TAMPERE UNIVERSITY
OF APPLIED SCIENCES

i-Locker

Selecting the main drive system

Jordy Declercq

Bachelor's thesis
May 2017
Electromechanics
Automation

ABSTRACT

Tampereen ammattikorkeakoulu
Tampere University of Applied Sciences
Electromechanics
Automation

JORDY, DECLERCQ:
i-Locker
Selecting the Main Drive System

Bachelor's thesis 66 pages, appendices 26 pages
May 2017

The purpose of this thesis was selecting the main drive system for the testing phase of the i-Locker. Different electric motors were studied and compared to see the benefits of each motor in combination with a frequency drive. The best suitable electric motor and frequency drive were selected to be used for the i-Locker application.

The main function of the drive system is to rotate the lockers mounted onto the i-Locker's frame. The electric motor converts the electrical energy into mechanical energy. This energy is transferred from the shaft of the servo motor to the lockers by using a transmission existing out of a drive gear, a driven gear, and an ANSI 50 chain. The driven gear and lower gear are both mounted onto the same axle, the lower gear is connected to an upper gear with an ANSI 50 chain. On this particular chain the lockers are mounted.

For choosing the most suitable electric motor and drive the theoretical background will be used for the needed information. Calculations are made and data is gathered from the i-Locker application at TAMK's Laboratories. The speed, power, and torque calculations were needed for selecting an electric motor. The data received from the calculations determines the size and type of the electric motor.

The biggest disadvantage of the AC variable frequency drive was the possibility that harmonics could occur if the AC variable frequency drive wasn't installed correctly. Therefore the installation and connections of the variable frequency drive should be taken very serious. This Thesis greatly explains and illustrates the physical connections as well as the software installation, to negate the disadvantage.

The best suitable main drive system for the i-Locker application was the brushless AC servo motor from Control Techniques and the Unidrive M700 from EMERSON Industrial Automation. There was a perfect communication and efficiency between the two components.

Key words: i-Locker, main drive system, servo motor, variable frequency drive

CONTENTS

GLOSSARY

A	Amps
AC	Alternating Current
ANSI	American National Standards Institute
CNC	Computer Numerical Control
CT	Control Techniques
DC	Direct Current
EMF	Electromotive Force
Hz	Hertz
IE	Incremental Encoder
TAMK	Tampere University of Applied Sciences
TI	Texas Instruments
V	Voltage
VFD	Variable Frequency Drive
VPWM	Variable Pulse Width Modulation
Gs	Gear speed
Ms	Motor speed

Mathematical abbreviations

v	Velocity
s	Seconds
t	Time
l	Length
d	Diameter
r	Radian
kg	Kilogram
h	Height
rev	Revolution
rpm	Revolutions per minute
rad	Radials
N	Newton [$\frac{kg\ x\ m}{s^2}$]

m	Meter
Nm	Newton Meter
W	Watt
g	gravitational acceleration

1 INTRODUCTION

This Thesis is written following the structural and formal requirements for written academic reports at the Tampereen ammattikorkeakoulu / Tampere University of Applied Sciences. Its aim is to elucidate the developing of the i-Locker, a smart locker for storing everyday goods like someone's backpack for example.

The i-Locker consists out of twelve single lockers evolving around two axles on which the gears are connected upon. The upper and lower gear are connected to each other by a chain which then spins the single lockers. Furthermore, the lower gear is driven by an electric motor which is controlled by a variable-frequency drive.
The peculiarity of this lockers is that it will remember the exact locker used by an individual.

Storing goods in for example locker number 6, will be remembered by the i-Locker so that in need of retrieval of someone's goods the single lockers are going to be turned until the needed locker, in this example locker number 6, is at its final destination and therefore reachable for the individual to make it possible to take out the stored goods after completing a safety procedure.

The further aspiration of this Thesis is to educate the students who are now developing the i-Locker as well as providing information for later participants working on the progression of this project.

Starting with theoretical background knowledge, emerged from and maintained by the students, this Thesis is taking further steps in to the insights and understanding of the i-Locker itself as well as the different components that, merged together, form this machine. Calculations and mathematical knowledge needed for researching the right components, as for example the electric motor, complete this Thesis.

This Thesis is going to focus primarily on the main drive system and the therefor needed selection procedure for the motor and frequency drive to ensure the optimal combination for the requirements of the i-Locker. The selected motor and frequency drive combination is discussed in detail, as well as its assembly and attributes, during this part as well. This thesis will also include a step by step guidance to connect the Unidrive M700 and communicate with it by using Ethernet. Developed for TAMK laboratory this project therefore is the property of the Tampereen ammattikorkeakoulu.

2 THEORETICAL BACKGROUND

In the next chapters the general working principle of a motor will be briefly explained. The different types of motors and frequency drives will be introduced, and thus also explained why a specific motor or drive was used for this thesis.

2.1 The General Working Principle of a Motor

The general working principle of a motor is that when a current-carrying conductor is placed in a magnetic field, it experiences a mechanical force this mechanical force is called the Lorentz Force. The Lorentz Force Law was named after the Dutch physicist Hendrik A. Lorentz (Britannica, 2017).

Definition of the Lorentz Force Law
” The Force on a charged particle moving in electric and magnetic fields, equal to the particle's charge times the sum of the electric field and the cross product of the particle's velocity with the magnetic flux density.” (McGraw-Hill, 2017)

Formula
$F = qE + qv \times B$

This formula can be rewritten into $F = B \times I \times L \times \sin\theta$ which is used to calculate the magnetic force on a current-carrying wire. Where as F is the Lorentz Force measured in Newtons, B is the flux density (the strength of a magnetic field) measured in Teslas (named after Nikola Tesla). I is current measured in amps, L is the length of conductor in the magnetic field measured in meters, θ is the angle the current makes with the magnetic field (WIKIBOOKS, 2016).

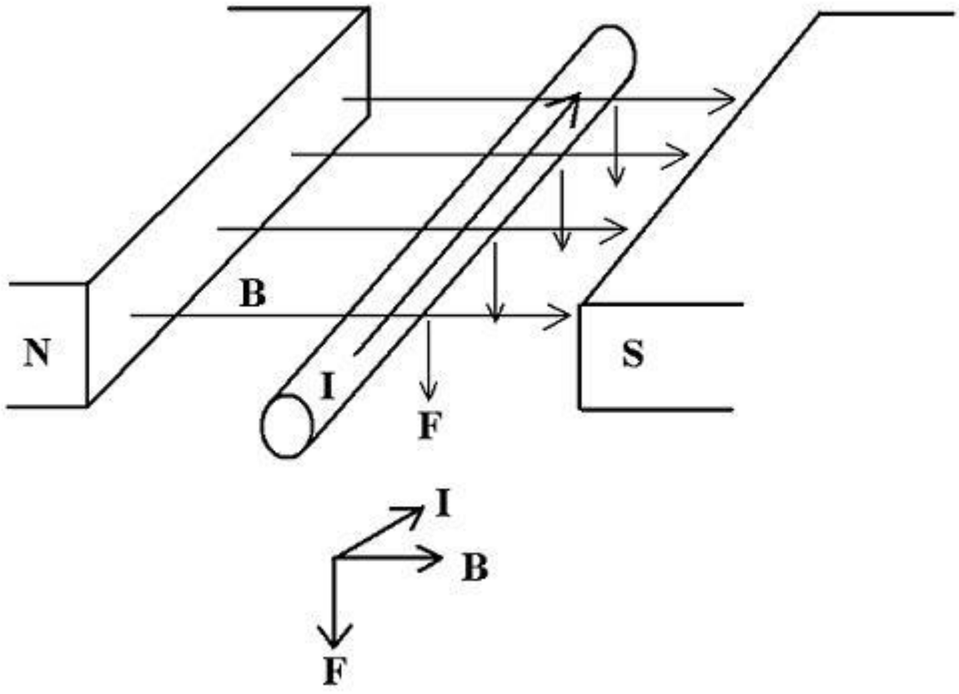


Figure 1. Explanation of the Lorentz Force (Anonymous)

If the formula and definition are combined the following can be said, the Lorentz force F is the force exerted on a charged particle q moving with velocity v through an electric field E and magnetic field B (Britannica, 2017).

Fleming's left hand rule is used mainly for electric motors, where Fleming's right hand rule is used mainly for generators. To know the direction of the Lorentz force Fleming's left hand rule is used. To know the direction of the induced current Fleming's right hand rule is used.

When using Fleming's left hand rule the thumb points to the direction of the force, the index finger shows the direction of the magnetic field. The direction of the magnetic field is from magnetic north to the magnetic south. The middle finger shows the direction of the current through the wire.

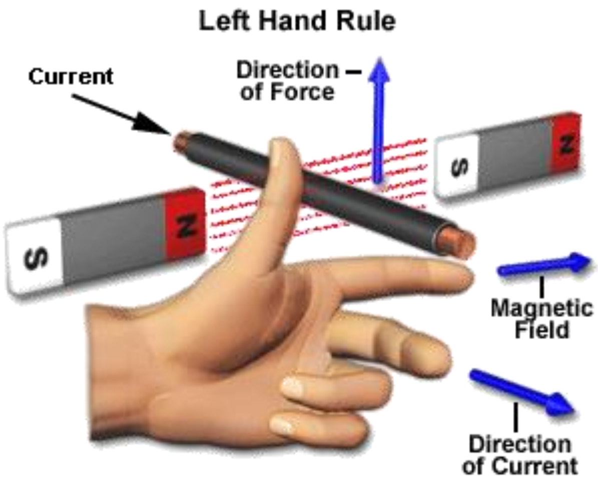


FIGURE 2. Fleming's Left Hand Rule (electrical4u, 2017)

When using Fleming’s right hand rule the thumb points to the direction of the force, the index finger shows the direction of the magnetic field. The middle finger shows the direction of the current through the wire.

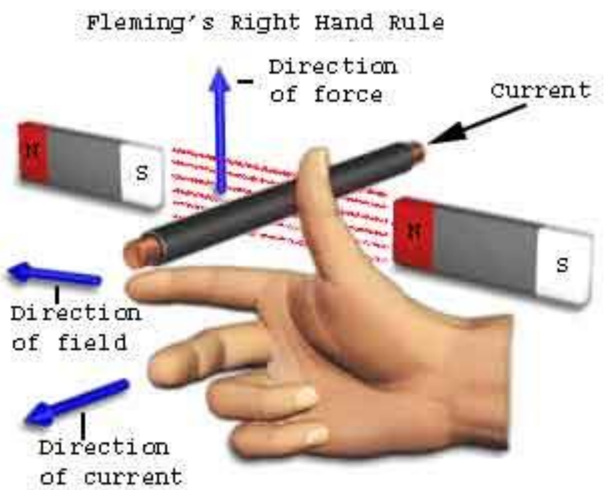


FIGURE 3. Fleming's Right Hand Rule (electrical4u, 2017)

The difference between Fleming’s left and right hand rules are that one is used for motors and the other for generators (electrical4u, 2017).

To understand the general working principle the laws of electromagnetism must be applied. Lorentz’s Law, Faraday’s Law, Lenz’s Law are just a few of the basic laws of electromagnetism discovered and defined by great physicists. Furthermore the EMF (Electromotive Force) will also shortly be explained.

Faraday's law of induction is a basic law of electromagnetism predicting how a magnetic field will interact with an electric circuit to produce an electromotive force (EMF). It is the fundamental operating principle of transformers, inductors, and many types of electric motors, generators and solenoids (Sadiku, 2007).

Faraday's law states that the EMF is also given by the rate of change of the magnetic flux:

$$\varepsilon = -\frac{d\Phi B}{dt}$$

Where $\mathcal{E}$ is the electromotive force (EMF) and ΦB is the magnetic flux. The direction of the electromotive force is given by Lenz's law (WIKIPEDIA, Wet van Lenz, 2017).

$$\varepsilon = -N\frac{d\Phi B}{dt}$$

For a tightly wound coil of wire, composed of N identical turns, each with the same ΦB, Faraday's law of induction states that where N is the number of turns of wire and ΦB is the magnetic flux through a single loop (Sadiku, 2007).

Definition of Lenz Law, “The direction of current induced in a conductor by a changing magnetic field due to Faraday's law of induction will be such that it will create a field that opposes the change that produced it.” – Emil Lenz (W. M., 1963).

There is a connection between Lenz’s Law and Faraday’s law of induction as in Faraday’s Law of Induction, the negative sign shows Lenz’s Law (WIKIPEDIA, 2017).

$$\varepsilon = -\frac{\partial\Phi}{\partial t}$$

This indicates that the induced EMF and the change in magnetic flux have opposite signs (Douglas C., 1998).

The following can be said as well, the Law of Lenz is a special case of Faraday’s Law since any magnetic flux change is counteracted by an induced electrical voltage according to the formula seen below.

$$U = -N\frac{d\Phi}{dt}$$

Where U is the generated electrical voltage, Φ is the magnetic flux, N is the number of turns of the coil and t is the time.

EMF or Electromotive Force is the voltage developed by any source of electrical energy such as a dynamo or battery and is measured in volts. It is generally defined as the electrical potential for a source in a circuit (Houghton, 1992).

In electromagnetic induction EMF can be defined around a closed loop as the electromagnetic work that would be done on a charge if it travels once around that loop. For a time-varying magnetic flux linking a loop, the electric potential scalar field is not defined due to circulating electric vector field, but nevertheless the force of an EMF can be measured as a virtual electric potential around that loop (David M., 2003).

To start telling how a motor works the components inside a motor should be explained first. Starting with the commutator used when there is an AC power supply, the commutator is a metal ring divided into two separate halves. The main role of the commutator is to reverse the current coming from the power supply. To reverse the electric current in the coil, one end of the coil is attached to each half of the commutator as seen on the figure below. For the current from the power supply to reach the commutator there is a need of brushes which carry the current from the supply to the commutator. To get a rotational force this must happen within a magnetic field (Woodford, 2017).

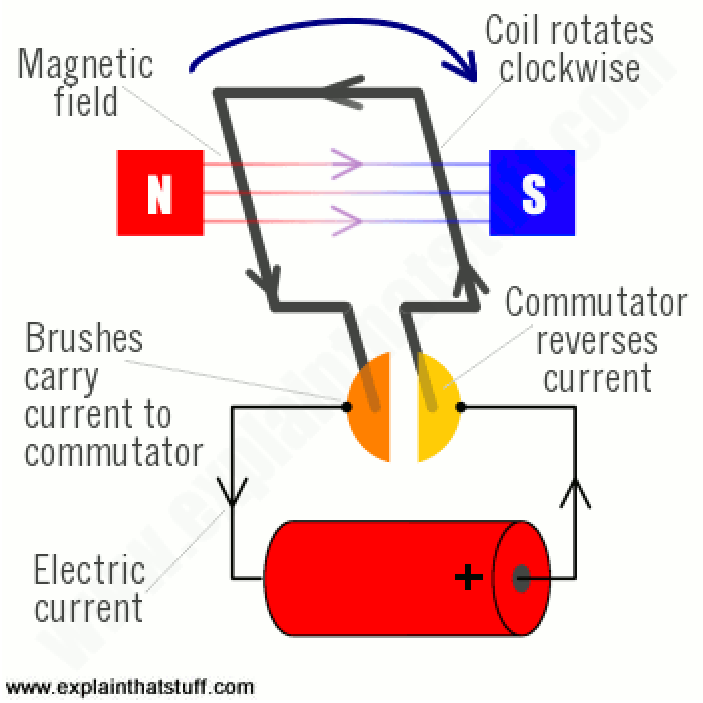


FIGURE 4. Diagram of the parts in an electric motor (Woodford, 2017)

The classification of motors can be based on the power supply, the principle of operation, the type of current, the speed of operation and on the structural features. To make it easy readable the splitting of the classification will be about the power supply meaning the differences between Alternating Current (AC) and Direct Current (DC).

Direct Current always flows in the same direction, but the current may increase or decrease. Thus there is always a pole that is negative and another pole that is positive. So it can be said if the current reverses direction it reverses its polarity.

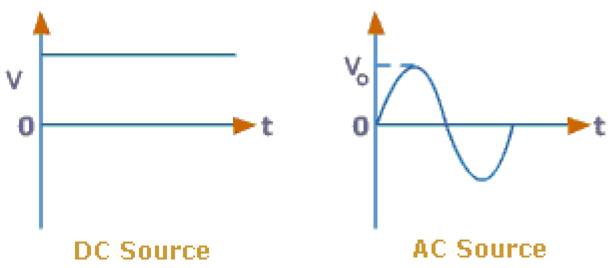


FIGURE 5. Comparison between DC and AC (GlobalSpec, 2017)

Alternating Current on the other hand flows first in one direction and then in the other, continuously changing of direction. It continuously quickly changes between positive and negative directions. The velocity in which the direction changes is called the frequency of the alternating current and is expressed in Hz (Hertz). This Hertz indicates the number of directional changes per second. Generally speaking an AC power supply in Europe has 50Hz and in America this power supply is 60Hz. For Europe this means that the alternating current changes its direction 50 times per second, in America this would be 60 times per second.

2.1.1 AC motors

AC motors are electric motors driven by an alternating current (AC). Generally speaking AC motors commonly consists of two basic parts, a stator and a rotor. The outside stationary stator has coils supplied with alternating current which produce a rotating magnetic field. Inside there is a rotor attached to an output shaft producing a second rotating magnetic field. This magnetic field can be produced in different ways and therefore also creates different types of motors. As example this magnetic field can be produced by reluctance saliency which then creates a type of reluctance motor. The other possibilities of producing a rotor magnetic field are by electrical windings supplied by an alternating current or direct current, or by permanent magnets (Woodford, Explainthatstuff, 2017).

In an AC motor, the stator is made up by a ring of electromagnets arranged around the outside, which are designed to produce a rotating magnetic field. Inside the stator, there's a solid metal axle, a loop of wire, a coil, a squirrel cage made of metal bars and interconnections, or some other freely rotating metal part that can conduct electricity. In an AC motor you send power to the outer coils that make up the stator. The coils are energized in pairs, in sequence, producing a magnetic field that rotates around the outside of the motor (Woodford, Explainthatstuff, 2017).

The rotor is an electrical conductor suspended inside the magnetic field. The magnetic field constantly changing because it is rotating. According to the laws of electromagnetism or Faraday’s Law, the magnetic field produces or induces an electric current inside the rotor. If the conductor is a ring or wire, the current flows around it in a loop. The induced current produces its own magnetic field and, according to Lenz's law tries to stop whatever it is that causes it, the rotating magnetic field, by rotating as well (Woodford, Explainthatstuff, 2017).

The key to an AC induction motor is the electromagnetic induction that makes this motor spin. To further explain this phenomenal the next pages will be about the working principle of an AC induction motor. A squirrel cage consists out of bars which are shortened by rings at each end as seen on the figure below (Learnengineering, 2011).

FIGURE 6. Squirrel cage rotor used in induction motors (Learnengineering, 2011)

A 3 phase AC current passing through a Stator winding produces a rotating magnetic field. Therefore current will be induced in the bars of the squirrel cage and it will start to rotate. This is due to the rate of change of magnetic flux in one squirrel bar pair which is different from another, due to its different orientation. This variation of current in the bar will change over time (Learnengineering, 2011).

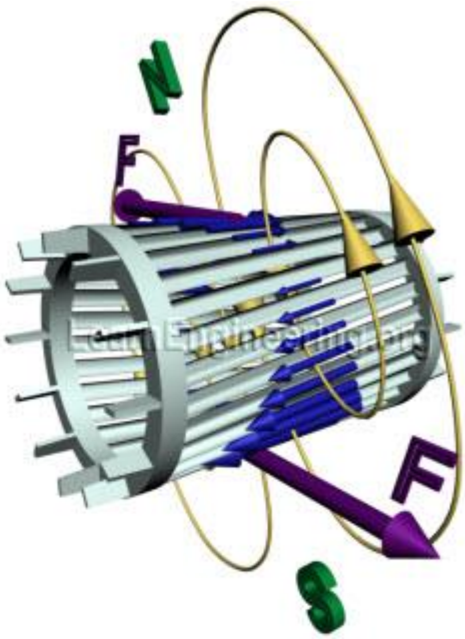


FIGURE 7. RMF produces a torque on the rotor (Learnengineering, 2011)

Electricity is induced in the rotor by magnetic induction rather than direct electric connection. To aid such electromagnetic induction, insulated iron core lamina are packed inside the rotor (Learnengineering, 2011).

FIGURE 8. Thin layers of iron lamina which are packed in the rotor (Learnengineering, 2011)

To make sure that the eddy current losses are minimal thin layers of iron lamina are used as seen on the figure above. Eddy currents are loops of electrical current induced within conductors by a changing magnetic field in the conductor, due to Faraday's law of induction (Learnengineering, 2011).

The advantages of an AC induction motor are that it is self-starting, meaning it doesn't need an external force to start rotating (not including the power supply of course).
They are also low-cost, long-lasting and don't make a lot of noise compared to some DC motors. They also need less maintenance since as example the DC motors have a commutator and carbon brushes that need to be replaced after a period of time (Woodford, 2017).

The disadvantages of an AC induction motor is the weight, the motor weights so much because of the heavy coil windings in the construction of the motor. Most of the time an inverter is needed to that turns DC into AC, as example when your power supply would be a battery, since the AC induction motor needs a changing magnetic field to operate. To control the speed of an AC induction motor variable-frequency drives are used, with DC motors this can be done easier with changing the value of the supply voltage (Woodford, 2017).

2.1.2 DC motors

A DC motor is a motor in which electrical energy in the form of a direct current is converted into mechanical energy. The working principle is based on the Lorentz Force (earlier discussed in chapter 2.1 The General Working Principle of a Motor) that is encountered by a current conductor in a magnetic field. The working principle of electric motors is based on an alternating magnetic field. Therefore, in the case of a DC motor, the direction of the magnetic field is constantly changed in the motor by means of the commutator (collector) as seen on FIGURE 4. Diagram of the parts in an electric motor in chapter 2.1 The General Working Principle of a Motor. It can also be changed electronically as applied in the so-called brushless electric motor.

There are three different types of electrical connections possible between the stator and rotor for a DC motor. These three different types consist out of a series, shunt and compound electrical connection. Each of these types has its own advantages, meaning the speed/torque characteristic is different for each type (L. Herman, 2010).

In a Series Wound DC Motor the entire armature current flows through the field winding as it is connected in series to the armature winding.

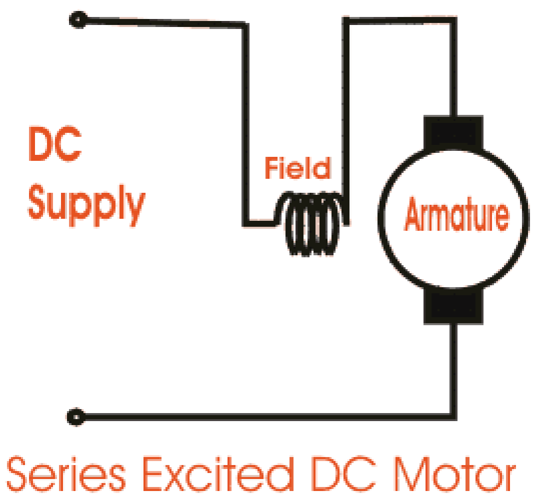


FIGURE 9. Series Excited DC Motor (Electrical4u, 2017)

A generalized torque speed characteristic from a Series Wound DC Motor can be seen on the figure below.

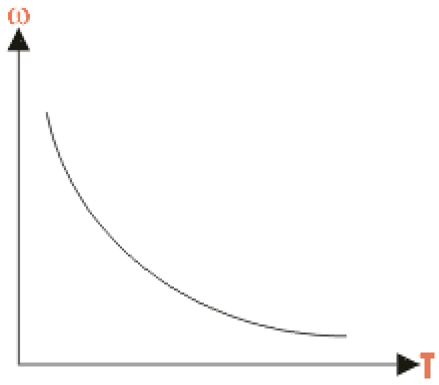


FIGURE 10. Torque speed characteristic Series Wound DC Motor (Electrical4u, 2017)

In a Shunt Wound DC Motor the field windings are connected parallel to the armature winding therefore the entire terminal voltage will flow through the field windings.

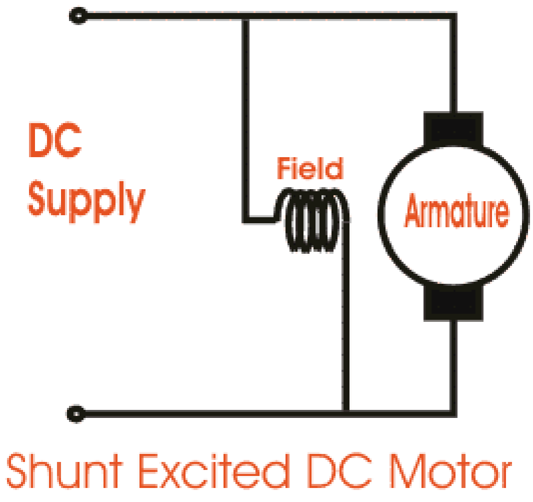


FIGURE 11. Shunt Excited DC Motor (Electrical4u, 2017)

A generalized torque speed characteristic from a Shunt Wound DC Motor can be seen on the figure below.

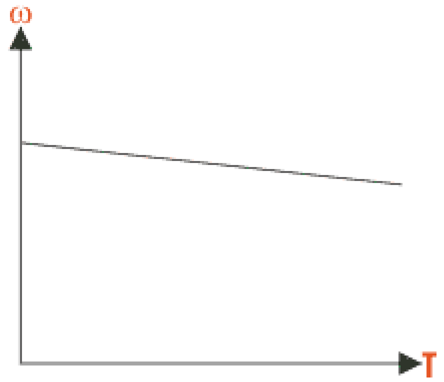


FIGURE 12. Torque speed characteristic Shunt Wound DC Motor (modified) (Electrical4u, 2017)

The Compound Wound DC Motor is a combination of both a Series and Shunt Wound DC Motor. This means the field windings are connected in both series and parallel to the armature winding.

