Bachelor Project

Czech
Technical
University
in Prague

F3

Faculty of Electrical Engineering
Department of Electric Drives and Traction

Workplace with SynRM Drive Fed by S120

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Supervisor: Doc. Ing. Jan Bauer, Ph.D.
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ZADÁNÍ BAKALÁŘSKÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

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Fakulta/ústav: **Fakulta elektrotechnická**

Zadávající katedra/ústav: **Katedra elektrických pohonů a trakce**

Studijní program: **Elektrotechnika, energetika a management**

Specializace: **Aplikovaná elektrotechnika**

II. ÚDAJE K BAKALÁŘSKÉ PRÁCI

Název bakalářské práce:

Zprovoznění pracoviště se SynRM motorem a S120

Název bakalářské práce anglicky:

Workplace with SynRM Drive Fed by S120

Pokyny pro vypracování:

1) z dostupných komponentů navrhněte a zprovozněte pracoviště s měničem Sinamics S120 a SynRM
2) porovnejte účinnost SynRM motoru s ASM motorem v různých pracovních bodech
3) připojte měnič na PLC a realizujte řízení motoru pomoci PLC a vizualizace
4) na PLC implementujte sběr dat z momentové hřídele + vizualizaci

Seznam doporučené literatury:

[1] Weidauer J., Messer R. Electrical Drives, Publics Erlangen, 2014
[2] SCE Training Curriculum. Siemens AG, 2016
[3] Durry B. The Control Techniques Drives and Controls Handbook 2nd ed., IeT, 2009

Jméno a pracoviště vedoucí(ho) bakalářské práce:

doc. Ing. Jan Bauer, Ph.D. katedra elektrických pohonů a trakce FEL

Jméno a pracoviště druhé(ho) vedoucí(ho) nebo konzultanta(ky) bakalářské práce:

Datum zadání bakalářské práce: **25.04.2023** Termín odevzdání bakalářské práce: **26.05.2023**

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podpis vedoucí(ho) práce

podpis vedoucí(ho) ústavu/katedry

prof. Mgr. Petr Páta, Ph.D.
podpis děkana(ky)

III. PŘEVZETÍ ZADÁNÍ

Student bere na vědomí, že je povinen vypracovat bakalářskou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací.
Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v bakalářské práci.

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Datum převzetí zadání

Podpis studenta

Acknowledgements

Firstly, I would like to thank my supervisor, Doc. Ing. Jan Bauer PhD., for his strong support and the opportunity to work on a topic which I enjoy and which interests me.

Also, I wouls like to thank my colleagues from Siemens for the priceless advice, which has enabled me to successfully complete my thesis.

Last but not least, I would like to thank my friends and family for emotional support and patience.

Declaration

I declare that this thesis has been composed solely by myself and that I have stated all information sources in accordance with the Methodical instruction of compliance to ethical principles for the preparation of university thesis projects.

Abstract

This thesis discusses the construction of a functional workstation with a frequency converter type S120, synchronous reluctance motor, PLC and a HMI panel to implement operable speed and torque closed-loop control with visualisation.

Furthermore, it introduces relevant theoretic knowledge regarding the means of driving synchronous reluctance motors with modern methods using frequency converters.

The aim is to measure efficiency as a function of torque and speed of a synchronous reluctance motor with comparisons to the same characteristics of an induction motor.

In describing each part of the program, the reader should have sufficient knowledge to operate the workstation.

Another task of my thesis is to implement data collection from a rotary torque sensor and to display the data on a HMI panel. In accordance with the first part of the thesis, it will also present relevant theoretical knowledge and describe each part of the program.

Keywords: Synchronous reluctance motor, variable frequency drives, S120, Vector control, efficiency

Supervisor: Doc. Ing. Jan Bauer, Ph.D.

Abstrakt

Tato práce se zabývá sestavením funkčního pracoviště s frekvenčním měničem řady S120, synchronním reluktančním motorem, PLC a HMI panelem k realizaci otáčkového a momentového řízení motoru včetně ovládání a vizualizace.

Součástí je také představit relevantní toerii k synchornním reluktančním motorům a způsobům jejich řízení pomocí moderních metod s frekvenčními měniči.

