motor braking methods were studied, and all these methods could be used in this system, but the best solution in this case would be a four-quadrant drive solution. If DES system price would be much lower, it would be the best suited solution. If we think commonly all industrial machines, common DC bus solution would be considered, because of its simplicity and moderate price. One way we could use a common DC bus solution in a lay-up tablet would be to expand the DC bus distribution to be factory wide.

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