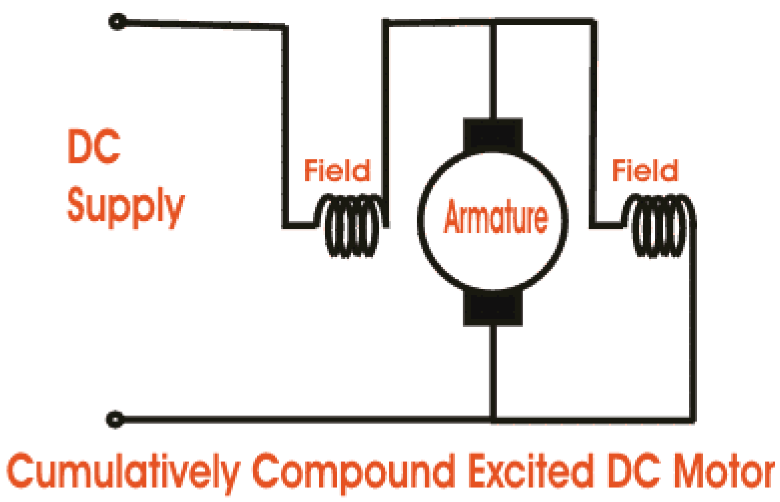


FIGURE 13. Cumulatively Compound Excited DC Motor (Electrical4u, 2017)

A generalized torque speed characteristic from a Cumulatively Compound Excited DC Motor can be seen on the figure below.

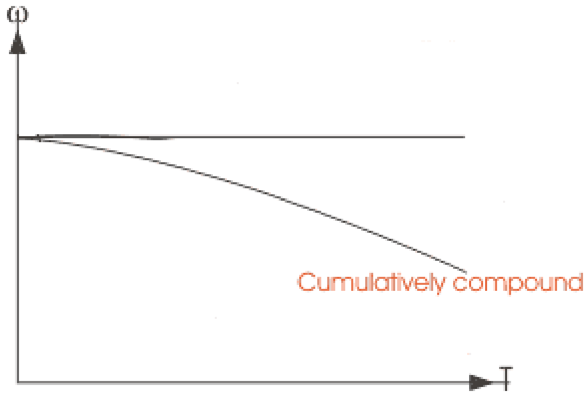


FIGURE 14. Torque speed characteristic Cumulatively Compound DC Motor (modified) (Electrical4u, 2017)

The excitation of compound wound DC motor can be of two types depending on the nature of compounding. When the shunt field flux assists the main field flux, produced by the main field connected in series to the armature winding then it’s called a cumulative compound DC motor. If the arrangement of the shunt and serie windings are such that the field flux produced by the shunt field winding diminishes the effect of flux by the main series field winding, then it’s called a differential compound DC motor (Electrical4u, 2017).

The compound motor is a combination of the series and shunt motor. The compound motor possesses both a series and a shunt actuation winding. The characteristics of this engine are between those of the series and the shunt motor.

To end the theoretical background of the DC motors, the different types of DC motors shortly explained are now put on a torque speed characteristic. This characteristic shows us what different windings of a DC motor can lead to, as example changing the torque and speeds when a load is applied.

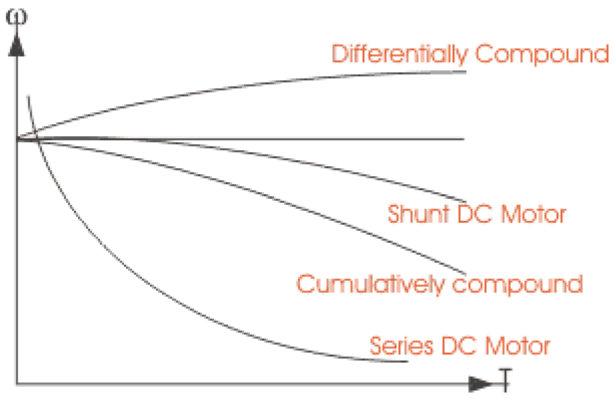


FIGURE 15. The different speed torque characteristics from DC motors (Electrical4u, 2017)

As seen on the figure 15. The different speed torque characteristics from DC motors, each winding creates its own unique DC motor with unique characteristics. Therefore each motor can be used for a different application or purpose.

The advantages of a general DC motor is the easy and fast speed control there is when changing the value of the supply voltage. If the DC motor is a DC series motor there is a high starting torque available aswell.

The disadvantages of a general DC motor are the high initial cost, also because of the commutator and brushes the DC motor has a high maintenance compared to an AC induction motor. Because of the sparking that can occur at the brushes, these DC motors are better not operated in explosive and hazard conditions.

2.2 Choice of Motor

Building upon the knowledge provided in chapter 2.1 The General Working Principle of a Motor, it is possible to discern multiple types of motors that could be used and list the advantages and disadvantages of these motors against the requirements for the i-Locker to find the best possible motor for this Thesis.

There are many factors which have to be taken into account to choose the perfect setup for this application. It is necessary to reflect on the advantages as well as the disadvantages given by every motor compared to the needs of the application.
A table is used to create a nice overview of the pros and cons of the different type of motors that could be used for this thesis.

Type of Motor	**Pros**	**Cons**	**Applications**
Stepper Motors	Inexpensive, can be run open loop, good low-end torque, clean rooms	Noisy and resonant, poor high-speed torque, not for hot environments, not for variable loads	Positioning, micro movement
Brushed DC Servo Motors	Inexpensive, moderate speed, good high-end torque, simple drives	Maintenance required, no clean rooms, brush sparking causes EMI and danger in explosive environments	Velocity control, high-speed position control
Brushless AC Servo Motors	Maintenance-free, long lifetime, no sparking, high speeds, clean rooms, quiet, run cool	Expensive and complicated drives	Robotics, pick-and-place, high-torque applications

TABLE 1. Overview of the pros and cons of different types of motors (NATIONALINSTRUMENTS, 2016)

The i-Locker requires the motor to be able to precisely rotate, rotate smoothly at low speeds and has a high torque. The Servo Motor meets these requirements best of all motor types, with negligible disadvantages that can be mitigated to ensure optimal working conditions.

To be more precise, the brushless AC servo motor is the best motor for the i-Locker application. As presented in TABLE 1. Overview of the pros and cons of different types of motors the brushless AC servo motor is made for pick-and-place and high-torque applications. The only disadvantage are the expensive and complicated drives, but these AC drives are becoming cheaper every year and there is even a market for it now.

The brushless AC servo motor has been ordered at SKS Group, the SKS Group is a Finnish family-owned enterprise founded in 1924. Their core businesses and six of their companies are in Finland. They have international units in China, Poland, Sweden, Russia and Estonia. There is a stable relationship of trust between SKS Group and TAMK this is also an important issue when considering to spend a grand sum of money for an electric motor.

Another factor was the cost and delivery time, a brushless AC servo motor had a delivery time of only one week at SKS and in their quotation the motor had a fair price tag. Considering that the after sales and customers support is as great as previously seen from SKS the choice to order this motor was quickly made.

2.2.1 Servo motor

A servo motor (often abbreviated to servo) is a device for automatically controlling a mechanical system, without a direct mechanical connection. For example, cruise control of a car or the position of the altitude of an aircraft. It can also be used in other applications involving robotics, CNC machinery or automation. A servo motor is also a rotary actuator or linear actuator that allows for precise control of angular or linear position. The servo motor is mostly used in a closed-loop control system. Servo motors are also high in efficiency and power (Reed, 2017).

The setup of the servo motor consists out of a gearing set, a DC motor, potentiometer, and a control circuit. The motor is connected by gears to the control wheel, as the motor rotates the resistance in the potentiometer changes. Therefore the control circuit can regulate in which direction the motor rotates as well how much movement there is. If the axle or shaft is at the desired position, no more power is needed so the power supply to the motor is stopped. Therefore the motor also stops turning and stands still at the desired position. If the axle or shaft is not on the desired position the power supply to the motor continuous until the desired position is acquired. This desired position is known through electrical pulses which are send over signal wires (Reed, 2017).

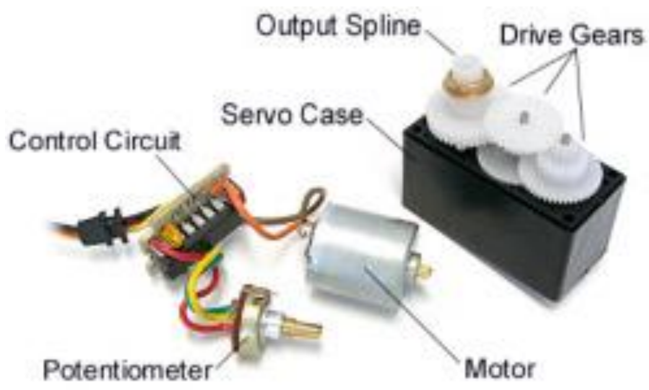


FIGURE 16. The inside of a servo motor and the assembly (Reed, 2017)

Servo motors are controlled by PWM (Pulse Width Modulation), this is an electrical pulse of variable width. This PWM determines the position of the shaft, the duration of a pulse sent via the control wire will turn the rotor to the desired position. There is a minimum and maximum pulse that a PWM can sent to the motor (Reed, 2017).

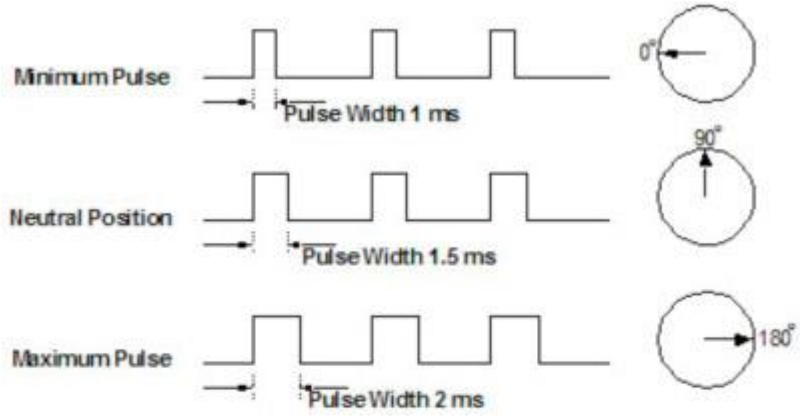


FIGURE 17. Variable Pulse Width Control Servo Position (Reed, 2017)

The next quote explains perfectly the critical part that involve these PWM signals to command the servo motor to move and hold their position.

“When these servos are commanded to move, they will move to the position and hold that position. If an external force pushes against the servo while the servo is holding a position, the servo will resist from moving out of that position. The maximum amount of force the servo can exert is called the torque rating of the servo. Servos will not hold their position forever though; the position pulse must be repeated to instruct the servo to stay in position.” – Frances Reed 2017 (Reed, 2017).

Servo motors can be either AC or DC type motors, AC servo motors can handle higher current surges and therefore tend are more useful in industrial machinery. DC servo motors are better suited for smaller applications as example remote-controlled cars. The AC servo motor can be used for position control in elevators or for example in this thesis for the lockers (Reed, 2017).

2.3 Choice of Frequency Drive

The choice of motor was a brushless AC servo motor therefore the frequency drive has to be an AC drive. The best combination with a brushless AC servo motor would be a VFD (Variable Frequency Drive). Variable speed drive, AC drive, micro drive, inverter drive, variable frequency inverter or frequency inverter are all synonyms of a VFD.

A table is used to create a nice overview of the pros and cons of the variable frequency drive that could be used for this thesis.

Pros	**Cons**
They provide substantial energy savings	Higher initial capital costs
Speed control is used to replace a valve or damper-type flow control	Inverter duty motors should be used with VFDs to optimize motor life
Smooth starting and stopping mechanisms reduce mechanical wear on loads	Harmonics may occur if VFDs aren't in-stalled per manufacturer specifications
Integrated features allow for easy imple-mentation of future modifications	You will require additional heat dissipa-tion
They allow for increased power factors	
They have regenerative braking	
They control speeds up to 100 Hz	
You can use VFD as motor electrical brake by sudden injection of DC	

TABLE 2. The Pros and Cons of the Variable Frequency Drive (DiCiaccio, 2015)

The biggest advantages for the application in this thesis would be the speed control, the smooth starting and stopping mechanisms and the electrical DC brake.

The biggest disadvantage of this type of frequency drive is the possibility that harmonics may occur if VFDs aren't installed correctly. Therefore the installation and connections of the variable frequency drive should be taken very serious.

Depending on which department the higher initial capital costs are also a big disadvantage. But when looking at a drive system including an AC motor and an AC drive the complete or end price is reasonable.

2.3.1 Variable Frequency Drive

“A variable-frequency drive (VFD; also termed adjustable-frequency drive, variable speed drive, AC drive, micro drive or inverter drive) is a type of adjustable-speed drive used in electro-mechanical drive systems to control AC motor speed and torque by varying motor input frequency and voltage. “ (Jaeschke, 1978)

A drive system consists out of three smaller systems, a main drive controller assembly, a drive operator interface and an AC motor as seen on Figure 18. Variable Frequency Drive System. Each sub-system allows ultimate control and makes this system as a whole incredibly efficient and productive. (TECH, 2014)

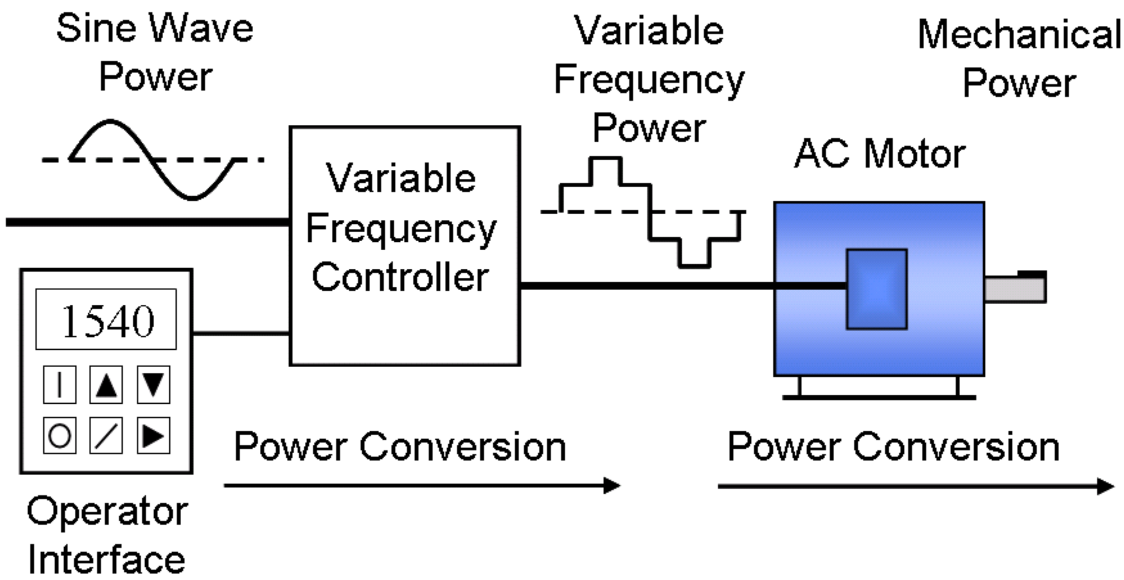


Figure 18. Variable Frequency Drive System (TECH, 2014)

The controller for the VFD is made up of a rectifier, a direct current and an inverter. The operator interface is used for operating the speed of the motor. It can also start or stop a motor sometimes the interface has other functions as example switching between automatic and manual functions and reverse. Generally speaking there is a numeric display and a keyboard available for inserting commands. (TECH, 2014)

Most are also provided with input and output (I/O) terminals for connecting push buttons, switches, and other operator interface devices or control signals. A serial communications port is also often available to allow the VFD to be configured, adjusted, monitored, and controlled using a computer. (Cleaveland, 2007)

The AC motor normally used in a VFD system is a three-phase induction motor. AC motors are the most economical choice, and fulfill standards as set by the law. These are appropriate for most purposes, although some applications require a one-phase induction motor. (TECH, 2014)

The drive applications can be categorized as single-quadrant, two-quadrant, or four-quadrant. The following figure has four quadrants defined as following:

- Quadrant I - Driving or motoring,forward accelerating quadrant with positive speed and torque
- Quadrant II - Generating or braking, forward braking-decelerating quadrant with positive speed and negative torque
- Quadrant III - Driving or motoring, reverse accelerating quadrant with negative speed and torque
- Quadrant IV - Generating or braking, reverse braking-decelerating quadrant with negative speed and positive torque.

(WIKIPEDIA, 2017)

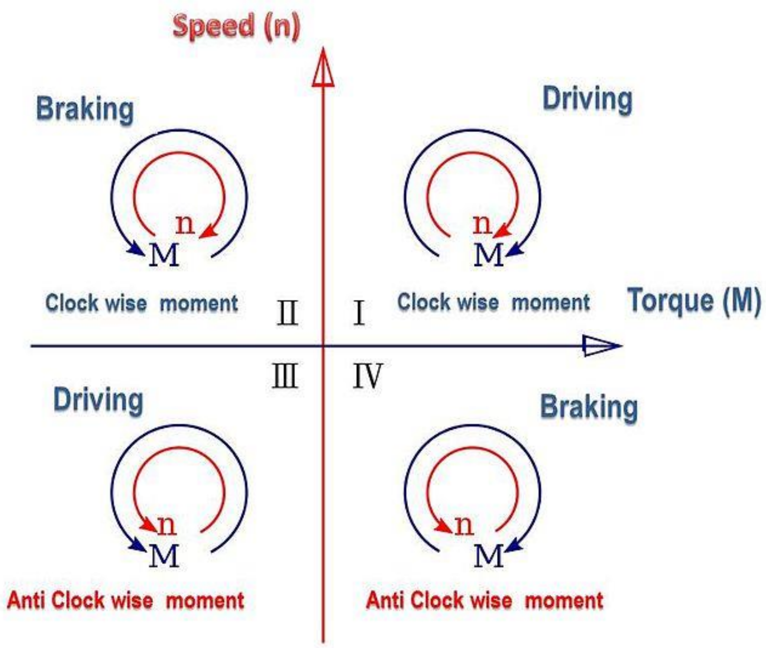


Figure 19. Four Quadrant Motion Control of a Motor (Shrikanthv, 2012)

3 THE PROJECT

In this chapter the calculations, the basics of the i-Locker, the servo motor, the frequency drive and finally the software will be explained.

PICTURE 1. The i-Locker (Photo: Jordy Declercq 2017)

3.1 The Mathematical Calculations

This chapter is meant to explain the mathematical calculations consisting of speed, power and torque calculations which were necessary for the project. For an easier explanation and for the ease of the reader some actual pictures of the project as well as drawn figures are added to the text. The first picture shows a front view of the i-Locker frame with one locker attached. In the figure following the i-Locker is viewed from the right side, a side view, for easier explanation of the calculations. All the calculations were done using TI-Nspire CAS Student Software except for the torque calculations. The torque calculations were doing using the SERVOsoft software.

3.1.1 The required Speed

Before explaining how the required speed was calculated, the i-Locker setup should be showed shortly. On the picture below the setup is shown of the i-Locker this setup has been used to calculate the required speed. But instead of one, there were two lockers attached, since two lockers were available for testing purposes.

PICTURE 2. Front view of the i-Locker (Photo: Jordy Declercq 2017)

First the i-Locker got tested out using human force, a person turns the lower gear by hand and thus the lockers start turning. The purpose of this was to find out what the maximum speed could be before the lockers start swaying. The maximum speed turned out to be around 2.5-3m/s, this was calculated by counting how long it took for one locker to do a full revolution. A full revolution means that the locker starts from the bottom of the lowest gear goes up to the top of the upper gear and when the locker is back at his starting position, then it completed one full revolution. To do one full revolution without swaying the lockers it takes around fifteen to twenty seconds. To be safe, twenty seconds were used for the following calculations the next step is to calculate the distance that the locker travels.

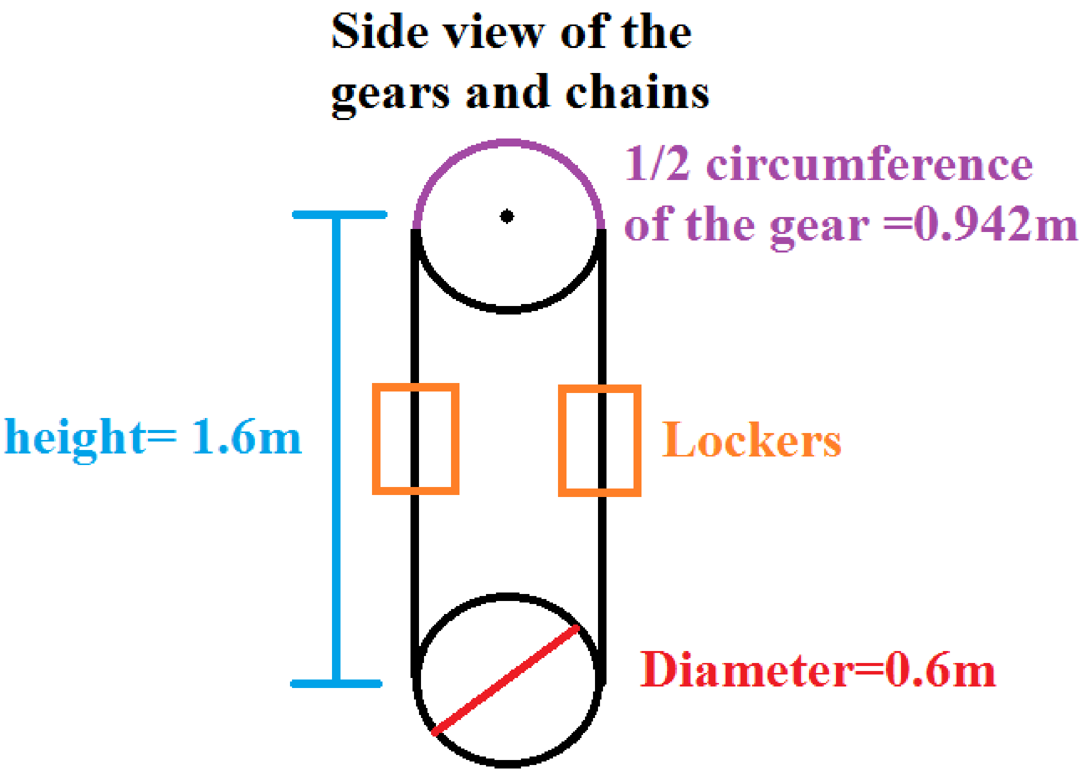


FIGURE 20. Side view of the gears and chains (Jordy Declercq 2017)

The length of the chain between the upper and lower axles is 1.6m and the diameter of the gear is 0.6m.

Circumference of a circle

$$l = \pi * \mathrm{D}$$

$$l = \pi * 0.6m$$

$$l = 1.88m$$

Since half of the circumference of two identical gears is needed, one step can be skipped but will be taken into account for a proper explanation. Half of the circumference of the upper gear is needed for the travelled distance, but also of the lower gear. Circumference of the gear is 1.88m, half of the circumference is 0.94m. The half of the circumference of the upper and lower gear must be travelled by the lockers. Therefore 0.94m can multiplied by two reaching a travelled distance of 1.88m.

The travelled distance of the locker is as followed, twice the height between the upper and lower axles plus twice the half of the circumference of the upper and lower gears.

$$L = (h * 2) + (0.94 * 2)$$
$$L = (1.6m * 2) + (0.94m * 2)$$
$$L = 5.08m$$

To calculate the velocity of the lockers, the travelled distance must be divided by the time used to do so.

$$v = \frac{L}{t}$$
$$v = \frac{5.08m}{20s}$$
$$v = 0.25m/s$$

Then the next question rises, how many revolutions does the lower gear has to do to equal one full revolution of the locker?
The lower gear has a circumference of 1.88m and the locker has to travel a distance of 5.08m. One revolution of the lower gear equals a distance travelled of 1.88m, therefore the following calculation is used for this thesis.