Cílem je naměřit závislost účinnosti synchronního reluktančního motoru na zatížení a otáčkách a porovnat ji s obdobnou závislostí asynchronního motoru v různých pracovních bodech.

Výsledkem této práce je popsat konfiguraci celého systému a umožnit tak čtenáři získat základní znalosti potřebné k možnému přístupu a ovládání pracoviště.

Dalším zadáním této práce je implementovat sběr dat z momentové hřídele pomocí PLC a vizualizaci v HMI panelu. Obdobně jako v prvním bodě je zde vysvětlena relevantní teorie a následný popis programu.

Klíčová slova: Synchronní reluktanční motor, frekvenční měniče, S120, vektorové řízení, účinnost

Překlad názvu: Zprovoznění pracoviště se SynRM motorem a S120

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Chapter 1

Synchronous Reluctance Motors

This chapter gives a basic introduction to synchronous reluctance motors (SynRMs) in terms of design, principle, mathematical model and usage in various applications. Due to high energy prices and increasing demand for highly efficient drives, SynRMs are gradually replacing standard induction motors in industrial applications. However, they still face some drawbacks, which are also discussed in this chapter.

1.1 Basic principle of a SynRM

The synchronous reluctance motor (or machine) is a type of electric motor that utilises magnetic resistance - reluctance - to produce torque. Similarly to an induction motor (IM), it has a sinusoidally distributed winding in a slotted stator, which creates a sinusoidal magnetic field. [1]

The main qualitative parameter of a SynRM is saliency ratio, which is defined as a ratio between the quadrature (q) and direct (d) axis inductance (some literature describe it inversely). An anisotropic magnetic material has different reluctances in the d and q axis. When inserted into a magnetic field under an angle between the d-axis, it produces a distortion field aligned to the q-axis. The object will try to align to the applied magnetic field along the d-axis, thus creating force and torque. In this sense, the best results will be achieved when the d-axis reluctance is minuscule and the q- axis reluctance is as large as possible. Therefore, a low saliency ratio is better - low reluctance corresponds to high inductance and vice versa. The easiest way to demonstrate the principle is in Fig. 1.1. When the applied field is rotating, the object will rotate with synchronous speed to the rotating field. [1]

There are many different types of rotor designs, but the most attention is directed towards axially laminated rotors (Fig. 1.2 left) and transversely laminated rotors (Fig. 1.2 right). These two designs showed the best results in terms of saliency ratio and other important parameters, such as torque ripple and iron losses. Other designs have performed insufficiently. For examples, see Fig. 1.3. Both the rotor and stator have the same amount of poles - most common are 4 or 6 pole motors. [2]

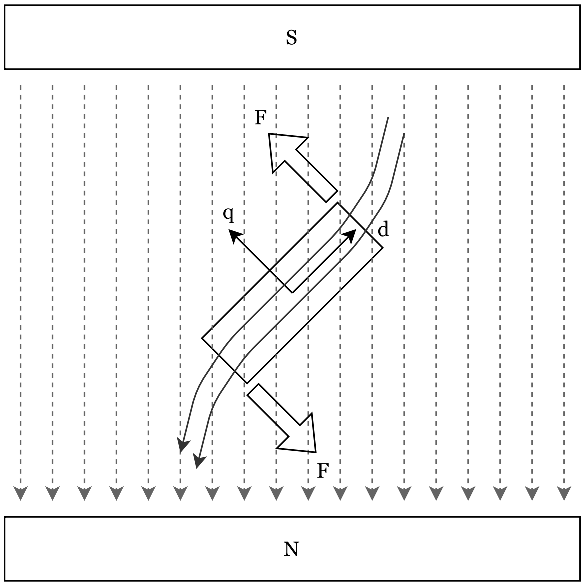


Figure 1.1: Principle of reluctance

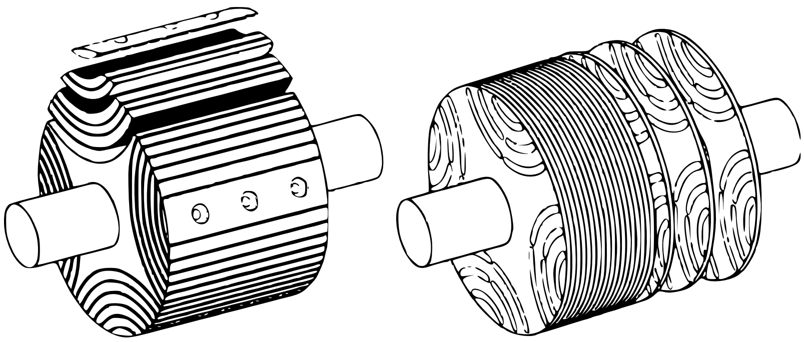


Figure 1.2: Axially laminated (left) and transversely laminated rotor (right). [1]