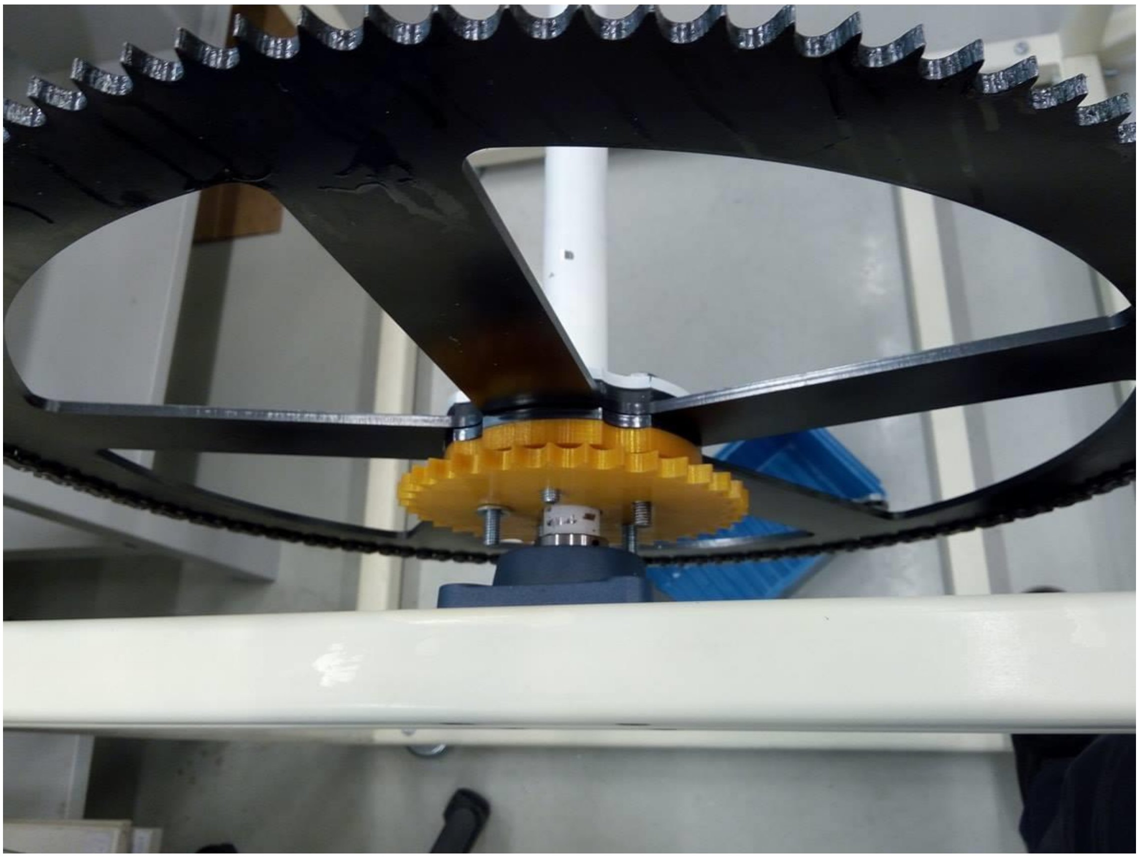
Revolution ratio gear to locker

$$Rev = \frac{5.08m}{1.88m}$$
$$Rev = 2.7$$

Knowing that the time is 20 seconds for the locker to make a full revolution, the lower gear must turn 2.7 revolutions in 20 seconds. Gs= Gear speed.

$$Gs = \frac{2.7rev}{20s}$$
$$Gs = 0.135rps$$
$$Gs = 0.135rps * 60$$
$$Gs = 8.1rpm$$

This makes up for a desired rotational speed of 8.1 revolutions per minute. To supply this desired rotational speed a drive is needed. A second gear gets mounted onto the lower axle which will be connected to the servo motor. This servo motor will be used as a drive to rotate the lockers by a connection of gears and chains.



PICTURE 3. The locker gear (black) and driven gear (orange) (Jordy Declercq 2017)

3.1.2 The required Gear Ratio

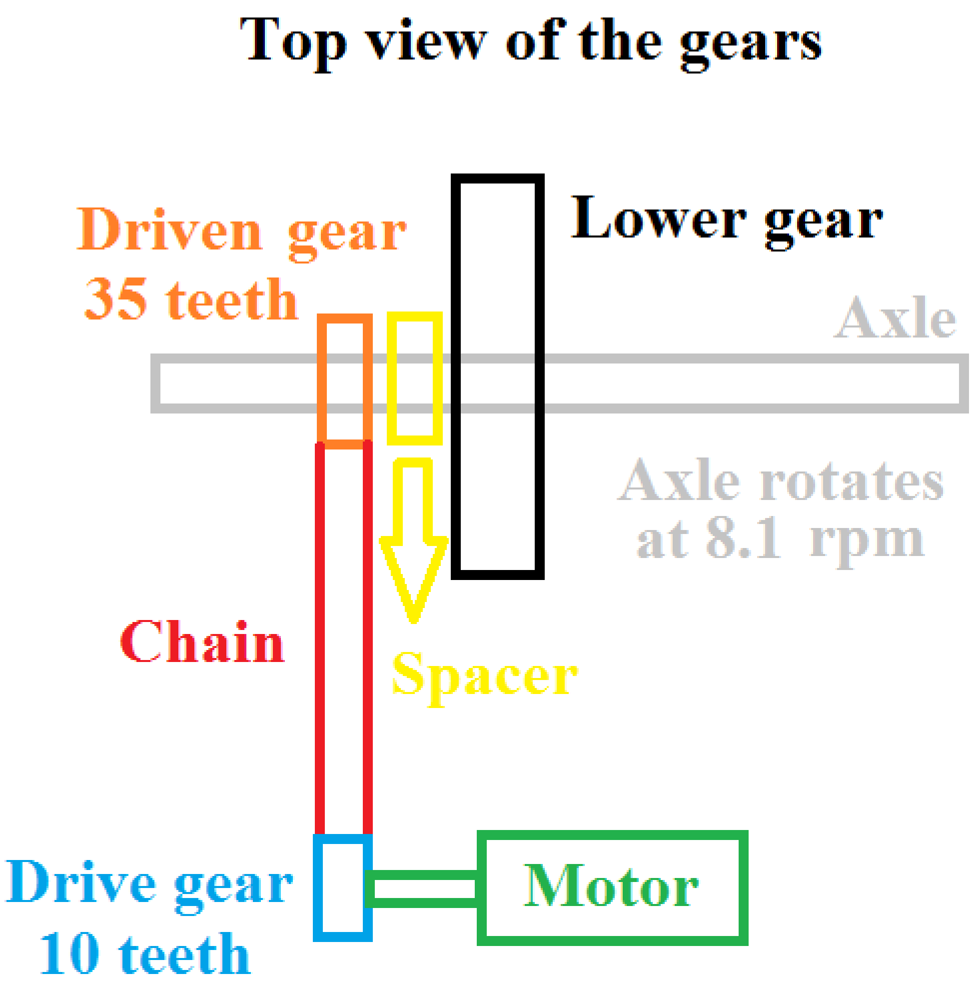


FIGURE 21. Top view of the gears (Jordy Declercq 2017)

Everything mounted onto the lower axle will turn at the same speed of the axle. The axle rotates at 8.1rpm therefore the lower gear and the driven gear will both rotate at this speed. The driven gear has 35 teeth and is connected to the drive gear through a chain while the drive gear, which is connected to the servo motor axle, has 10 teeth. The gear ratio is a measurement of the ratio between rotational speeds of different gears. In this specific case between two gears which are connected through a chain. The general rule states the drive gear as the gear connected to the motor, and the second gear, which is receiving power from this drive gear is called the driven gear. The formula for gear ratio is T2/T1 where T1 is the number of teeth on the drive gear and T2 the number of teeth on the driven gear.

$$Gear\ ratio = \frac{T2}{T1}$$
$$Gear\ ratio = \frac{35}{10}$$
$$Gear\ ratio = 3.5$$

With this gear ratio the rotational speed at the shaft of the servo motor can be calculated. If the driven gear has 35 teeth and a rotational speed of 8.1rpm, and the drive gear has 10 teeth with a gear ratio of 3.5 the following can be calculated. The speed at which the servo motor rotates, Ms= Motor speed.

$$Ms = gear\ ratio * SG$$
$$Ms = 3.5 * 8.1rpm$$
$$Ms = 28.35rpm$$

As seen, the servo motor is rotating at a very low speed, due to the transmission. For testing purposes this speed can be used but for the final result a different transmission would be recommended. Even at this low speed, the servo motor is able to turn the lockers, but in an energy inefficient way.

3.1.3 The required Power

Now to calculate the needed power that the servo motor has to supply, the weight of the lockers is the start. The weight of an empty locker is 7kg, the maximum weight of a locker can be 20kg. The amount of lockers at this moment is two, but in the future this should be increased to twelve lockers in total. With this in mind the moment with the highest torque on the shaft of the servo motor is when there are 6 lockers full and 6 empty. You might wonder why not with 12 full lockers, this is because when all lockers are full they also help with the turning because of their weight.

The total weight of the lockers

6 empty lockers = 6*7kg = 42kg
6 full lockers =6*20kg= 120kg
120kg-42kg=78kg

Now the weight that should be driven is known and the desired speed is known, the power needed can be calculated. If a mass m is lifted for a distance of height h in a time t the required power can be calculated with the following formula:

$$W = \frac{m * g * h}{t}$$

But for using this formula the height and travelled distance would have to be measured again, therefore using the already calculated velocity is a more efficient approach, as v=0.25m/s. But for safety reasons the maximum velocity is taken into account which is 0.3m/s.

$$W = \frac{m * g * h}{t} = m * g * v$$

The reason the velocity can be used instead of the height is because the velocity equals the height divided by the time v=h*t. In this case the height is actually the travelled distance of the locker.

$$W = m * g * v$$
$$W = 78kg * 9.81m/s^2 * 0.3m/s$$
$$W = 229.55\ Watt$$

A rule of thumb is to take 10-15 percentage tolerance with this calculation because the energy losses of the transmission and friction, heat losses are not put in to account. After adding the tolerance the power needed is around 265 Watt (263.98 Watt).

3.1.4 The required Torque

For the torque calculations the software SERVOsoft v3.3.507 was used, the calculations as the following images or pictures are therefore all property of ControlEng Corporation (the creaters of SERVOsoft) in cooperation with EXLAR and SKS. The need to use these kinds of software is because of the complexity of the torque calculations.

For the testing phase of the i-Locker only two lockers will be used, therefore the following calculations are with two lockers. The first calculation will consist out of one full and one empty locker, the second calculation will consist out of two full lockers.

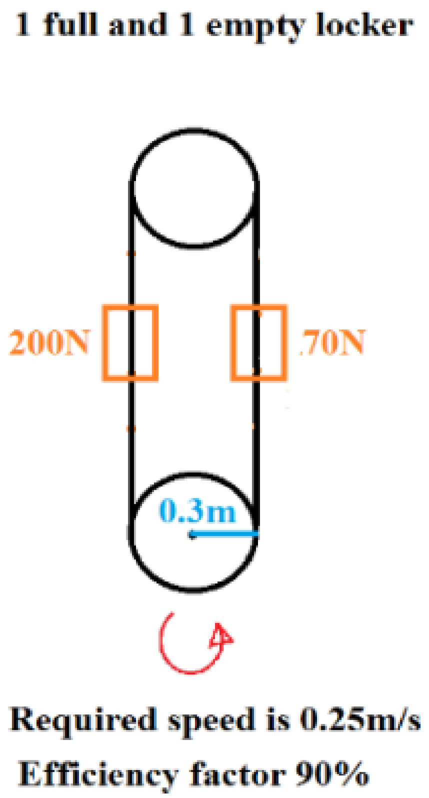


FIGURE 22. Model of 1 full and 1 empty locker (Jordy Declercq 2017)

The figure above is just to demonstrate one of the possibilities on how the lockers could be balanced. With this combination of one full and one empty locker the following maximum torque of 0.509Nm was calculated as seen on the figure below.

MOTOR:

	Rated	Req'd		Margin
Type	Synchronous servo motor			
Cooling	Natural convection [0K]			
LF [25°C, 1000m]		1		
Bus voltage	0	0	V	
Cont standstill torque	0		Nm	
Max torque	0	0,509	Nm	-100%
Max current	0	0	A	
Torque constant	0		Nm/A	
Max speed	0	716	rpm	
RMS torque	0	0,507	Nm	-100%
Mean speed		477	rpm	
Inertia	0		kg-m²	
Dwell torque		0,371	Nm	
Shaft diameter	0		mm	
I²t		0	%	
Inertia mismatch		0	: 1	

FIGURE 23. Max Torque calculation 1 (SERVOsoft, 2017)

The maximum speed is also an important value, the brushless AC servo motor used in this thesis has a speed range of 0-3000rpm. The maximum speed needed in this setup is 716rpm, which is definitely in the speed range.

For the second torque calculation two full lockers are used which are in a balanced situation, meaning that the lockers are weighing the same and therefore are both equally filled. This is important data, as this balancing situation requires less torque.

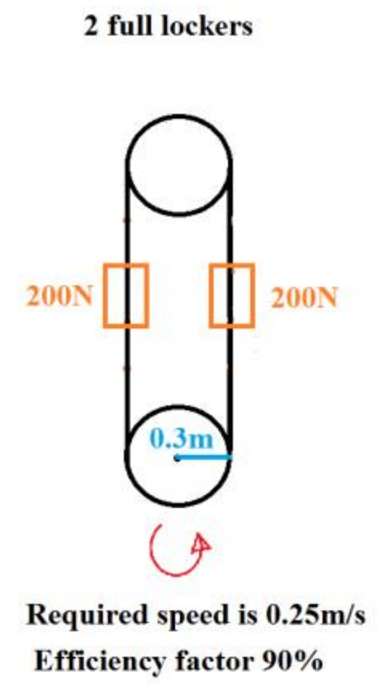


FIGURE 24. Model of two full lockers (Jordy Declercq 2017)

Once again is the figure above just to demonstrate one of the possibilities on how the lockers could be balanced. With this combination of two full lockers the following maximum torque of 0.001949Nm was calculated as seen on the figure below.

MOTOR:

	Rated	Req'd		Margin
Type	Synchronous servo motor			
Cooling	Natural convection [0K]			
LF [25°C, 1000m]		1		
Bus voltage	0	0	V	
Cont standstill torque	0		Nm	
Max torque	0	0,001949	Nm	-100%
Max current	0	0	A	
Torque constant	0		Nm/A	
Max speed	0	716	rpm	
RMS torque	0	0,001394	Nm	-100%
Mean speed		477	rpm	
Inertia	0		kg-m²	
Dwell torque		0	Nm	
Shaft diameter	0		mm	
I²t		0	%	
Inertia mismatch		0	: 1	

FIGURE 25. Max torque calculation 2 (SERVOsoft, 2017)

Keep in mind for this calculation a gearbox of i=90 has also been used. Even thou if the required torque would be multiplied with 100, the needed torque would still only be 0.1949Nm.

As seen with the torque calculations, the torque can vary a lot depending on the balance of the weight of the lockers. Not meaning just the weight of a locker itself, but the weight of the items that could be stored inside the lockers. This data is unknown at the time, since somebody could store a 10kg backpack in the first locker and another person could store a 700gram Ipad in the second locker. Therefore the calculations must be done under an unbalanced condition as seen in the first calculation, one full locker and one empty locker.

The value of this unbalanced torque calculation was 0.509Nm, meaning the maximum torque the motor should be able to produce for the testing phase is 0.509Nm. Of course it is advised to take a motor with a surplus which can provide 0.8Nm-1Nm of torque.

3.2 The Basics of The i-Locker

In this paragraph the basic functions of the i-Locker will be shown. As seen on the picture below there is a backpack in the orange locker, the other locker is closed at this moment. Once you close the locker after putting in your items and the next person wants his belongings from the previous locker, the gears start turning and thus will the other locker come in front. The locker will open and the person can take out his belongings.

PICTURE 4. The i-Locker basics (Photo: Jordy Declercq 2017)

To make the i-Locker turn there are a lot of actions and communication needed between the components. Therefore in the following chapters each of the components will be shortly explained. The main drive system components consisting of the brushless AC servo motor and the variable frequency drive will be explained more thoroughly in chapter 3.3 Brushless AC Servo motor and chapter 3.4. Variable Frequency Drive.

3.2.1 The Electric Motor

The electric motor converts electrical energy taken from the grid to mechanical energy which will drive the transmission. This transmission will drive the gears and the gears in their turn will turn the lockers. The electric motor used in this project is the FM 055 E2 B 301 BAKRA 063110 which is a brushless AC servo motor.

PICTURE 5. The Brushless AC Servo Motor (Photo: Jordy Declercq 2017)

3.2.2 The Transmission

Transmissions are used to transfer or convert energy from one point to the other and their goal is to transfer as much of the energy as possible.

The electric motor supplies power, this power is transferred by using a mechanical transmission consisting of a drive gear, driven gear and an ANSI 50 chain. The chain that was used for connecting the drive gear with the driven gear was an ANSI 50 chain. ANSI 50 stands for the dimensions of the chain, it includes the length of the gap between two links and also the width.

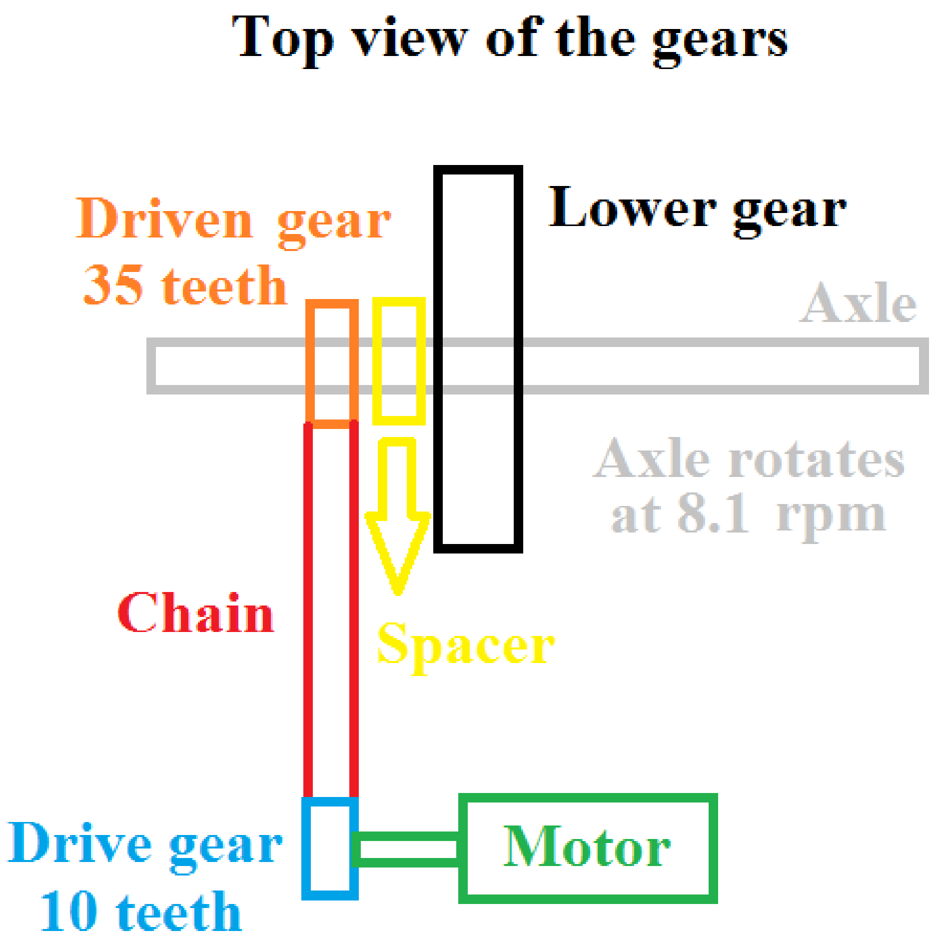


FIGURE 26.Top view of the gears (Jordy Declercq 2017)

In this thesis the transmission transfers energy from the drive gear connected to the electric motor to the driven gear connected to the lower axle. On the lower axle the driven gear and the lower gear are mounted. The speed of the lower gear determines the speed of the lockers mounted onto the i-Locker.

3.2.3 The Variable Frequency Drive

“A variable-frequency drive (VFD; also termed adjustable-frequency drive, variable speed drive, AC drive, micro drive or inverter drive) is a type of adjustable-speed drive used in electro-mechanical drive systems to control AC motor speed and torque by varying motor input frequency and voltage. “ (Jaeschke, 1978)

PICTURE 6. The Unidrive M700 from EMERSON Industrial Automation (INDUSTRIAL, 2016)

3.3 Brushless AC Servo motor

The electric motor used in this project is the FM 055 E2 B 301 BAKRA 063110 which is a brushless AC servo motor. This motor is delivered by the company SKS but made in France by control techniques and EMERSON.

PICTURE 7. The Brushless AC Servo Motor (Photo: Jordy Declercq 2017)

3.3.1 Nameplate

In the next chapter the abbreviations on the nameplate of the brushless AC servo motor will be explained. It is a quick way to learn about the characteristics of the electric motor.

PICTURE 8. Nameplate of the Servo Motor (Photo: Jordy Declercq 2017)

A table has been generated to create a nice overview of the abbreviations seen on the picture above. The table consists out of two columns, one column is showing the abbreviation and info, the other column is displaying the value or data.

Abbreviation	**Value or data**
Three Phase AC Motor	3~
Ics (Nominal Current)	1,3 A
Ke (Voltage per Krpm)	52,5 V/Krpm
Amb (Ambient Temperature)	40°C Δ 100 K
Nn (Nominal Speed)	3000 rpm
Pn (Nominal Power)	0,33 kW
Kt (Torque per Amp)	0,87 Nm/A
IE (Incremental Encoder)	1024PPR
Tcw (Motor Thermal Time Constant)	38s
Mcs (Continuous Stall Torque) Mn (Torque in Nominal Speed)	1,18 Nm 1,05 Nm
Insul. CI.F (Insulation)	IP 65

Drive VPWM BUS	230VAC 310VDC
Brake	1,8 Nm 0,35A 24V DC
Type	055E2B301BAKRA063110
Made in	France
Serial Number	N180440/002/2011/05
Manufacturer	Control Techniques
Manufacturer	EMERSON Industrial Automation

TABLE 3. Nameplate Abbreviations of the Servo Motor

The most important abbreviations mentioned in the above table will be further explained in the following pages.

Three Phase AC Motor 3~

An AC electric motor can run on either single phase or three phase AC power supply. In this thesis the motor runs on a three phase AC power supply.

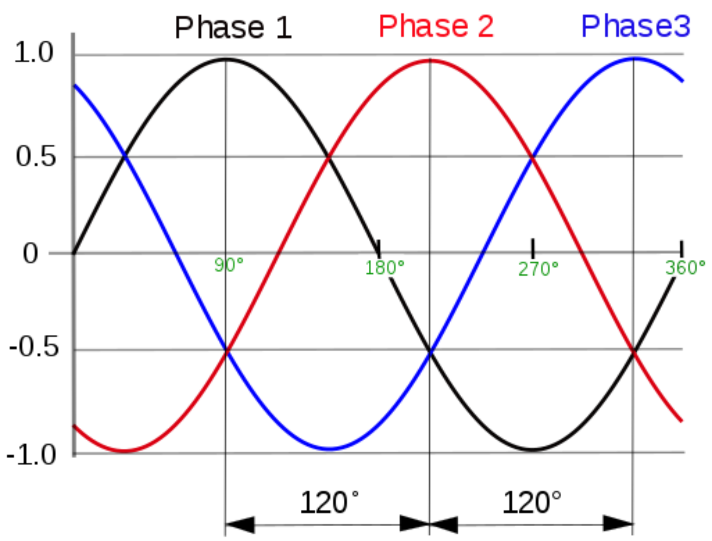


FIGURE 27. Three Phase AC Waveform (WIKIPEDIA, 2008)

The figure above illustrates a three phase AC waveform.

Ke: 52.5 V/Krpm

Voltage (emf) constant: Ke (a.k.a. Kemf, KE and Kb) defined as the maximum line-to-line voltage developed per some velocity unit. Note: When the Voltage constant velocity unit is rad/second and Kt is in Nm/A, the specific motor constants are equal:

$$\frac{V}{Krpm} = \frac{1000 * Ke(\frac{V}{rad}/sec)}{\left\{\frac{60\ sec/min}{2\pi\ rad/rev}\right\}}$$

$$= 1000 * \frac{Ke(\frac{V}{rad}/sec)}{9.55}$$

(MACHINEDESIGN, 2013)

Kt: 0.87Nm/A

Kt is the torque factor, this means that with 1 Amp the motor will produce 0.87 Nm torque, this is not in relation to the speed of the servo motor. If the speed of the servo motor is 28 rpm and the motor current is 2 Amps, then the motor will produce 1.74 Nm of torque (2 A x 0,87 Nm/A = 1,74 Nm). This same calculation is valid for a motor speed of 0rpm or 3000rpm.

Brake: 1.8Nm 0.35A 24V DC

The brake can hold up to 1.8Nm, to release the brake an external power supply is needed that supplies 0.35A and 24V DC.

Mcs/Mn: 1.18/ 1.05Nm

Mcs stands for continuous stall torque, which means the amount of torque when the motor is not moving or in order words has zero speed.

Mn stands for torque in nominal speed, the nominal speed is 3000rpm. The following data is illustrated on the figure below.

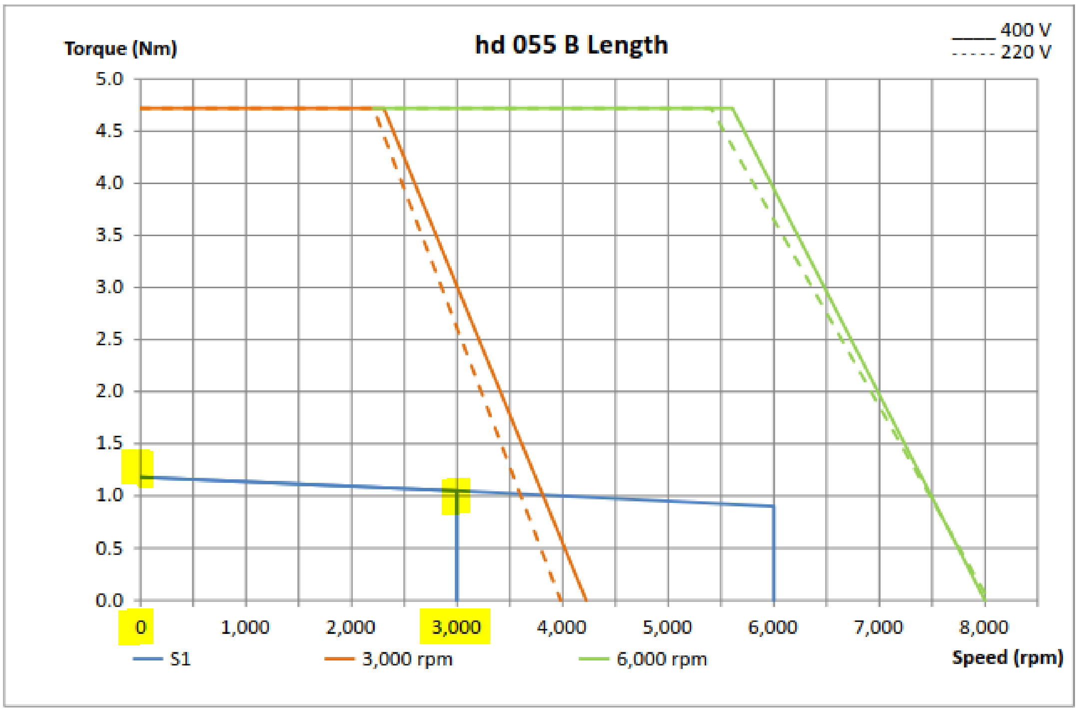


FIGURE 28.Torque Speed Characteristic (EMERSON I. A., 2017)

VPWM

VPWM or Variable Pulse Width Modulation.

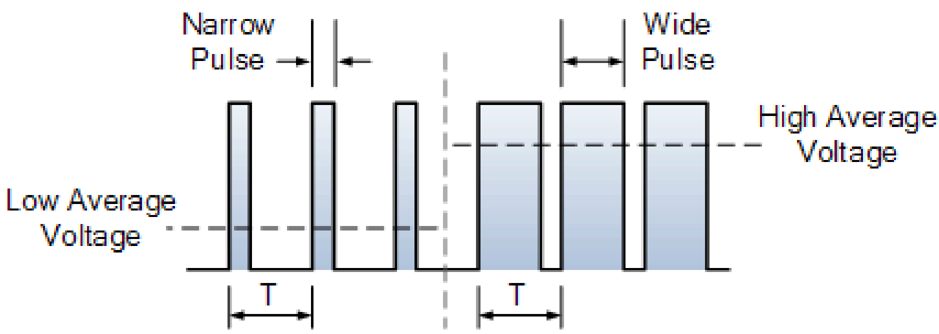


FIGURE 29. Pulse Width Modulated Waveform (Electronics, n.d.)

“The use of pulse width modulation to control a small motor has the advantage in that the power loss in the switching transistor is small because the transistor is either fully “ON” or fully “OFF”. As a result the switching transistor has a much reduced power dissipation giving it a linear type of control which results in better speed stability.” (Electronics, n.d.)

3.3.2 Frame

The frame size of the servo motor used in this thesis is a frame size 055. The advantages of this frame is the small size and room needed to install the motor onto the application. The less space a motor uses in an application the more space is left for other components.

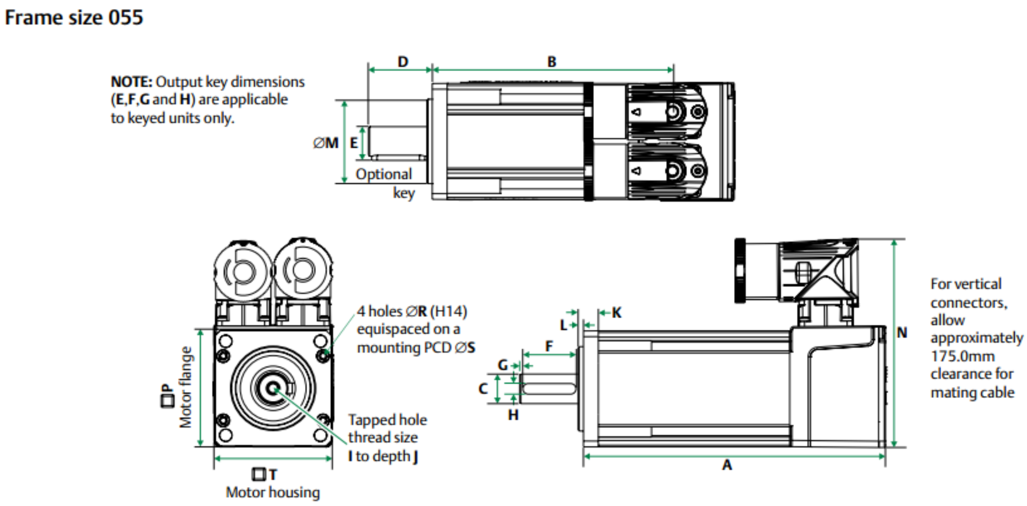


FIGURE 30. Frame size 055 (EMERSON I. A., 2017)

The dimensions seen on the figure below were needed for attaching the drive gear onto the shaft of the servo motor. Notice that the key dimensions are very important when attaching a gear onto a shaft. A key is an element used to connect a gear to a rotating shaft without losing grip. The key prevents relative rotation between the two parts and may enable torque transmission. For a key to function, the shaft and rotating machine element must have a keyway and a key seat, which is a slot and pocket in which the key fits. The whole system is called a keyed joint. (Bhandari, 2007)

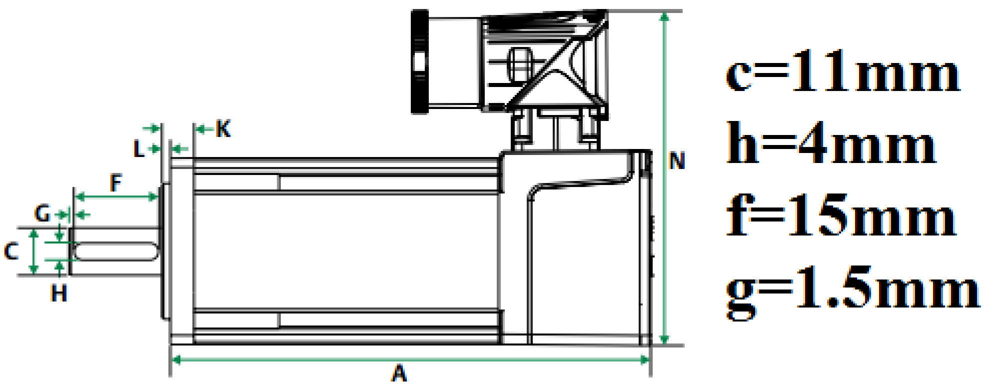


FIGURE 31. Frame size 055 (modified) (EMERSON I. A., 2017)

3.3.3 Torque Speed Characteristics

The torque speed characteristic of a servo motor is created by the curve plotted between the torque and the speed. A torque speed characteristic of an AC servomotor is linear, the slope of the torque speed characteristic is negative. The characteristics are parallel to one another for various values of the control voltage that would be applied as seen on the figure below.

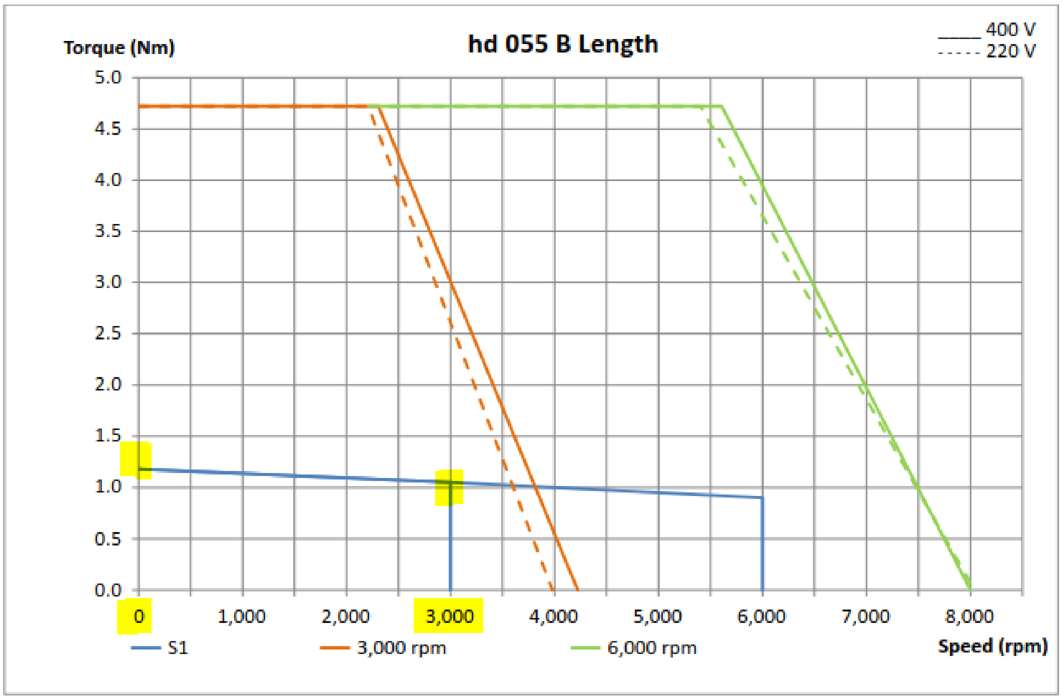


FIGURE 32.Torque Speed Characteristic (EMERSON I. A., 2017)

As seen on the figure above when the servo motor is not rotating or has zero speed it has a continuous stall torque of 1.18Nm, this can also be used as a brake. At nominal speed which is 3000rpm the torque is 1.05Nm.

Following the blue line called S1 drawn on the torque speed characteristic, the rated torque at a given speed can be found. It is normal for an AC servo motor to be running at nominal speed and torque. Depending on the application and transmission used the speed can vary between 0-3000rpm.

An AC servo motor controls the current according to the state of the load. Because of the low heat generation and efficiency of the motor, continuous operation is possible within the rated torque. (ORIENTALMOTOR, 2017)

3.4 Variable Frequency Drive

“A variable-frequency drive (VFD; also termed adjustable-frequency drive, variable speed drive, AC drive, micro drive or inverter drive) is a type of adjustable-speed drive used in electro-mechanical drive systems to control AC motor speed and torque by varying motor input frequency and voltage. “ (Jaeschke, 1978)

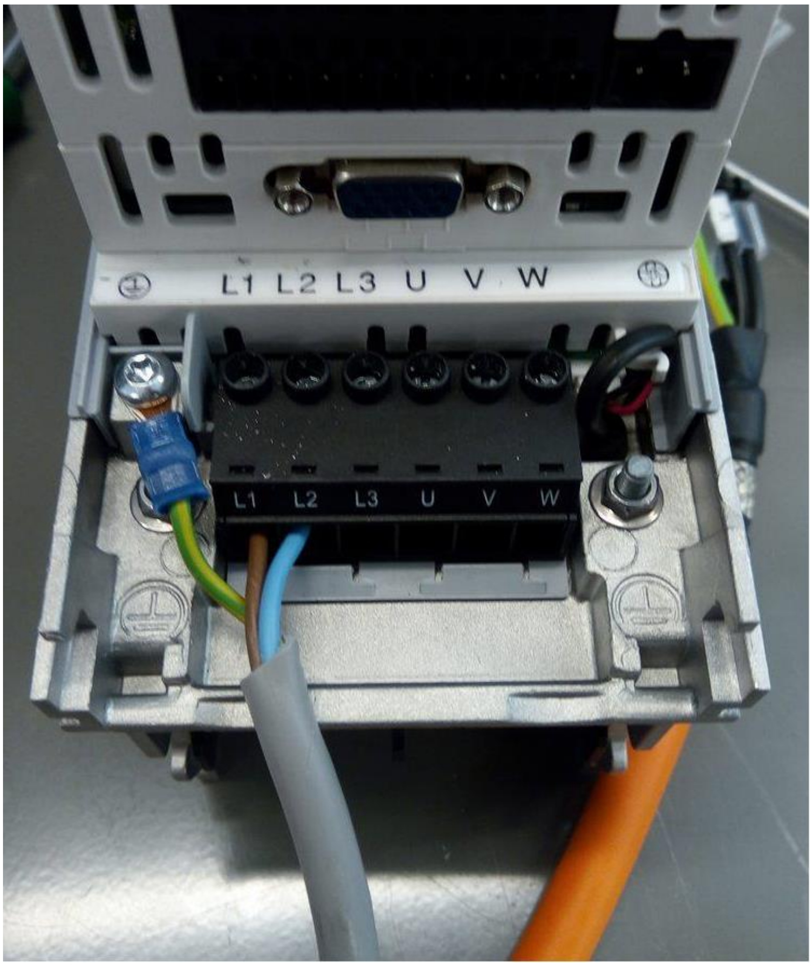
The variable-frequency drive used in this project is the Unidrive M700 from EMERSON Industrial Automation as seen on the picture below. It is a universal variable speed AC drive for induction and permanent magnet motors. The operating mode used in this project was the RFC-S mode which stands for Rotor Flux Control for Synchronous (permanent magnet brushless) motors. There are two loops to choose from one with position feedback and one without position feedback.

PICTURE 9. The Unidrive M700 from EMERSON Industrial Automation (INDUSTRIAL, 2016)

3.4.1 Connection of the Power Supply

To have a communication between two intelligent devices there has to be a connection of some sort in this case the connections exist out of Ethernet and signal wires. There is also a need of a power supply to power the devices. For powering the Unidrive M700 from EMERSON Industrial Automation the current from a wall socket is sufficient.

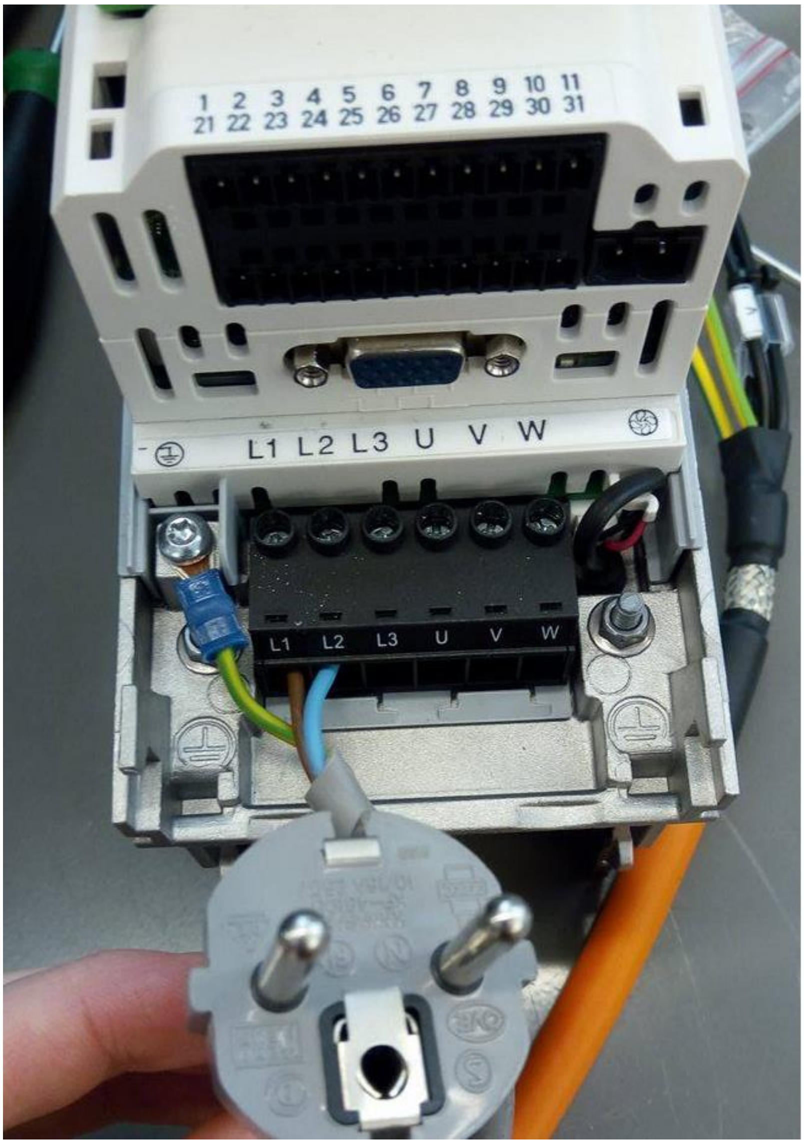
The first connection that was made was the power supply to the variable-frequency drive, this existed of a normal wall socket power supply consisting of 230VAC 50Hz single phase. The connection of the Unidrive M700 from EMERSON Industrial Automation is as seen on the picture below.



PICTURE 10. Power supply connection to the Unidrive M700 (Photo: Jordy Declercq 2017)

There are three wires in this cable, the brown wire is the phase, the blue wire is the neutral and the green with yellow wire is the ground or earth protection. On the next picture both ends of the power supply cable are seen.

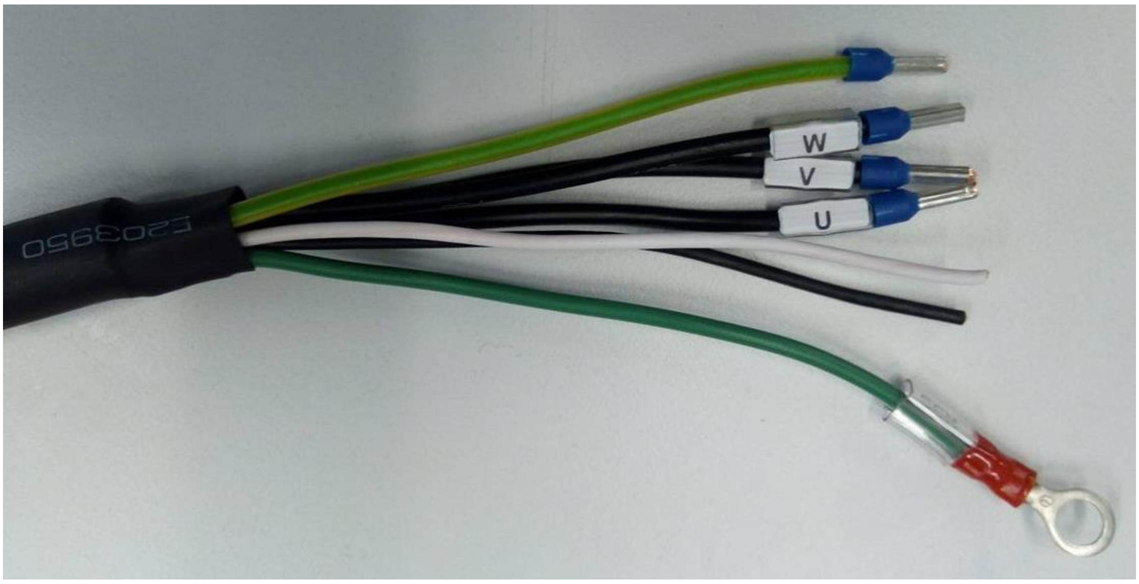
The plug that has to be plugged into the wall socket and the other end that has to be connected to the Unidrive M700 from EMERSON Industrial Automation.



PICTURE 11. Power supply connections (Photo: Jordy Declercq 2017)

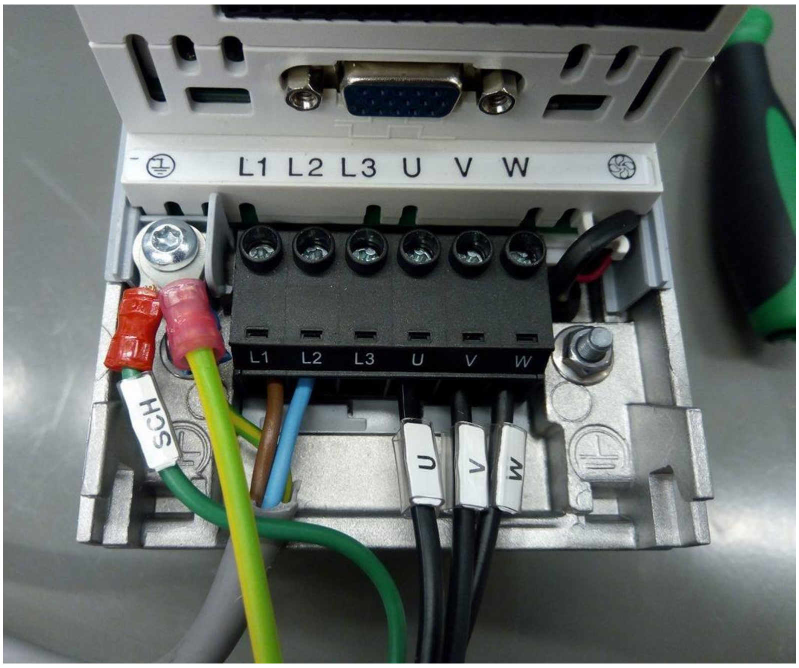
The second connection exist out of the power supply for the servo motor coming from the variable-frequency drive. As seen on the picture below this cable consists out of 7 wires including:

- 1 ground or earth protection (green and yellow)
- 1 shielded ground (green and yellow)
- 2 wires (black and white) for releasing the brake of the servo motor
- 3 phase wires, u-v-w



PICTURE 12. Power supply cable (Photo: Jordy Declercq 2017)

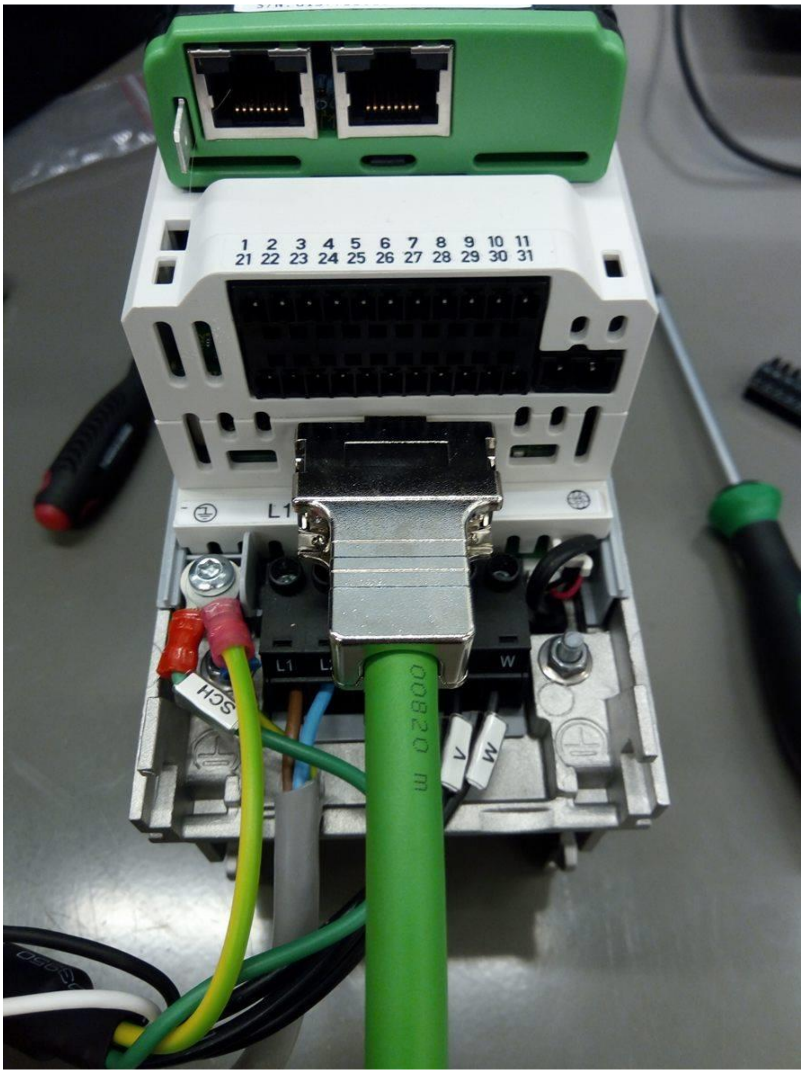
The servo motor should be supplied by a 3 phase current from the variably frequency drive. These wires should be connected correctly as seen on the picture below, for more information see Appendix 1 Power Supply Cable.



PICTURE 13. Power supply connection from Unidrive M700 to the servo motor (Photo: Jordy Declercq 2017)

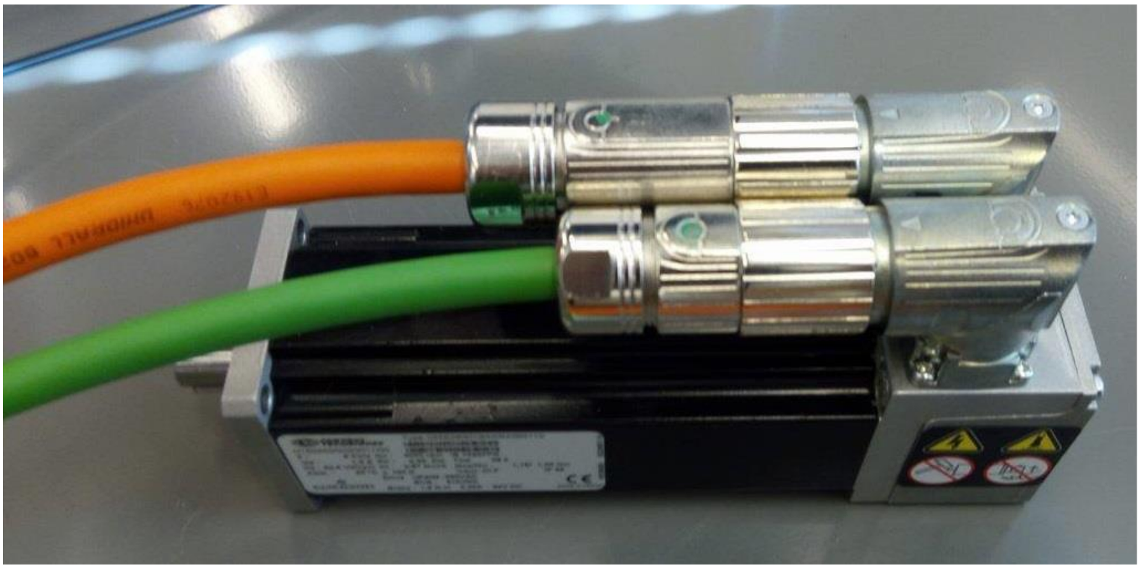
3.4.2 Connection of the Encoder Cable

The next connection that should be made is the encoder cable, simply mount the cable onto the drive for more information see Appendix 2. Encoder Cable.