1.2 Comparison of axially and transversely laminated rotors

In theory, axially laminated rotors appear to reach an ideal anisotropic structure, which would result in the best performance. However, this is only true for 2-pole motors, as it was proved that otherwise a variable ratio between the depths of magnetic and non-magnetic structures is desired. [1]

Another disadvantage of axial lamination is that the additional harmonics produced by stator slots cause torque ripple and iron losses in the rotor. This can be avoided by skewing the rotor, though highly impractical. Moreover, the technology required to manufacture this kind of design is complicated and not easily serialised, not to mention that for slight changes in the rotor design, the technology would have to be overhauled to a large extent. [1]

Conversely, transverse lamination is significantly more practical to manufacture - punching out holes into a sheet of magnetic material. Also, by

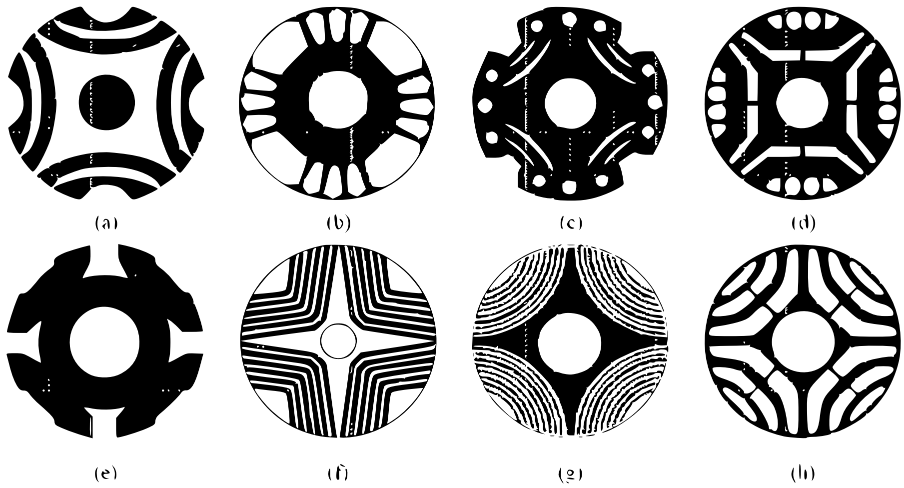


Figure 1.3: (a) Original Kostko rotor; (b) rotor adapted from an induction motor rotor; (c) rotor with multiple barriers; (d) rotor with saturable bridges; (e) segmented rotor; (f) axially laminated V rotor (g) axially laminated U-rotor; (h) modern transverse laminated rotor. [3]

applying the aforementioned solutions, problems can be avoided, thus reaching comparable or better parameters than axial lamination. Moreover, this technology is easy to serialise, which enables simple changes in design without the need to overhaul the manufacturing process or tools.

Generally, synchronous reluctance motors suffer from high q-axis inductance caused by the field distribution in the rotor and cannot be avoided. This drawback is overcome by inserting magnets into the rotor, thus changing the type of motor to a PMA-SynRM (Permanent Magnet Assisted Synchronous Reluctance Motor). [1]

1.3 Mathematical model

For general analysis let's imagine the position of each winding in space (simplified for a 2-pole 3-phase motor, Fig. 1.4). This is called the abc system. The Synrm basically has the same model as a classical synchronous motor without rotor salient pole winding and a squirrel cage. [2]

Equations for each winding can now be deduced. Because the magnetic fluxes and voltages are symmetrical, the equations have the same structure and therefore only two are sufficient to describe the principle.