PICTURE 14. Connection of the encoder cable (Photo: Jordy Declercq 2017)

Now the other end of the power supply and encoder cable should be connected onto the servo motor. The connections on the servo motor are seen on the picture below. The orange cable is the power supply for the servo motor which consists out of three phases 230VAC 50Hz. Within this cable there is also a black and white wire used to power the brakes of the servomotor. These wires transmit a +24VDC supply on the brakes which then releases the brakes off the servomotor so the servomotor can safely rotate.

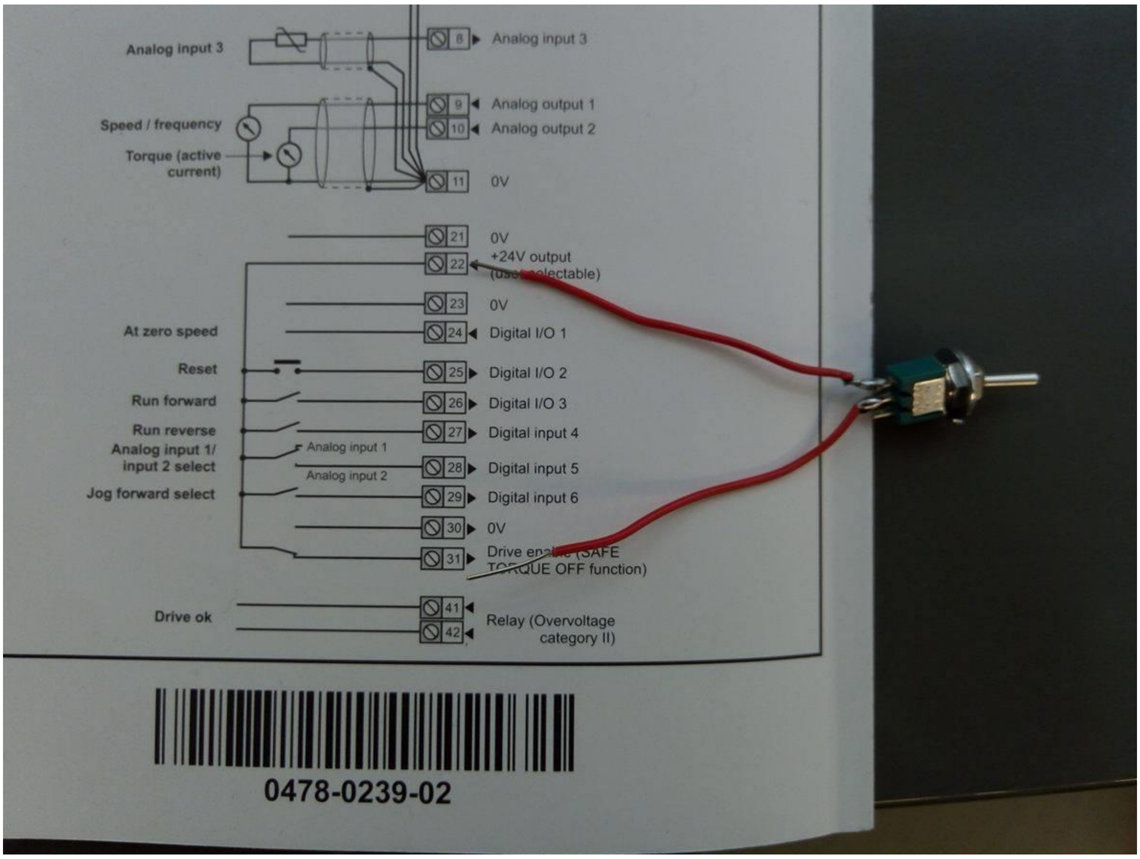


PICTURE 15. Connection of power supply and encoder cable to servo motor (Photo: Jordy Declercq 2017)

The orange cable is the power supply for the servo motor and the green cable is used for communication by sending signals or commands between the servomotor and the Unidrive M700 from EMERSON Industrial Automation.

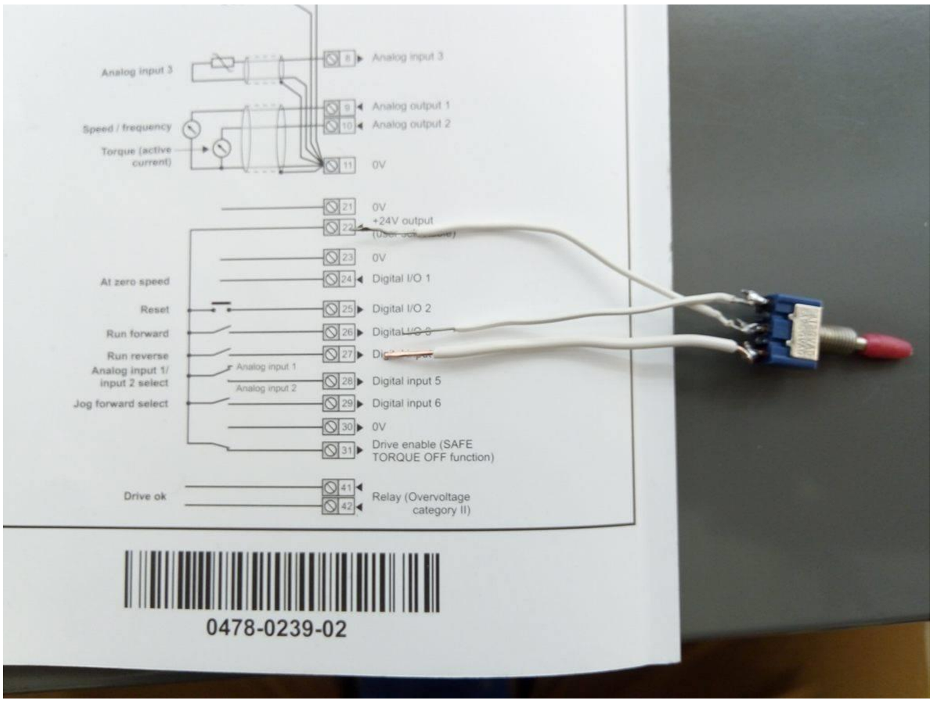
3.4.3 Connection of the Switches

On the back cover of the manual delivered with the Unidrive M700 from EMERSON Industrial Automation. The analog and digital inputs terminals are shown with a short description of which terminal is used for what purpose. To enable the drive and put safe torque off, terminal 31 should be supplied with +24V. This power supply can be taken from terminal 22 the +24V output terminal. In this project there is also a switch installed so it’s easier to enable and disable the drive and safe torque on/off function. (EMERSON C. T., Control Getting Started Guide, 2016)



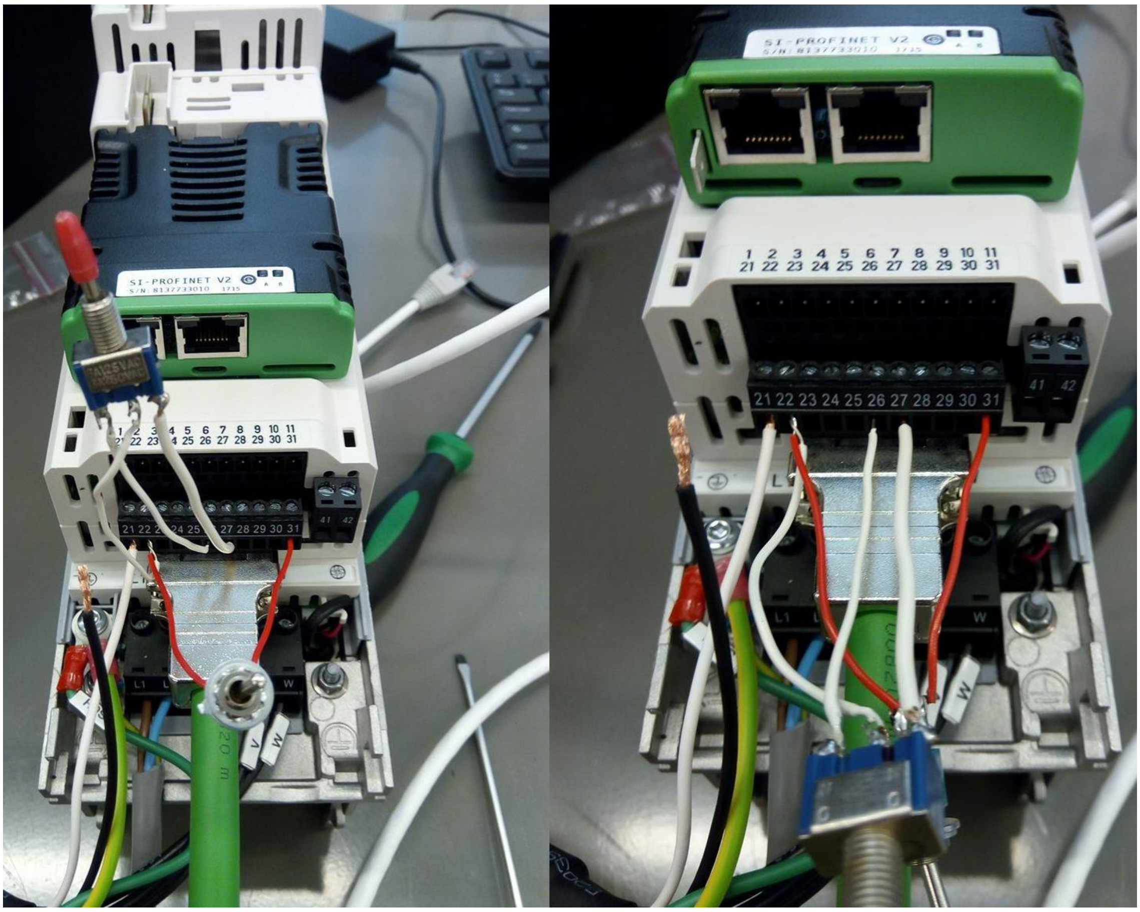
PICTURE 16. Back Cover of the manual with the enable drive switch (EMERSON C. T., Control Getting Started Guide, 2016)

To control in which direction the servomotor rotates, terminal 26 or terminal 27 must be supplied with +24V. This power supply can be taken from terminal 22 the +24V output terminal as seen before with the drive enable switch. Only one terminal at a time should be supplied otherwise the motor can be damaged. A switch is installed which can only supply voltage to either terminal 26 or terminal 27. Terminal 26 is used to run the servomotor in the forward direction, terminal 27 is used to run the servomotor in the reversed direction.



PICTURE 17. Back Cover of the manual with the direction switch (EMERSON C. T., Control Getting Started Guide, 2016)

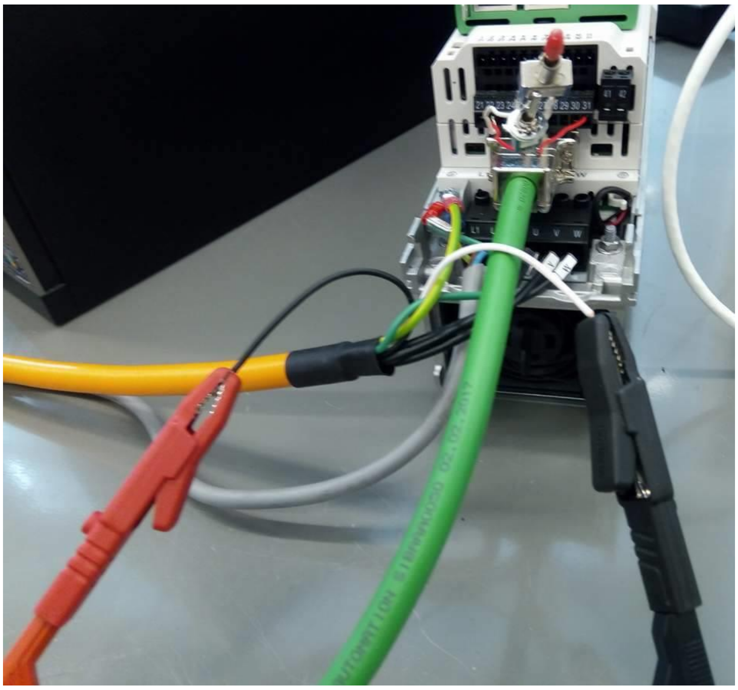
Both these switches are connected upon the drive as seen on PICTURE 18. Connection of the switches onto the Unidrive M700, the terminals talked about earlier are now in use.



PICTURE 18. Connection of the switches onto the Unidrive M700 (Photo: Jordy De-clercq 2017)

3.4.4 Connection of the External Power Supply

To release the brake of the servo motor an external +24VDC power supply is needed. In the laboratory at TAMK an external power supply was used and connected as seen on PICTURE 19. Connection of the external power supply used to release the brake. The black wire is the +24VDC and the white wire is the zero, the external power supply uses the colors red for +24VDC and black for zero seen by the crocodile clips connected to the drive.



PICTURE 19. Connection of the external power supply used to release the brake (Photo : Jordy Declercq 2017)

The external power supply used was called the “Virtalähde Thandar TS3022S” as seen on PICTURE 20. External power supply "Virtalähde Thandar TS3022S".

PICTURE 20. External power supply "Virtalähde Thandar TS3022S" (Photo: Jordy Declercq 2017)

In the next picture the electrical circuit of the brake wires is visible. If +24VDC is added then the brake releases and the servo motor can freely rotate. The full brake wire diagram can be seen at Appendix 3. Brake Wire Diagram.

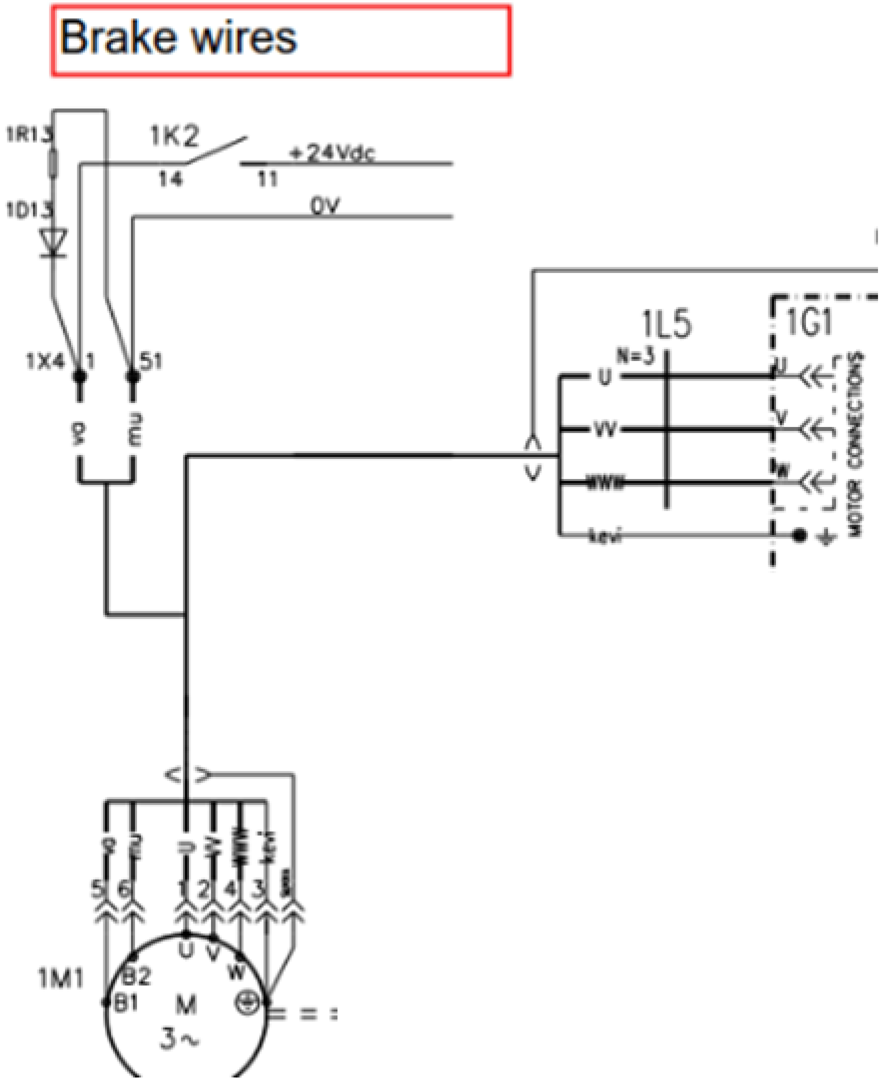


FIGURE 33. Brake Wire Diagram (modified) (EMERSON C. T., Brake Wire Diagram)

3.4.5 Connection of the Ethernet Cable

The connection between the computer and the Unidrive M700 from EMERSON Industrial Automation by Ethernet cable is the last connection to be completed. The one end of the Ethernet cable is connected to the Unidrive M700 Ethernet input, the other end to the user's computer. There is a possibility to connect two computers to the drive with the use of Ethernet cables.

PICTURE 21. Ethernet connection between the Unidrive M700 and a computer (Photo: Jordy Declercq 2017)

4 CONCLUSION AND DISCUSSION

The two main goals of this thesis were selecting the correct drive system for the i-Locker application as well as the completion of the application to be operated in a testing phase. These goals were fulfilled with the needed theoretical background and data to support it. As all calculations, that were necessary to be made in advance to develop this project, have been proven to be correct, the i-Locker is operating as expected.

The main drive system now consists out of a brushless AC servo motor and a variable frequency drive. The brushless AC servo motor was the best choice for this application due to its technical advantages and quality-cost ratio which has been discussed in this thesis. The DC brake included inside the servo motor was one of the biggest advantages, as this brake was useful for safety purposes. In case of an emergency for example, or in case of no more available power to be supplied to the motor, the lockers would stay at a fixed position because of the beforehand mentioned brake. The Unidrive M700 of EMERSON Industrial Automation was chosen because it fits perfectly together with the chosen motor. The Unidrive M700 communicates perfectly with the brushless AC servo motor and all interfaces can be used.

One thing I learned during this thesis is that an intended delivery time never equals the actual delivery time, which sometimes can be a vital point when connecting components or creating parts.

In every thesis or group project there is a grey zone, which in this certain case has been the transmission. The thesis is divided into three main areas, excluding the transmission in all three of them. Thus the part about the transmission became an area multiple students had to work together on, which in the end worked out, but lead to the personal knowledge for future projects, that communication is a necessary part to avoid such problems as the mentioned grey zones.

There is always room for improvement and for this thesis the improvements would be considered in the transmission, interface module, tracking sensors, and safety areas.

A potential topic for further research would be the transmission as having more lockers attached could vastly change the torque and momentum but a higher gear ratio might be a solution. The use of a Planetary Gear for example could be implemented into the i-Locker to provide a higher gear ratio which would be needed to operate the i-Locker with the final number of twelve, or even more, lockers attached.

REFERENCES

Bhandari, V. (2007). Design of machine elements (2nd ed.). In V. Bhandari, Design of machine elements (p. 340). New York: Tata McGraw-Hill.

Britannica, T. E. (2017). Lorentz force. Retrieved from Encyclopædia Britannica: https://www.britannica.com/science/Lorentz-force

Cleaveland, P. (2007). AC Adjustable Speed Drives.

CONTROLTECHNIQUES. (2017).

CONTROLTECHNIQUES. (2017).

David M., C. (2003). The Theory of the Electromagnetic Field. In C. David M., The Theory of the Electromagnetic Field (p. 157). Courier Dover.

DiCiaccio, F. (2015, October 12). Pros and Cons of VFD Use. Retrieved from www.industrialknowledgezone.com: http://www.industrialknowledgezone.com/pros-and-cons-of-vfd-use/

Douglas C., G. (1998). Physics: principles with applications (5th ed.). In G. Douglas C., Physics: principles with applications (5th ed.) (p. 624).

electrical4u. (2017). Fleming Left Hand rule and Fleming Right Hand rule. Retrieved from www.electrical4u.com: https://www.electrical4u.com/fleming-left-hand-rule-and-fleming-right-hand-rule/

Electrical4u. (2017). Types of DC Motor Separately Excited Shunt Series Compound DC Motor. Retrieved from www.electrical4u.com: https://www.electrical4u.com/types-of-dc-motor-separately-excited-shunt-series-compound-dc-motor/

Electronics, t. (n.d.). Pulse Width Modulation. Retrieved from www.electronics-tutorials.ws: http://www.electronics-tutorials.ws/blog/pulse-width-modulation.html

EMERSON, C. T. (2016). Control Getting Started Guide. In C. T. EMERSON, Control Getting Started Guide M700.

EMERSON, C. T. (n.d.). Brake Wire Diagram.

EMERSON, C. T. (n.d.). Control Getting Started Guide.

EMERSON, I. A. (2017).

GlobalSpec, I. (2017). Tachometer Generators and Tachogenerators Information. Retrieved from www.globalspec.com: http://www.globalspec.com/learnmore/sensors_transducers_detectors/velocity_sensing/tachogenerators

Houghton, M. (1992). American Heritage Dictionary of the English Language 3rd ed. In M. Houghton, American Heritage Dictionary of the English Language 3rd ed. Boston.

INDUSTRIAL, E. (2016). UNIDRIVE M700. Retrieved from www.emersonindustrial.com: http://www.emersonindustrial.com/ImagesControlTechniques/Products/UnidriveM M700_face_1mb.jpg

Jaeschke, R. L. (1978). Controlling Power Transmission Systems. In R. L. Jaeschke, Controlling Power Transmission Systems (pp. 210-215). Cleveland: OH: Penton/IPC.

L. Herman, S. (2010). Industrial Motor Control. 6th ed. In S. L. Herman, Industrial Motor Control. 6th ed. (p. 251). Delmar, Cengage Learning.

Learnengineering. (2011). How does an Induction Motor Work ? Retrieved from www.learnengineering.org: http://www.learnengineering.org/2013/08/three-phaseinduction-motor-working squirrel-cage.html

MACHINEDESIGN. (2013, May 22). Clarifying Servo Parameters. Retrieved from www.machinedesign.com: http://www.machinedesign.com/controllers/servoparameters-clarified

McGraw-Hill. (2017). Lorentz Force. In H. McGraw, & P. Sybil P., Dictionary of the Scientific and Technical Terms (6th Edition). The McGraw-Hill Companies, Inc.

NATIONALINSTRUMENTS. (2016, elo 24). Fundamentals of Motion Control. Retrieved from www.ni.com: http://www.ni.com/white-paper/3367/en/

ORIENTALMOTOR. (2017). Servo Motor Features Overview. Retrieved from www.orientalmotor.com: http://www.orientalmotor.com/servomotors/technology/servo-motor-features.html

Reed, F. (2017). How Do Servo Motors Work. Retrieved from http://www.jameco.com: http://www.jameco.com/jameco/workshop/howitworks/how-servo-motorswork.html

Sadiku. (2007). Elements of Electromagnetics (4th ed.). In Sadiku, Elements of Electromagnetics (4th ed.) (p. 386). New York & Oxford: Oxford University Press.

SERVOsoft. (2017, May 17). Max torque calculation 1. Tampere, Finland.

SERVOsoft. (2017, May 22). Max torque calculation 2. Tampere, Finland.

Shrikanthv. (2012, April 19). Four quadrant motion control of a motor. Retrieved from www.wikipedia.org: https://en.wikipedia.org/wiki/Variable frequency_drive#/media/File:Four_quadrant_motion_control_of_a_motor.jpg

TECH, F. (2014). Variable Frequency Drive. Retrieved from www.tech-flo.net: http://www.tech-flo.net/variable-frequency-drive.html

Techniques, C. (2017). Unidrive M Connect Software.

W. M., M. (1963). A Source Book in Physics. In M. W. M., A Source Book in Physics (pp. 511-513). Harvard: Cambridge MA.

WIKIBOOKS. (2016, May 24). A-level Physics/Forces, Fields and Energy/Electromagnetism. Retrieved from WIKIBOOKS: https://en.wikibooks.org/wiki/Alevel_Physics/Forces,_Fields_and_Energy/Electromagnetism

WIKIPEDIA. (2008, December 30). 3 phase AC waveform. Retrieved from www.wikipedia.org: https://en.wikipedia.org/wiki/Three phase_electric_power#/media/File:3_phase_AC_waveform.svg

WIKIPEDIA. (2017). Lenz's law. Retrieved from WIKIPEDIA: https://en.wikipedia.org/wiki/Lenz%27s_law

WIKIPEDIA. (2017, May 1). Variable-frequency drive. Retrieved from www.wikipedia.org: https://en.wikipedia.org/wiki/Variablefrequency_drive#cite_note-6

WIKIPEDIA. (2017). Wet van Lenz. Retrieved from WIKIPEDIA: https://nl.wikipedia.org/wiki/Wet_van_Lenz

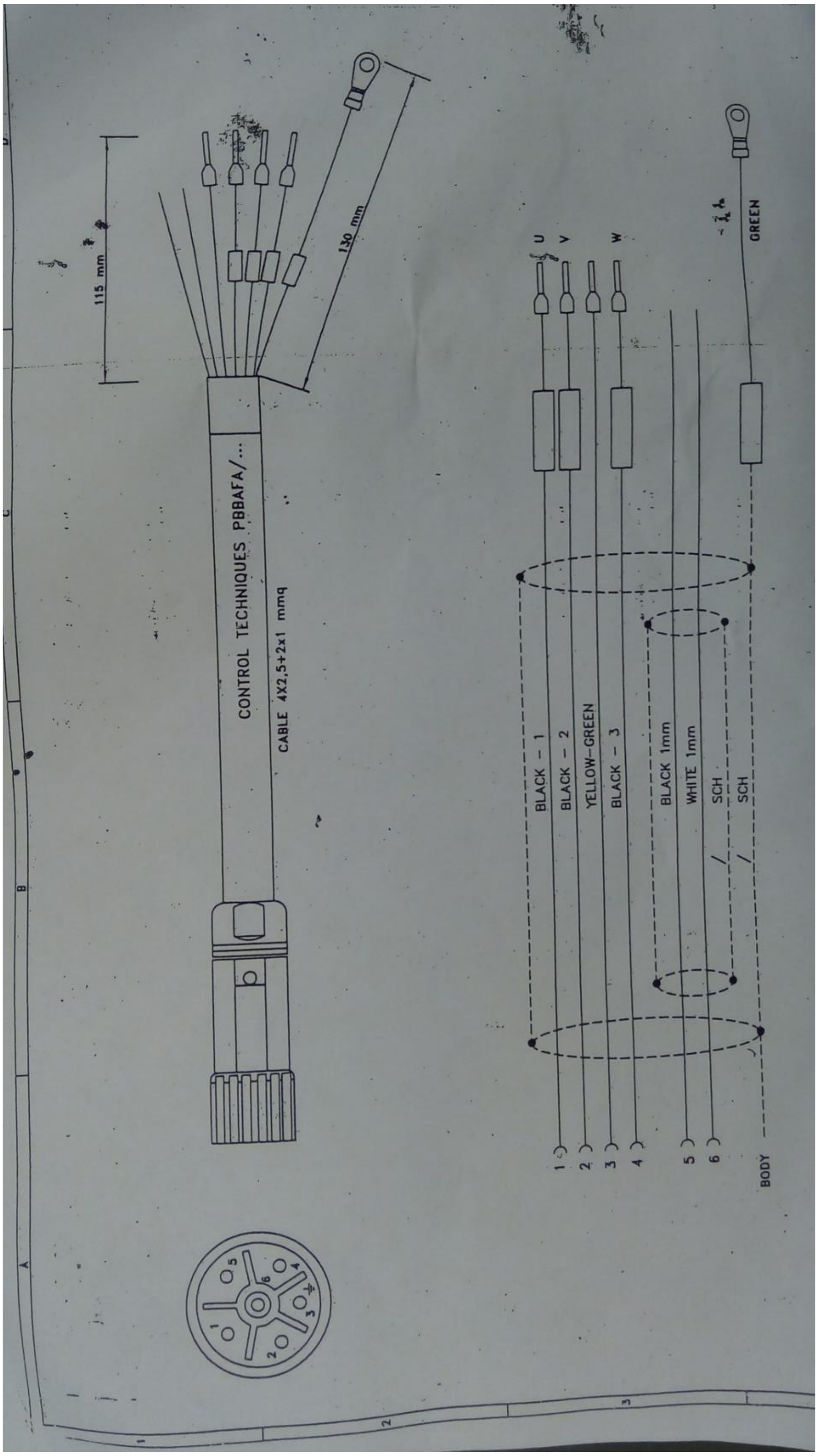
Woodford, C. (2017, March 24). Electric motors. Retrieved from www.explainthatstuff.com: http://www.explainthatstuff.com/electricmotors.html

Woodford, C. (2017, February 21). Explainthatstuff. Retrieved from Explainthatstuff: http://www.explainthatstuff.com/induction-motors.html

Woodford, C. (2017, February 21). Induction Motors. Retrieved from www.explainthatstuff.com: http://www.explainthatstuff.com/induction-motors.html

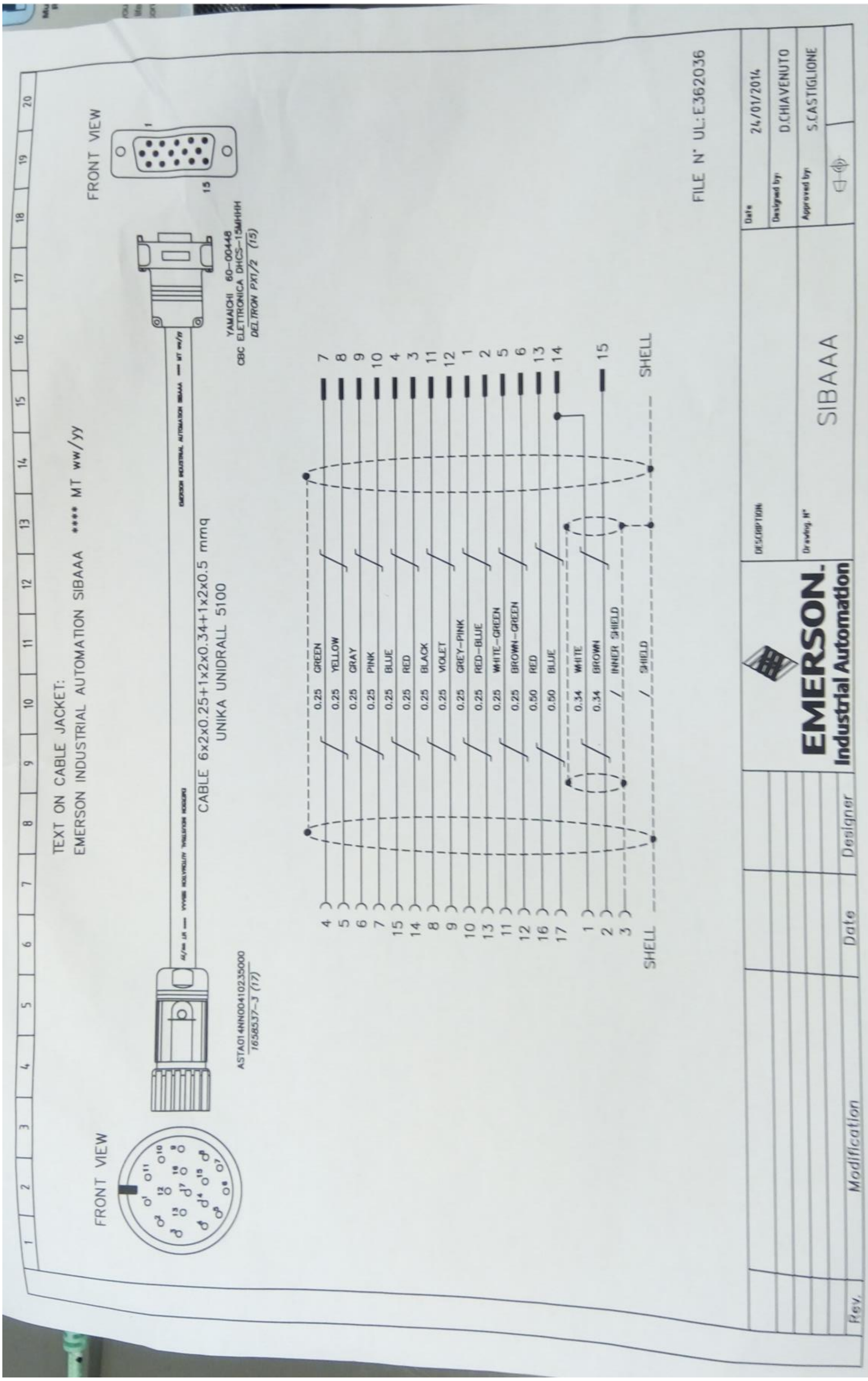
APPENDICES

Appendix 1. Power Supply Cable



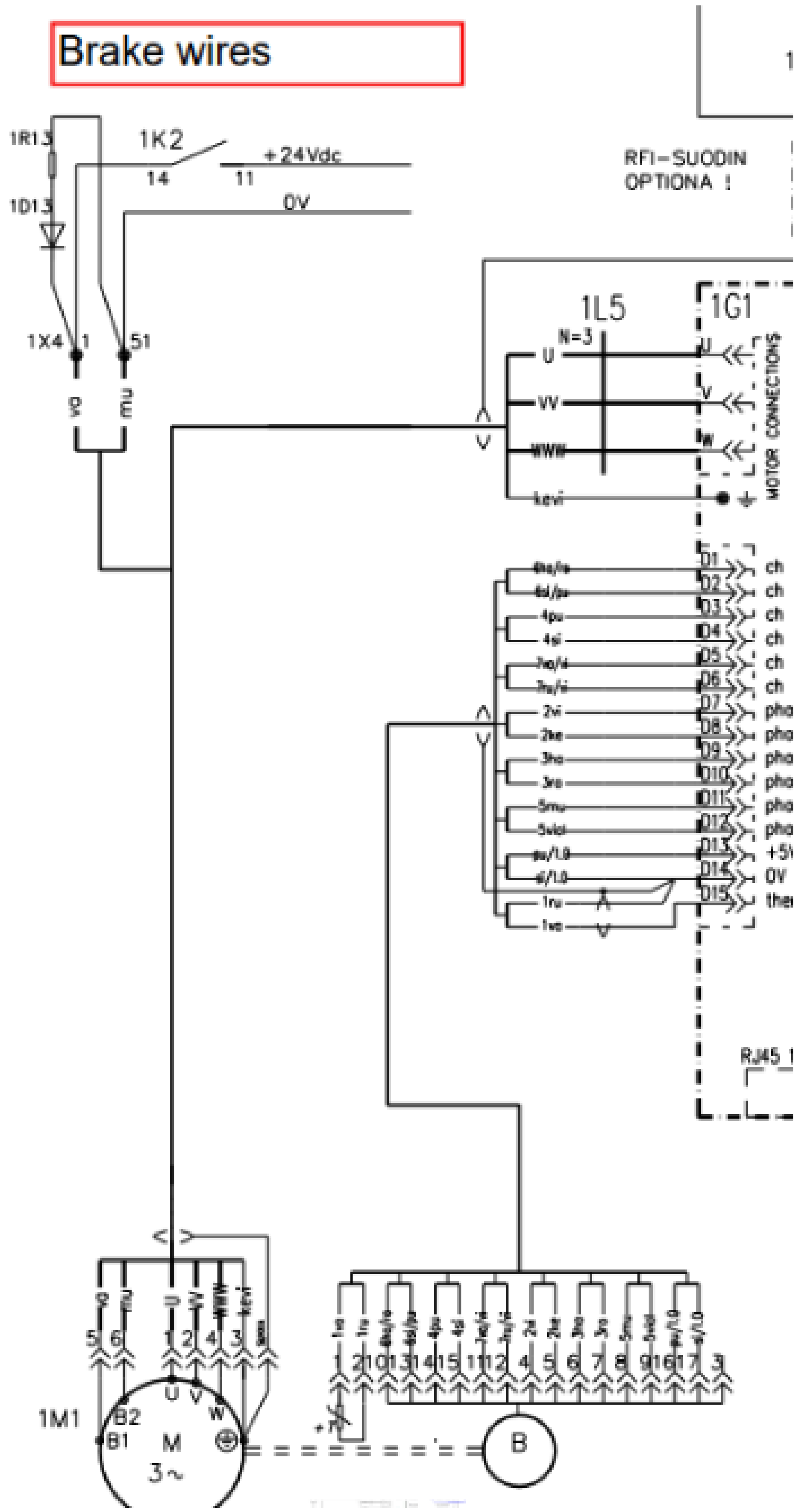
(CONTROLTECHNIQUES, 2017)

Appendix 2. Encoder Cable



(EMERSON I. A., 2017)

Appendix 3. Brake Wire Diagram



(EMERSON C. T., Brake Wire Diagram)

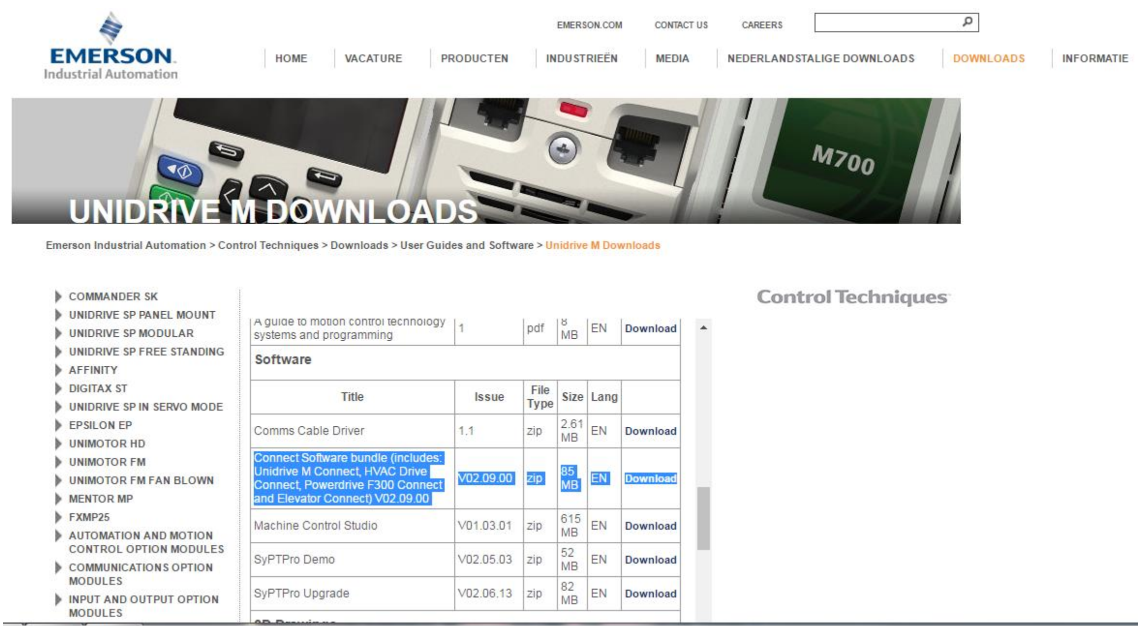
Appendix 4. Set-Up Guide/Instructions

Unidrive M Connect Software Guide 1 (22)

“Unidrive M Connect is a Windows based software commissioning / start-up tool for Unidrive M/HS. Unidrive M Connect can be used for commissioning / start-up and monitoring, drive parameters can be uploaded, downloaded and compared and simple or custom menu listings can be created. Drive menus can be displayed in standard list format or as live block diagrams. Unidrive M Connect is able to communicate with a single drive or a network. Unidrive M Connect can be downloaded from www.controltechniques.com” this can be found on page 13 of the Control Getting Started Guide. (EMERSON C. T., 2016)

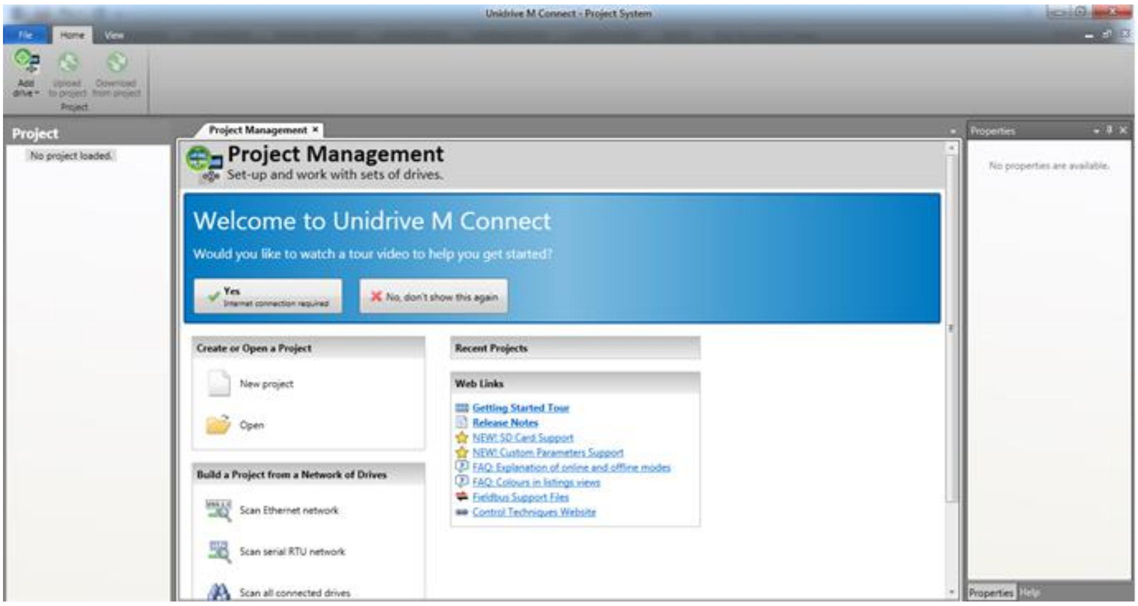
The Siemens PLC S7-1200 with TIA Portal software can always be added at any time later on in the project. The software of Unidrive M Connect was a cheap, fast and reliable way to communicate, install and start-up the drive. The link to download the software is as followed:

http://www.emersonindustrial.com/nl-NL/controltechniques/downloads/userguidesand-software/Pages/unidrivem.aspx



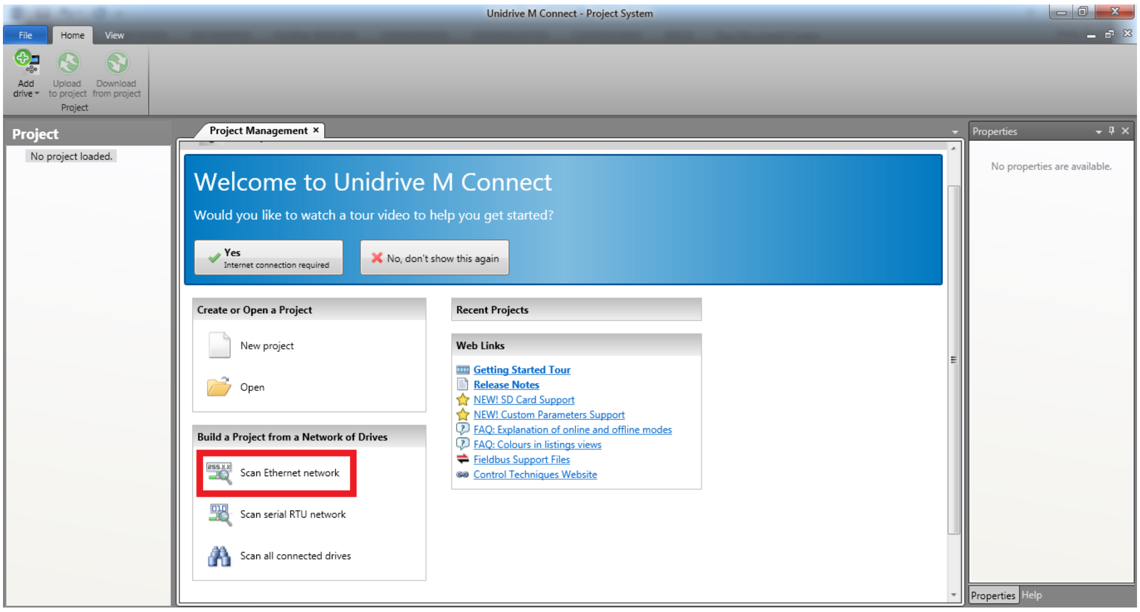
PICTURE 21. Official website of Unidrive M downloads (Photo: Jordy Declercq 2017)

To be sure that the correct software is downloaded upon the computer the picture above shows which particular software was downloaded and used within this project. The title of the software download package is “Connect Software bundle (includes: Unidrive M Connect, HVAC Drive Connect, Powerdrive F300 Connect and Elevator Connect)V02.09.00”. As the title refers to it is the version V02.09.00. this version was used with the operating system Windows 7. After installing the software the startup screen should look as presented on the picture below.



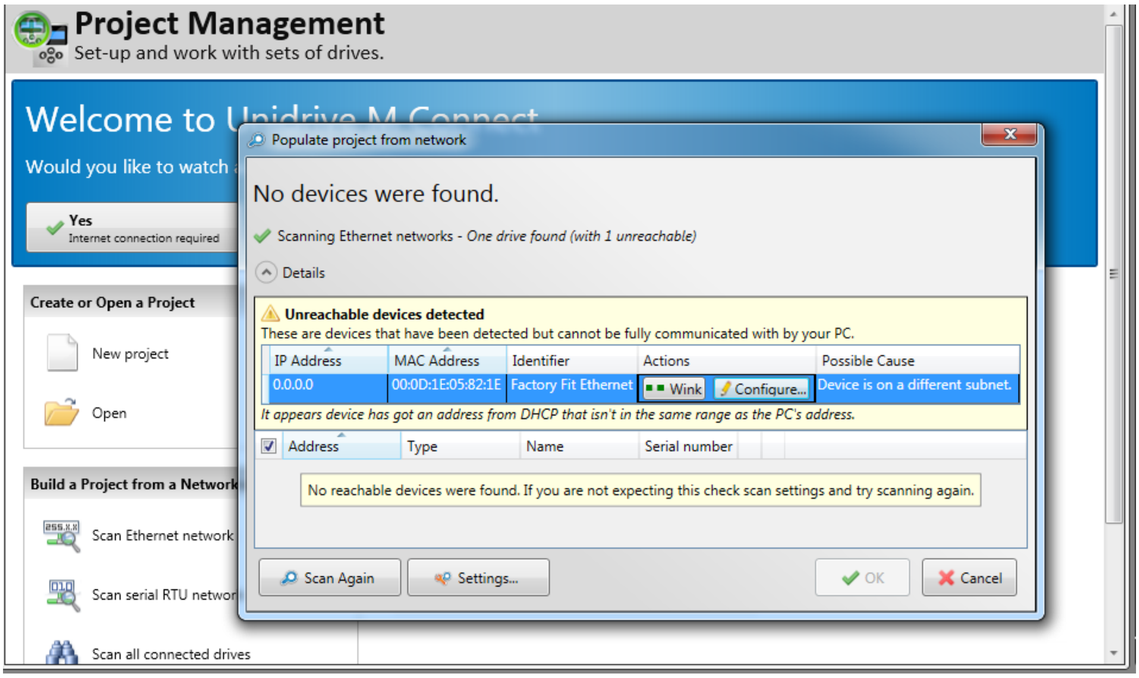
PICTURE 22. Startup screen (Photo : Jordy Declercq 2017)

It is highly recommended to watch the tour video for information purposes and basic understanding of the program. A new browser will open with a youtube video, if the video is not appearing there is also the possibility of going straight to the video by using this link: https://www.youtube.com/watch?v=qV5-OYNNpjs&feature=youtu.be
After watching the tour video or understanding the basic functions of the software, which will also be further explained in the next chapters, the connection should be completed by now. Meaning the connection between the computer and the Unidrive M700 from EMERSON Industrial Automation by Ethernet cable.



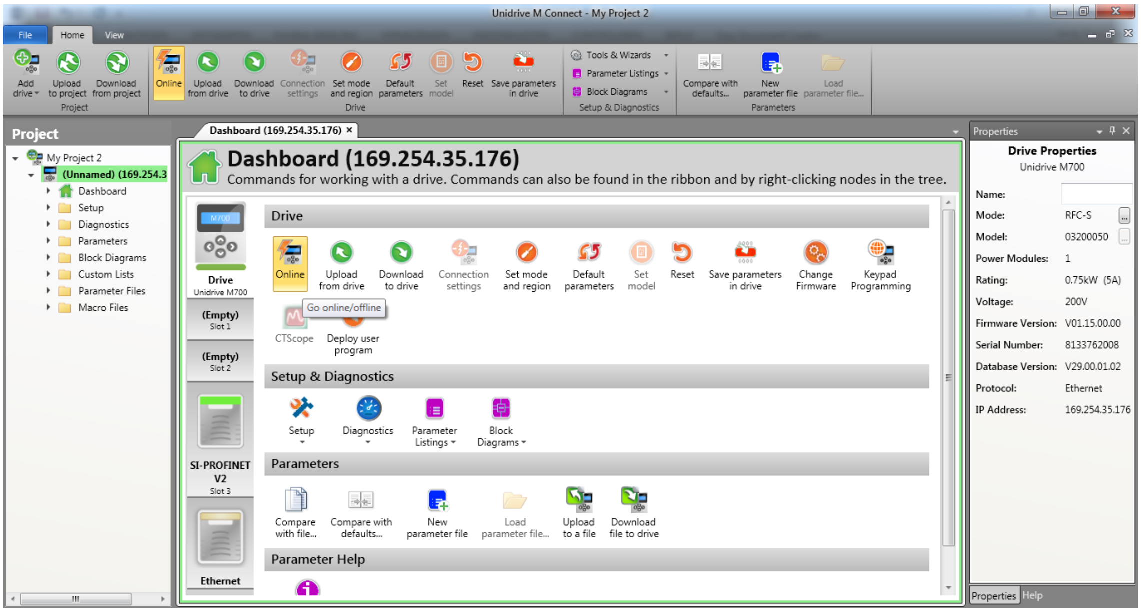
PICTURE 23. Project Management (Photo : Jordy Declercq 2017)

Because the connection in this project is made by Ethernet the function Scan Ethernet network should be used. If there is another connection made, then the function Scan all connected drivers should be used. If any problems occur considering finding the Unidrive M700 from EMERSON Industrial Automation or IP issues, the following IP address should be used 169.254.35.176. This IP address is used throughout the whole project and can be found under the Unidrive M700 drive properties.