$$\Psi_\mathrm{a} = L_\mathrm{a} \cdot i_\mathrm{a} + L_\mathrm{m} \cdot \cos\left(\frac{2\pi}{3}\right) \cdot i_\mathrm{b} + L_\mathrm{m} \cdot \cos\left(-\frac{2\pi}{3}\right) \cdot i_\mathrm{c}$$

$$\Psi_\mathrm{a} = L_\mathrm{a} \cdot i_\mathrm{a} + \frac{1}{2} L_\mathrm{m} \cdot i_\mathrm{a}$$

$$\Psi_\mathrm{s} = L_\mathrm{s} \cdot i_\mathrm{s} \tag{1.1}$$

where $L_\mathrm{s} = L_\mathrm{a} + \frac{1}{2} L_\mathrm{m}$

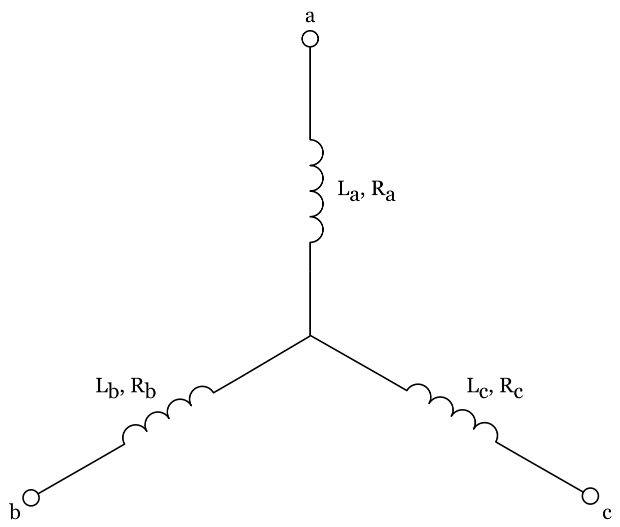


Figure 1.4: Model of SynRM in abc system

$$u_{\mathrm{s}} = R_{\mathrm{s}} \cdot i_{\mathrm{a}} + \frac{\mathrm{d}\Psi_{\mathrm{s}}}{\mathrm{d}t} \tag{1.2}$$

Transformation into complex numbers in stator system (axis system tied with the stator, top index s).

$$\mathbf{\Psi}_{\mathrm{s}}^{\mathrm{s}} = L_{\mathrm{s}} \cdot \mathbf{I}_{\mathrm{s}}^{\mathrm{s}} \tag{1.3}$$

$$\mathbf{U}_{\mathrm{s}}^{\mathrm{s}} = R_{\mathrm{s}} \cdot \mathbf{I}_{\mathrm{s}}^{\mathrm{s}} + \frac{\mathrm{d}\mathbf{\Psi}_{\mathrm{s}}^{\mathrm{s}}}{\mathrm{d}t} \tag{1.4}$$

Transformation into general system k rotating with angular velocity ω_{k} around the stator system.

$$\mathbf{U}_{\mathrm{s}}^{\mathrm{s}} = \mathbf{U}_{\mathrm{s}}^{\mathrm{k}} \cdot e^{i\omega_{\mathrm{k}}t}$$

After a few deductions:

$$\mathbf{U}_{\mathrm{s}}^{\mathrm{k}} = R_{\mathrm{s}} \cdot \mathbf{I}_{\mathrm{s}}^{\mathrm{k}} + \frac{\mathrm{d}\mathbf{\Psi}_{\mathrm{s}}^{\mathrm{k}}}{\mathrm{d}t} + j\omega_{\mathrm{k}} \cdot \mathbf{\Psi}_{\mathrm{s}}^{\mathrm{k}} \tag{1.5}$$

$$\mathbf{\Psi}_{\mathrm{s}}^{\mathrm{k}} = L_{\mathrm{s}} \cdot \mathbf{I}_{\mathrm{s}}^{\mathrm{k}} \tag{1.6}$$