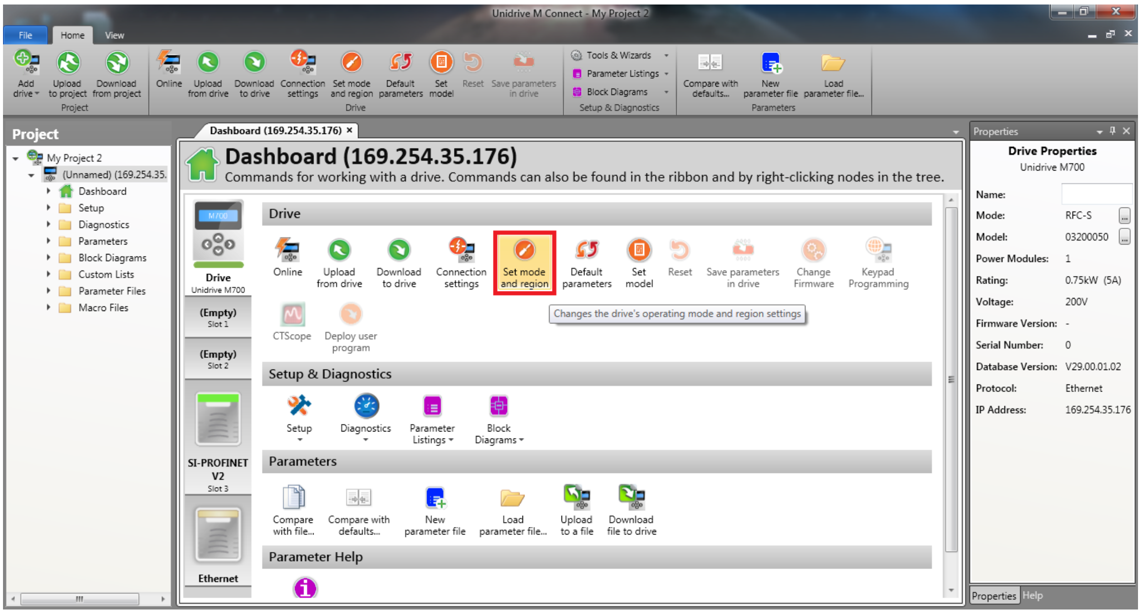
PICTURE 24. No devices were found (Photo : Jordy Declercq 2017)

If no devices were found the first action that should be tried is the Wink action, if the two green lights on the variable frequency drive are winking it means the connection is properly done. Then the error is possibly the IP address as seen it is shown as 0.0.0.0 while it should be 169.254.35.176, by changing the IP address the error is solved.
Also on the next screen in the program the IP address will be shown next to the title of the page as example Dashboard (169.254.35.176).



PICTURE 25. Dashboard (Photo : Jordy Declercq 2017)

The following screen is one of the main screens in the program it has a nice overview of all the functions needed to use the drive. The first thing that should be done is making an online connection with the drive. This was done by clicking on the “Online” pictogram seen on the Dashboard. If the pictogram saying “Online” stays orange it means the connection to the drive through the software is successful and the setup can begin.



PICTURE 26. Set mode and region (Photo : Jordy Declercq 2017)

Now the mode and region can be set by clicking on the following Pictogram Set mode and region. The regions are based on the 50Hz or 60Hz electric power grid and the modes are based upon which motor is used.

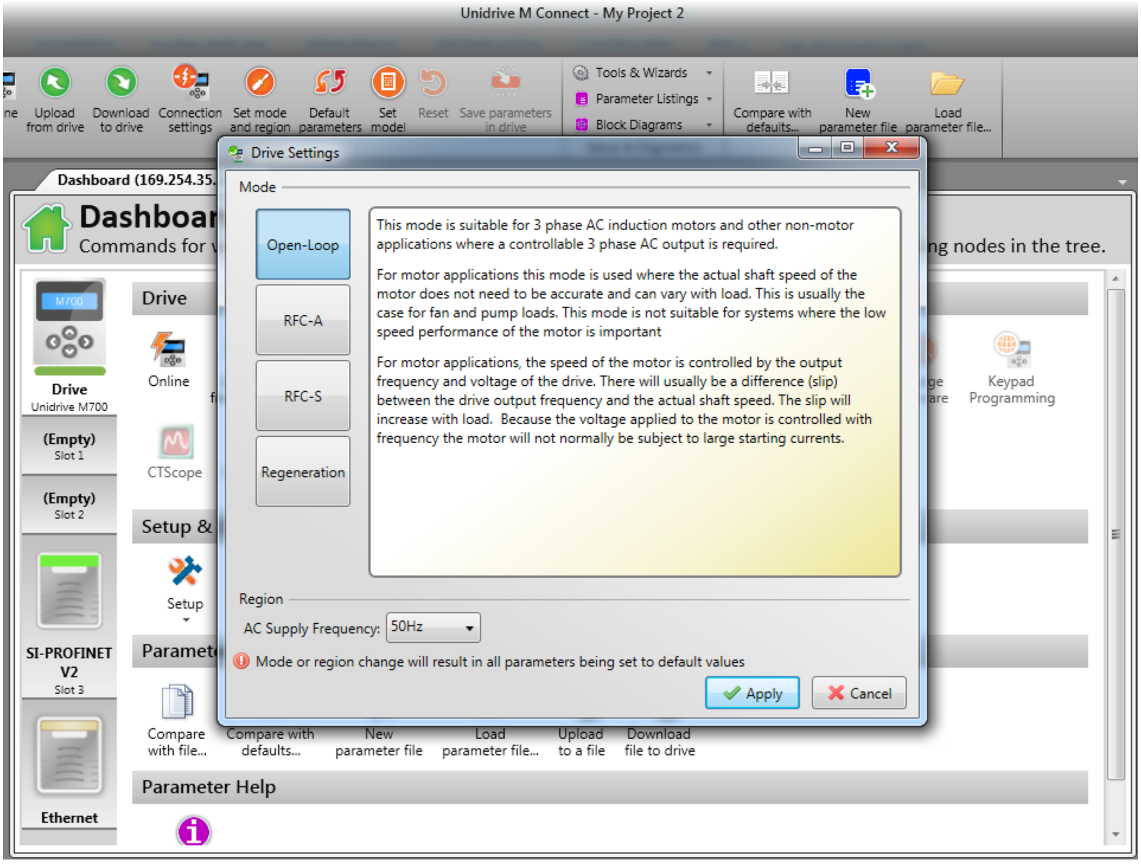
This will pop up a tab where one of the following modes can be chosen:

- Open-Loop
- RFC-A
- RFC-S
- Regeneration

“The Open-Loop mode is suitable for three phase AC induction motors and other non-motor applications where a controllable three phase AC output is required.

For motor applications this mode is used where the actual shaft speed of the motor does not need to be accurate and can vary with load. This is usually the case for fan and pump loads. This mode is not suitable for systems where the low speed performance of the motor is important.

For motor applications, the speed of the motor is controlled by the output frequency and voltage of the drive. There will usually be a difference (slip) between the drive output frequency and the actual shaft speed. The slip will increase with the load. Because the voltage applied to the motor is controlled with frequency the motor will not normally be subject to large starting currents.” (Techniques, 2017)

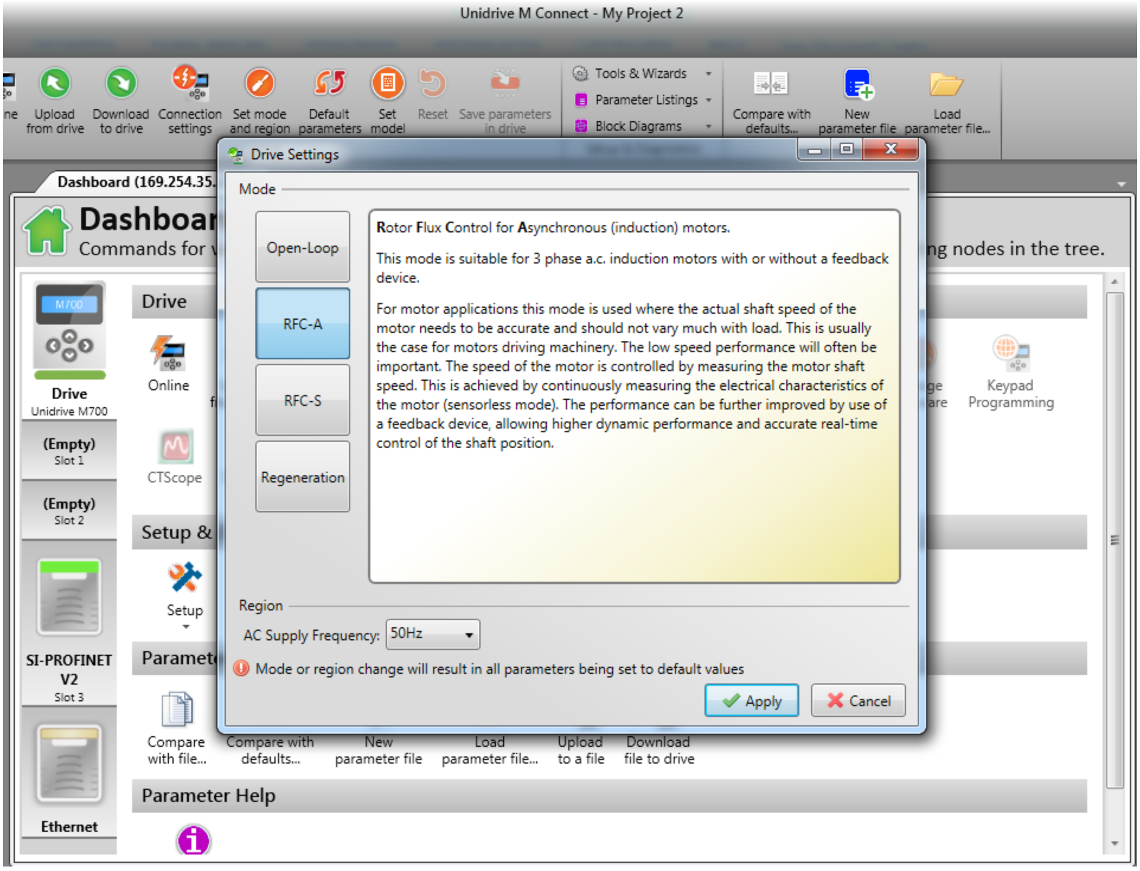


PICTURE 27. Open-Loop Mode (Photo : Jordy Declercq 2017)

“RFC-A stands for Rotor Flux Control for Asynchronous (induction) motors.

This mode is suitable for three phase a.c. induction motors with or without a feedback device.

For motor applications this mode is used where the actual shaft speed of the motor needs to be accurate and should not vary much with load. This is usually the case for motors driving machinery. The low speed performance will often be important. The speed of the motor is controlled by measuring the motor shaft speed. This is achieved by continuously measuring the electrical characteristics of the motor (sensorless mode). The performance can be further improved by use of a feedback device, allowing higher dynamic performance and accurate real-time control of the shaft position.” (Techniques, 2017)

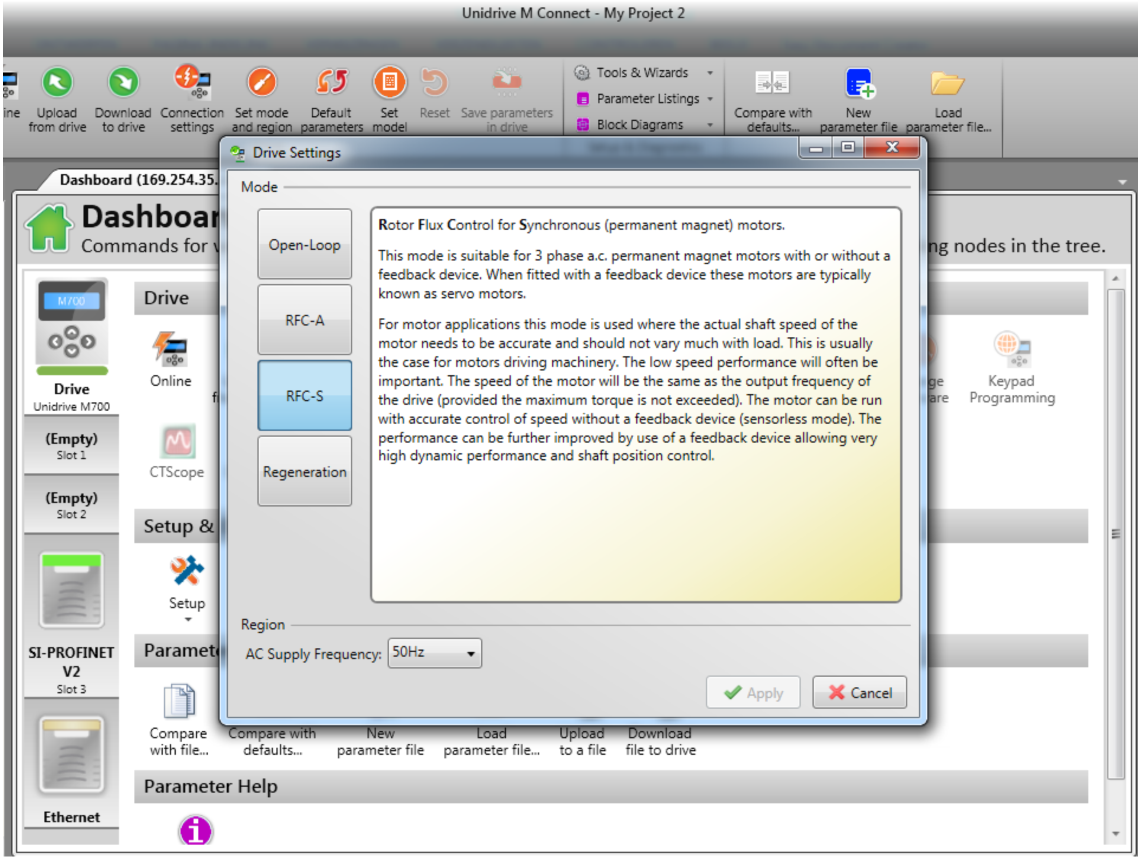


PICTURE 28. RFC-A Mode (Photo : Jordy Declercq 2017)

“RFC-S stands for Rotor Flux Control for Synchronous (permanent magnet) motors.

This mode is suitable for three phase a.c. permanent magnet motors with or without a feedback device. When fitted with a feedback device these motors are typically known as servo motors.

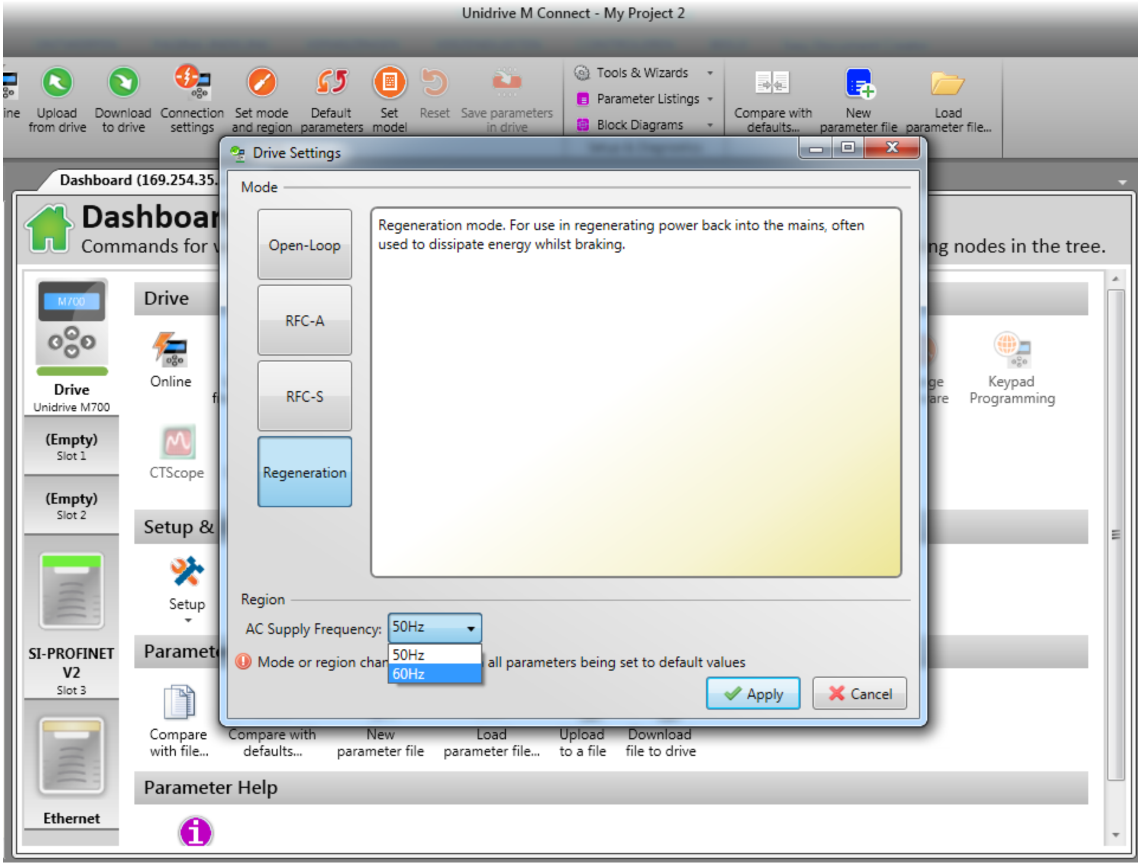
For motor applications this mode is used where the actual shaft speed of the motor needs to be accurate and should not vary much with load. This is usually the case for motors driving machinery. The low speed performance will often be important. The speed of the motor will be the same as the output frequency of the drive (provided the maximum torque is not exceeded). The motor can be run with accurate control of speed without a feedback device (sensorless mode). The performance can be further improved by use of a feedback device allowing very high dynamic performance and shaft position control.” (Techniques, 2017)



PICTURE 29. RFC-S Mode (Photo : Jordy Declercq 2017)

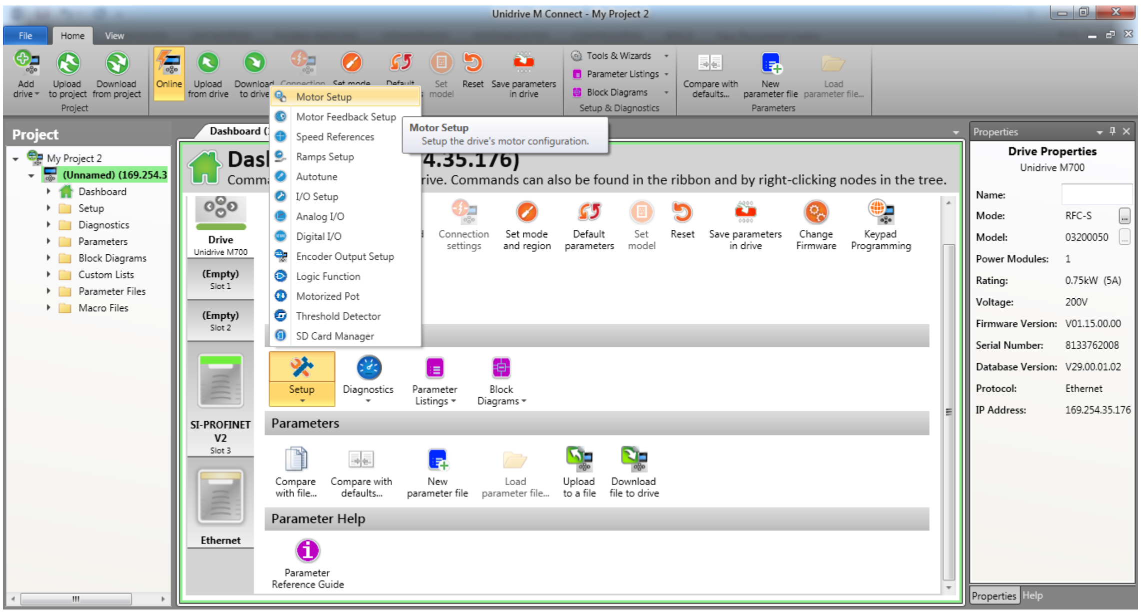
“The last and fourth mode is the regeneration mode. For use in regenerating power back into the mains, often used to dissipate energy whilst breaking.” (Techniques, 2017)

With any mode you can change the Region settings with the AC Supply Frequency from 50Hz to 60Hz. In Finland the 50Hz AC Supply Frequency is used because of the electrical power grid being 50Hz. In America this should be set to 60Hz because of the American electrical power grid. Also keep in mind that changing the mode or region will result in all parameters being set to their default values.



PICTURE 30. Regeneration Mode (Photo : Jordy Declercq 2017)

In this thesis a brushless AC servo motor is used therefore the correct mode is the RFC-S mode, the project is taking place in Finland therefore the AC Supply Frequency should be 50Hz.

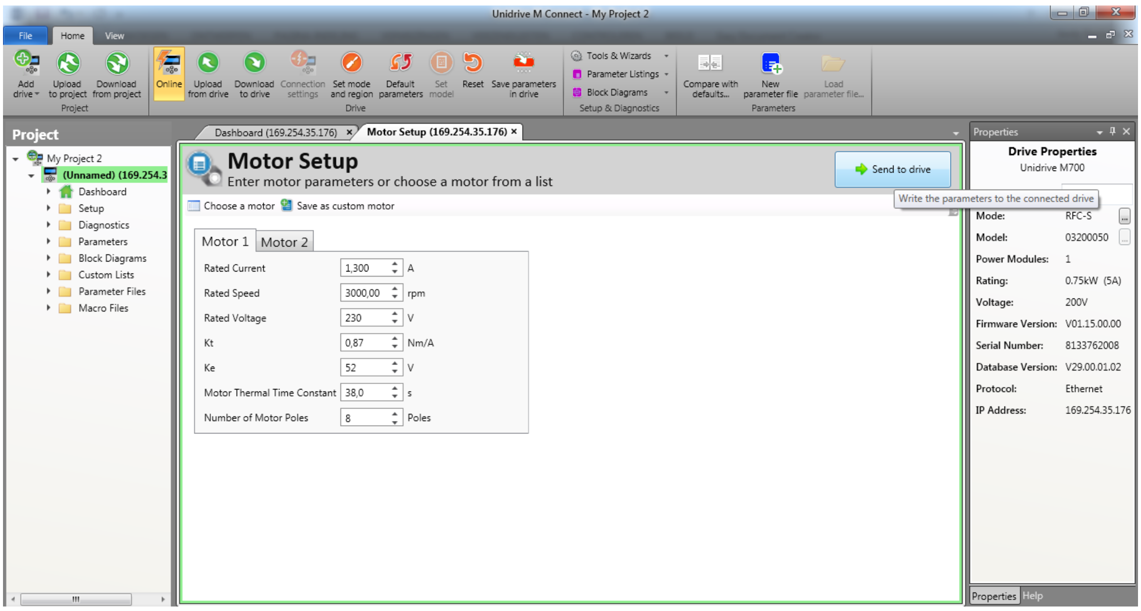


PICTURE 31. Motor Setup (Photo : Jordy Declercq 2017)

By following the instructions shown on the picture above a new tab will pop up called Motor Setup. Here the most important values of the servo motor will be inserted, as example the rated current, the rated speed, the rated voltage, etc. All these values can be found on the nameplate of the servomotor.

PICTURE 32. Nameplate of the servo motor (Photo : Jordy Declercq 2017)

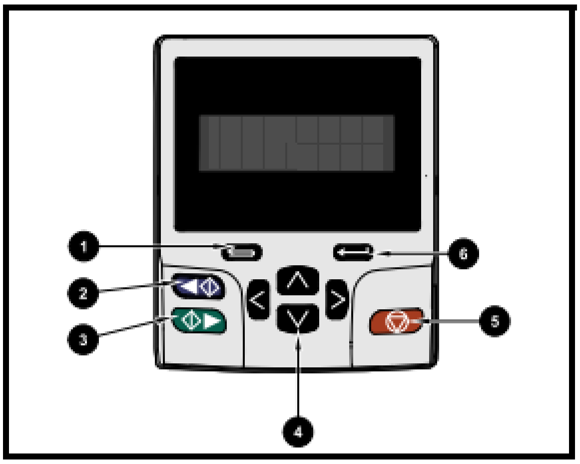
When the values are filled in correctly, these can be send to the drive by clicking on the Send to Drive button in the upper right corner. The drive will save these values of the servomotor.



PICTURE 33. Motor setup with inserted values (Photo : Jordy Declercq 2017)

To see if the drive has correctly received and saved the inserted values of the brushless AC servo motor, parameters 00.042 to parameters 00.048 and parameter 00.053 can be checked. This can either be looked upon the LCD display of the Unidrive M700 from EMERSON Industrial Automation or into the software program at the parameter listing tab.