Then the equations are separated into real and imaginary parts (called d and q axes) with angular velocity of the system $\omega_{\mathrm{k}} = \omega_{\mathrm{s}}$ (ω_{s} being the electrical angular frequency of the stator field). This is called the d-q system and is a rotating system tied with the stator field (Fig. 1.5). [4]

$$u_{\mathrm{sd}} = R_{\mathrm{s}} \cdot i_{\mathrm{sd}} + \frac{\mathrm{d}\Psi_{\mathrm{sd}}}{\mathrm{d}t} - \omega_{\mathrm{s}} \cdot \Psi_{\mathrm{sq}} \tag{1.7}$$

$$u_{\mathrm{sq}} = R_{\mathrm{s}} \cdot i_{\mathrm{sq}} + \frac{\mathrm{d}\Psi_{\mathrm{sq}}}{\mathrm{d}t} + \omega_{\mathrm{s}} \cdot \Psi_{\mathrm{sd}} \tag{1.8}$$

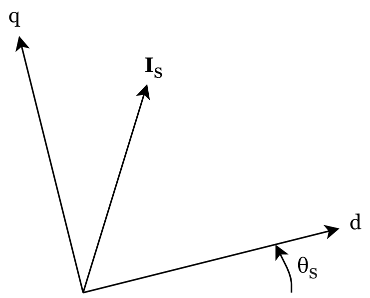


Figure 1.5: Model of a SynRM in d-q system

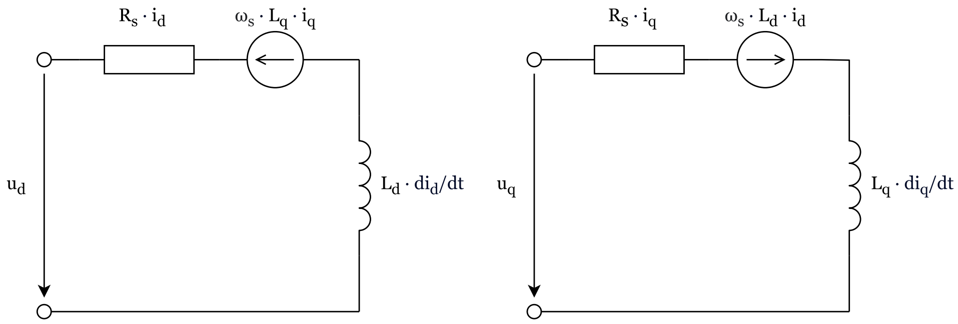


Figure 1.6: Equivalent circuit of a SynRM

$$\Psi_{\mathrm{sd}} = L_{\mathrm{d}} \cdot i_{\mathrm{sd}} \tag{1.9}$$

$$\Psi_{\mathrm{sq}} = L_{\mathrm{q}} \cdot i_{\mathrm{sq}} \tag{1.10}$$

1.4 Equivalent circuit and phasor diagram

An equivalent circuit can be designed from equations (1.7) - (1.10) (Fig. 1.6).

Equations (1.7) - (1.10) in steady state ($\frac{\mathrm{d}}{\mathrm{d}t} = 0$) are:

$$u_{\mathrm{sd}} = R_{\mathrm{s}} \cdot i_{\mathrm{sd}} - \omega_{\mathrm{s}} \cdot \Psi_{\mathrm{sq}} \tag{1.11}$$

$$u_{\mathrm{sq}} = R_{\mathrm{s}} \cdot i_{\mathrm{sq}} + \omega_{\mathrm{s}} \cdot \Psi_{\mathrm{sd}} \tag{1.12}$$

$$\Psi_{\mathrm{sd}} = L_{\mathrm{d}} \cdot i_{\mathrm{sd}} \tag{1.13}$$

$$\Psi_{\mathrm{sq}} = L_{\mathrm{q}} \cdot i_{\mathrm{sq}} \tag{1.14}$$

When Park transform (1.15) with $K = \frac{2}{3}$ is applied to a space vector in the abc system at any given time in steady state ($\omega_{\mathrm{r}} = \omega_{\mathrm{s}}$ and $u_{\mathrm{a,b,c}}$ are symmetrical), the vector sizes in both systems are equal. Since the d-q system rotates with equal angular velocity as the space vector, the d and q components are constant and determinable (1.16), (1.17). [2]

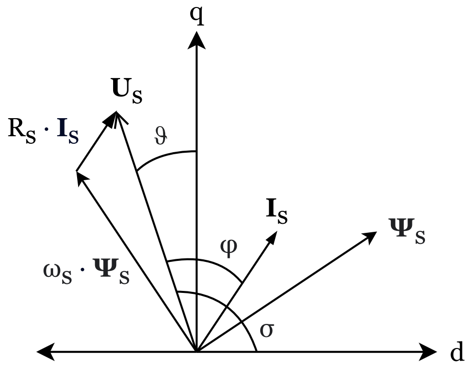


Figure 1.7: Phasor diagram of a SynRM

$$P(\theta_\mathrm{s}) = \frac{2}{3} \cdot \begin{bmatrix} \cos(\theta_\mathrm{s}) & \cos(\theta_\mathrm{s} - \frac{2\pi}{3}) & \cos(\theta_\mathrm{s} + \frac{2\pi}{3}) \\ -\sin(\theta_\mathrm{s}) & \sin(\theta_\mathrm{s} - \frac{2\pi}{3}) & \sin(\theta_\mathrm{s} + \frac{2\pi}{3}) \end{bmatrix} \tag{1.15}$$

where $\theta_\mathrm{s} = \omega_\mathrm{s} \cdot t - \sigma$. θ_s is the electrical angle of the d-q system and σ the angle between the space vector of stator voltage and the d axis.

$$U_\mathrm{d} = U_\mathrm{smax} \cdot \cos(\sigma) = -\sin\vartheta \cdot U_\mathrm{smax} \tag{1.16}$$

$$U_\mathrm{q} = U_\mathrm{smax} \cdot \sin(\sigma) = U_\mathrm{smax} \cdot \cos\vartheta \tag{1.17}$$

where ϑ is the rotor offset. Phasor diagram of a SynRM can now be constructed using equations (1.11) - (1.17) (Fig. 1.7)

1.5 Torque calculation

In order to deduce electromagnetic torque, motor active electrical power must be calculated.

$$P_\mathrm{s} = A \cdot \mathrm{Re}(\mathbf{U}_\mathrm{s} \cdot \mathbf{I}_\mathrm{s}^*) = A \cdot \mathrm{Re}((u_\mathrm{Re} + i \cdot u_\mathrm{Im}) \cdot (i_\mathrm{Re} - i \cdot i_\mathrm{Im}))$$

The voltage is calculated from (1.2) and because $K = \frac{2}{3}$ was chosen in Park transform and A must be inverse, $A = \frac{3}{2}$. After a few calculations: [4]

$$P_\mathrm{s} = \frac{3}{2} \cdot [R_\mathrm{s} \cdot (i_\mathrm{Re}^2 + i_\mathrm{Im}^2) + \omega_\mathrm{s} \cdot (\Psi_\mathrm{Re} \cdot i_\mathrm{Im} - \Psi_\mathrm{Im} \cdot i_\mathrm{Re})]$$

From which

$$\delta P_\mathrm{j} = \frac{3}{2} \cdot R_\mathrm{s} \cdot (i_\mathrm{Re}^2 + i_\mathrm{Im}^2)$$

are Joule losses in stator winding and

$$P_\mathrm{e} = \frac{3}{2} \omega_\mathrm{s} \cdot (\Psi_\mathrm{Re} \cdot i_\mathrm{Im} - \Psi_\mathrm{Im} \cdot i_\mathrm{Re}) \tag{1.18}$$

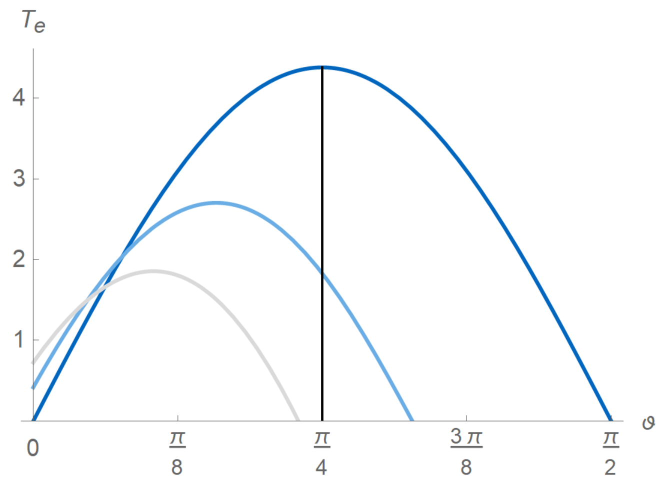


Figure 1.8: Maximum torque as a function of rotor offset

is the motor power in the air gap - mechanical power plus iron losses, which are for the sake of transparency omitted. The real and imaginary parts can now be substituted for d and q components. If equation (1.19) is applied, electromagnetic torque in d-q can be deduced (1.20). [2]