Figure 4-1 KI-Keypad



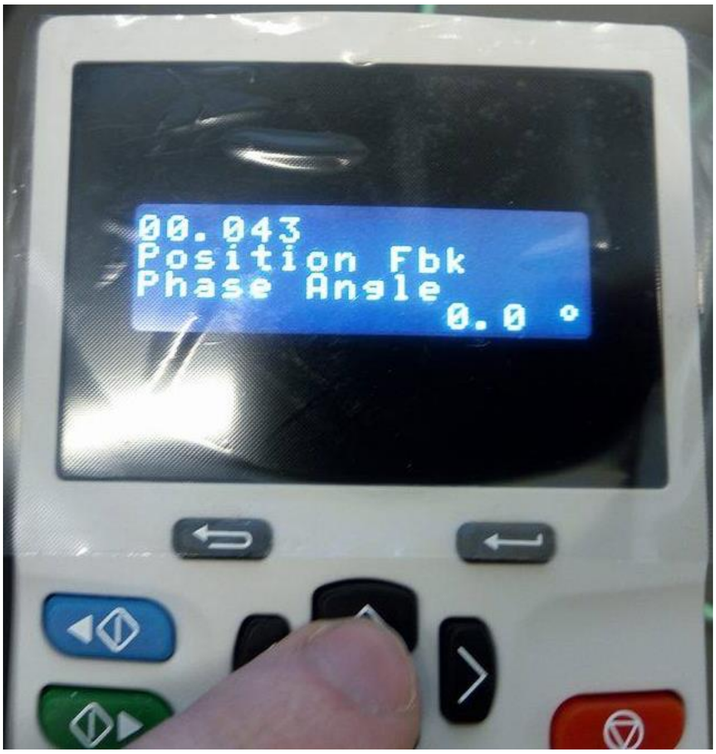
1. Escape button
2. Start reverse (Auxiliary button)
3. Start forward
4. Navigation keys (x4)
5. Stop / Reset (red) button
6. Enter button

FIGURE 34. KI-Keypad (EMERSON C. T., Control Getting Started Guide, 2016).

To check the parameters on the KI-Keypad the navigation keys will be used, if the lowest navigation key of the four possible navigation keys is pressed, the parameter window will open. To scroll between the parameter windows the upper and lower navigation keys are used. The two navigation keys, the left and right navigation key, are used to go to the quick setup window. When parameter 00.042 is reached by using the navigation keys on the KI-Keypad of the Unidrive M700 from EMERSON Industrial Automation it should look as on the following picture. This information can also be found in the manual: Control Getting Started Guide Page 16. (EMERSON C. T., Control Getting Started Guide, 2016).

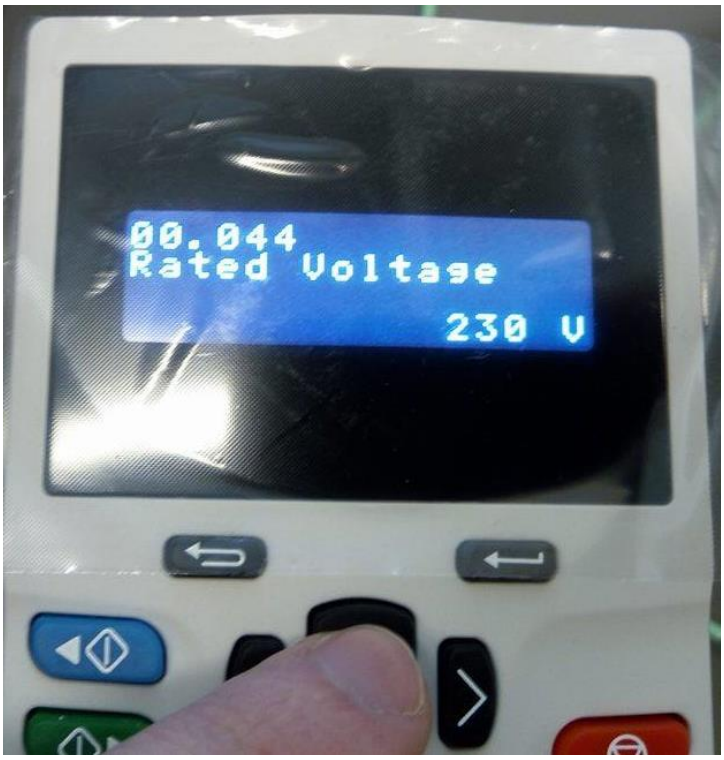
PICTURE 34. Parameter 42 (Photo : Jordy Declercq 2017)

Parameter 00.042 displays the number of motor poles there are in the brushless AC servo motor connected to the AC drive. Make sure the number of poles are the same as on the nameplate of the brushless AC servo motor as earlier inserted into the software. Since the amount of poles in a motor define the speed and torque of the motor. Generally speaking the higher the amount of poles a motor has, the slower the speed of the motor, therefore the torque is higher at these slower speeds. The default setting is 6.



PICTURE 35. Parameter 43 (Photo : Jordy Declercq 2017)

Parameter 00.043 displays the position of the feedback phase angle which at that moment was 0.0 degrees. This was due to the servo motor not rotating but standing still in starting position. The minimum value is 0.0 degrees the maximum value is 359.9 degrees which makes up for a full rotation.



PICTURE 36. Parameter 44 (Photo : Jordy Declercq 2017)

Parameter 00.044 displays the rated voltage of the servo motor, which is at default 230V the maximum value is 265V the minimum 0V.

PICTURE 37. Parameter 45 (Photo : Jordy Declercq 2017)

Parameter 00.045 displays the rated speed of the servo motor, which is at default 3000.00 rpm the maximum value is 33000.00rpm the minimum value is 0rpm.

PICTURE 38. Parameter 46 (Photo : Jordy Declercq 2017)

Parameter 00.046 displays the rated current of the servo motor which is 1.3A. The default value is 5A, the maximum value is 6A and the minimum is 0A.

PICTURE 39. Parameter 47 (Photo : Jordy Declercq 2017)

Parameter 00.047 displays the volts per 1000 rpm which are 52V in this case. This value can be found on the nameplate of the servo motor as in Ke: 52.5 V/Krpm. The default value is 98V the maximum is 10000V and the minimum is 0V.

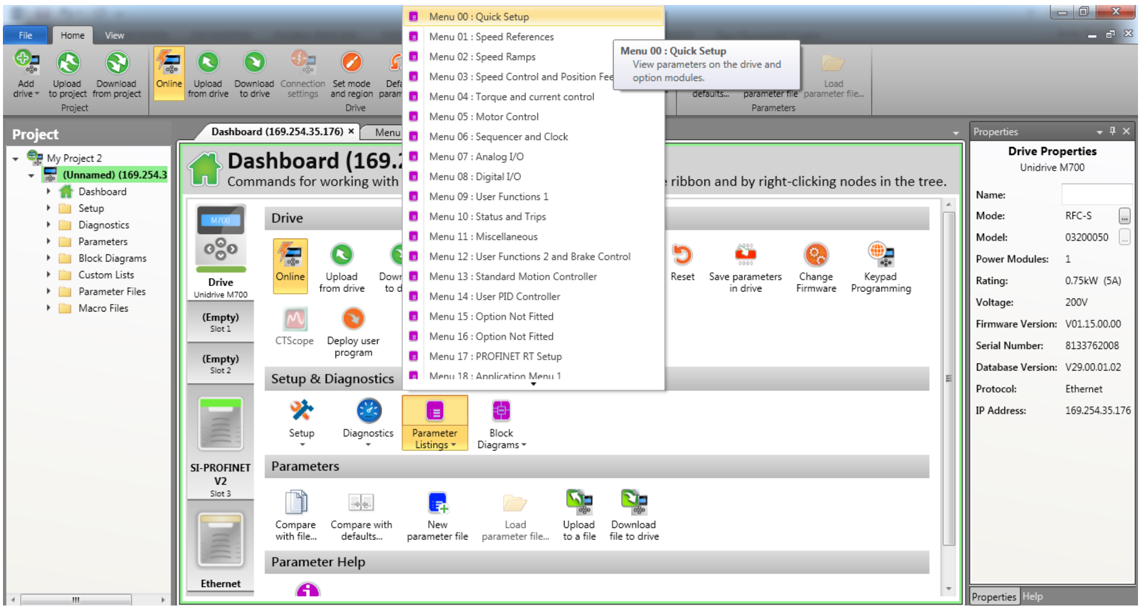
PICTURE 40. Parameter 48 (Photo : Jordy Declercq 2017)

Parameter 00.048 displays the user drive mode, this mode should be set on RFC-S. It is important that the correct user drive mode is used or it could damage the servo motor.

PICTURE 41. Parameter 53 (Photo : Jordy Declercq 2017)

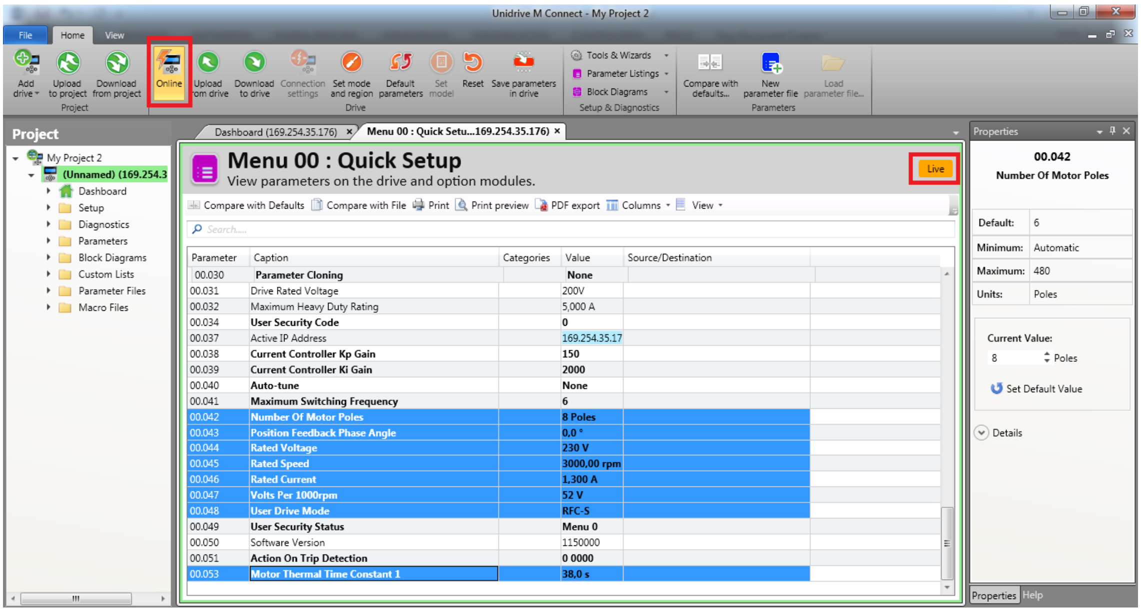
Parameter 00.053 displays the motor thermal time constant 1 which is 38.0s. The default value is 89.0s and the maximum value can be 3000.0s.

If you wish to check the parameters through use of the Unidrive M Connect software click on the Parameter Listings icon and go to Menu 00: Quick Setup.



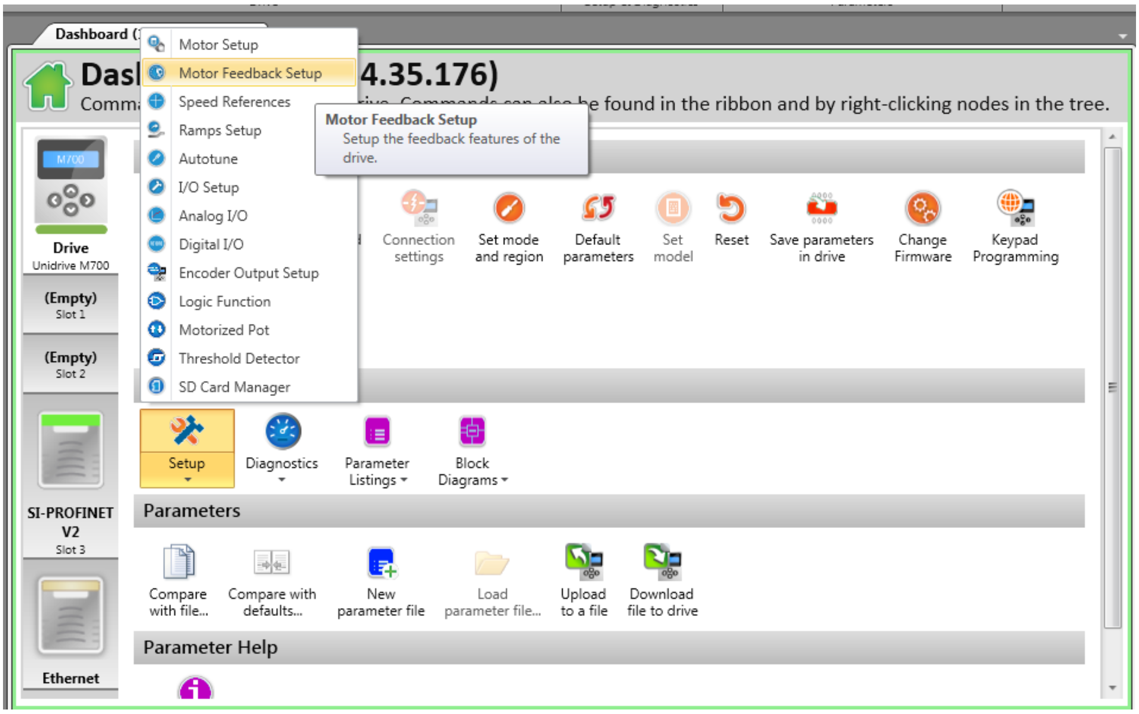
PICTURE 42. Dashboard to Menu 00: Quick Setup (Photo : Jordy Declercq 2017)

In tab Menu 00: Quick Setup you see a nice overview of the parameters that need to be checked.



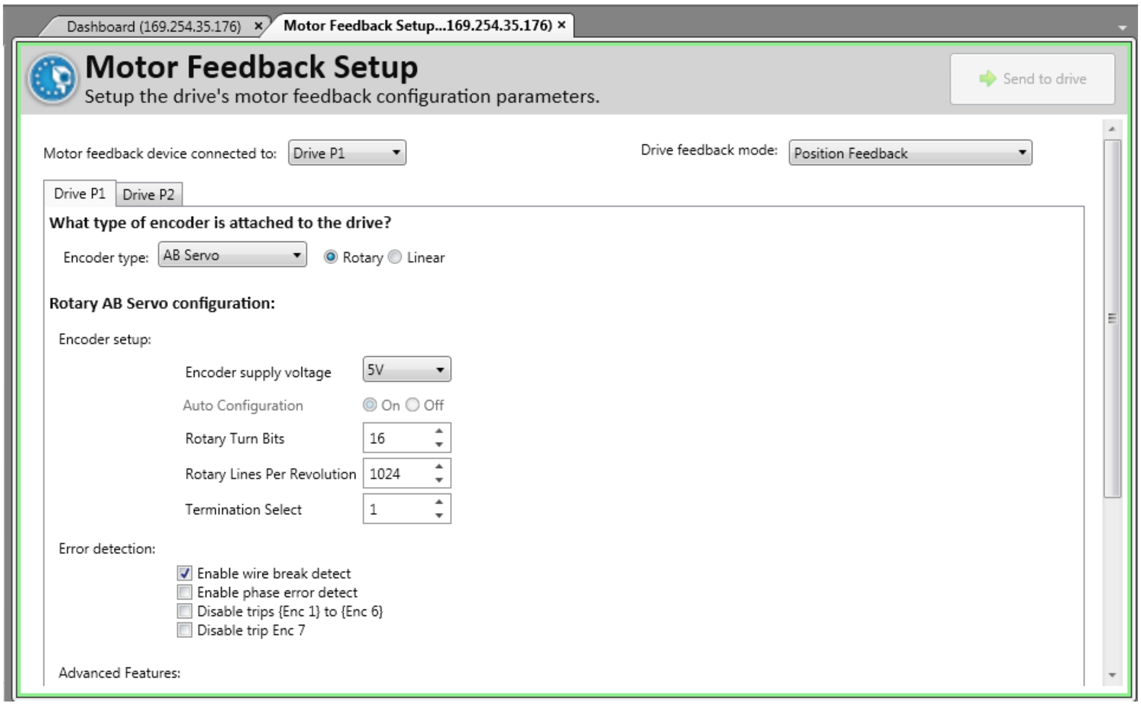
PICTURE 43. Menu 00: Quick Setup (Photo : Jordy Declercq 2017)

To perform an autotune one more step has to be completed, this step includes the Motor Feedback Setup. To get to the Motor Feedback Setup tab click on the Setup icon and then go to Motor Feedback Setup as seen on the picture below.



PICTURE 44. Dashboard to Motor Feedback Setup (Photo : Jordy Declercq 2017)

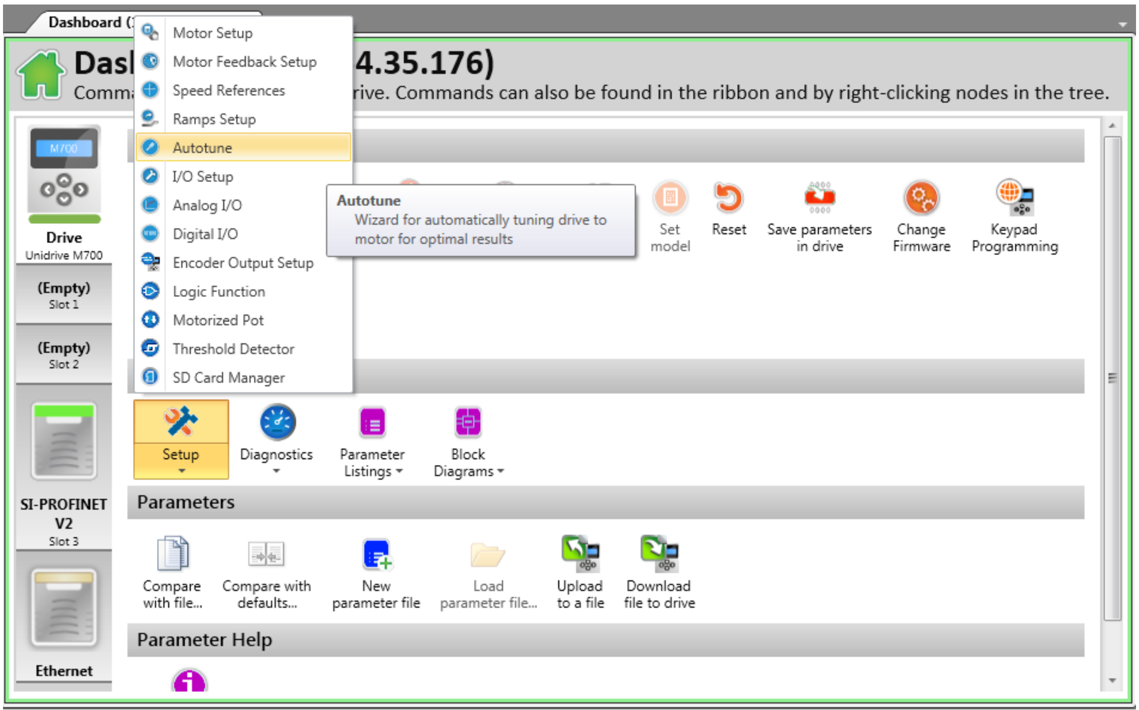
The Motor Feedback Setup tab will pop up, once configuring this tab make sure you are on the Drive P1 page as seen on the picture below. Then the used encoder type of the motor should be selected, in this thesis the Encoder Type is a rotary AB Servo encoder. The encoder setup is mostly as default, 5V, 16 rotary turn bits and 1024 Rotary lines per revolution. Also make sure the drive feedback mode is on position feedback.



PICTURE 45. Motor Feedback Setup (Photo : Jordy Declercq 2017)

When the values are filled in correctly, these can be send to the drive by clicking on the Send to Drive button in the upper right corner. The drive will then save these values of the motor feedback setup.

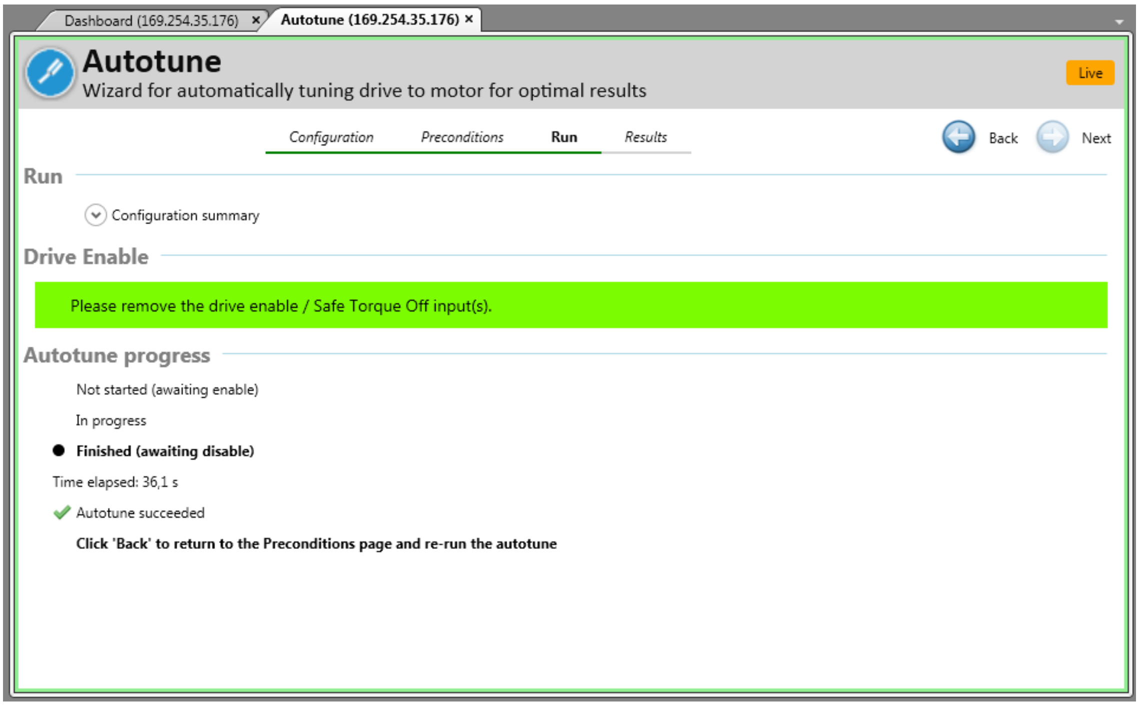
To start the Autotune once again click on the Setup icon and go to Autotune as seen on the picture below.



PICTURE 46. Dashboard to Autotune (Photo : Jordy Declercq 2017)

Explaining the Autotune procedure would give no extra information since the steps are simple and are clearly explained throughout the progress by the Software itself. Therefore simply follow the instructions given by the program for running an Autotune.

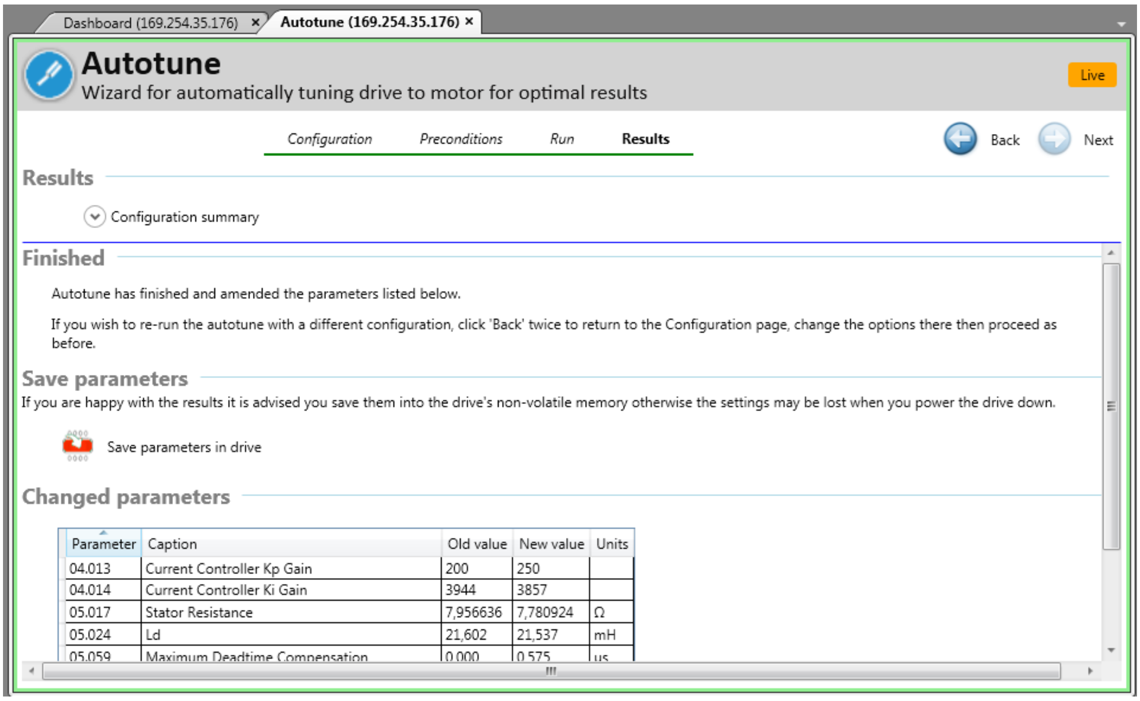
After the Autotune is successful the following picture should be seen.



PICTURE 47. Autotune succesful (Photo : Jordy Declercq 2017)

Then once again follow the instruction and " Please remove the drive enable / Safe Torque Off input(s)." When this is removed, continue to the Results page by clicking on Next in the upper right corner.

Finally at the end of the Autotune procedure the results can be seen in the Results tab. If the user is satisfied with the results it is highly advised to save the changed parameters.



PICTURE 48. Results of Autotune (Photo : Jordy Declercq 2017)

The Autotune procedure is now completed and therefore the servo motor setup is also completed. The servo motor can now be used to its highest efficiency for its application. These steps are also generally explained shortly on page 14 and 15 in the Emerson Unidrive M700 Getting Started Guide (EMERSON, Control Getting Started Guide, 2016). But be cautious the steps explained on those page are for general use, in other words for any given motor. The steps explained in this thesis were specifically for the servo motor used in this thesis.