$$P_\mathrm{e} = T_\mathrm{e} \cdot \frac{\omega_\mathrm{s}}{p} \tag{1.19}$$

$$T_\mathrm{e} = \frac{3}{2} p \cdot (L_\mathrm{d} - L_\mathrm{q}) \cdot i_\mathrm{sq} \cdot i_\mathrm{sd} \tag{1.20}$$

Where p is the number of pole pairs. The complex expression for the space vector of stator voltage is

$$\mathbf{U}_\mathrm{s} = R_\mathrm{s} \cdot (I_\mathrm{sd} + i \cdot I_\mathrm{sq}) + i \cdot \omega_\mathrm{s} \cdot (L_\mathrm{d} \cdot I_\mathrm{sd} + i \cdot L_\mathrm{q} \cdot I_\mathrm{sq})$$

Real and imaginary parts are separated and currents I_sd and I_sq calculated and applied to (1.20). Motor saliency ratio α (1.21) and impedance ratio β (1.22) are defined and also applied to (1.20). Torque as a function of saliency ratio and impedance ratio can now be deduced. [2]

$$\alpha = \frac{L_\mathrm{q}}{L_\mathrm{d}} \tag{1.21}$$

$$\beta = \frac{R_\mathrm{s}}{\omega_\mathrm{s} \cdot L_\mathrm{d}} \tag{1.22}$$

$$T_\mathrm{e} = \frac{3}{2} p \cdot \frac{U_\mathrm{s}^2}{\omega_\mathrm{s}^2 \cdot L_\mathrm{d}} \cdot \frac{1-\alpha}{(\alpha+\beta^2)^2} \cdot [(\alpha - \beta^2) \cdot \sin 2\vartheta - 2\beta \cdot (1+\alpha) \cdot \sin \vartheta^2 + 2\alpha \cdot \beta] \tag{1.23}$$

The characteristic for fixed saliency ratio and different impedance ratios as a function of rotor offset can be seen in Fig. 1.8. The rotor offset that corresponds to maximum torque is calculated by partially derivating (1.23) by rotor offset. [2]

$$\vartheta_{\mathrm{T}} = \frac{1}{2}\arctan[\frac{\alpha - \beta^2}{2\beta \cdot (1+\alpha)}] \leq \frac{\pi}{4} \tag{1.24}$$

With lower β, the motor's properties improve. For a specific field generating current, the condition for maximum torque is calculated by partially derivating (1.20) by i_{d}.

$$\frac{i_{\mathrm{dT}}}{i_{\mathrm{qT}}} = \frac{L_{\mathrm{q}}}{L_{\mathrm{d}}} \tag{1.25}$$

Chapter 2

Comparison of qualitative parameters with an induction motor

Induction motors dominate the market for their evident advantages - cost, low maintenance andDOL (direct on line) operation. The most common synchronous reluctance motors have radially laminated rotors, which do not have a squirrel cage for DOL startup and therefore need to be operated by variable frequency drives. This inflicts higher costs on the system, which is why SynRMs are only used for variable speed applications. However, they still have some significant advantages.

2.1 Maximum torque

Equation (1.20) is compared to the equivalent equation of an induction motor (2.1) (definition of L_s and L_sc in [10]) with the same direct axis and quadrature axis current i_sd and i_sq. Higher torque of a SynRM is achieved when the difference of inductances is larger than that of an IM, i.e. the saliency ratio is lower. [2]

$$T_{ea} = \frac{3}{2} p \cdot (L_\mathrm{s} - L_\mathrm{sc}) \cdot i_\mathrm{sq} \cdot i_\mathrm{sd} \tag{2.1}$$

$$L_\mathrm{s} - L_\mathrm{sc} < L_\mathrm{d} - L_\mathrm{q} \tag{2.2}$$

This condition is fulfilled with a suitable rotor design and small air gap. However, due to the lack of mass production and the need for the same shaft heights as induction motors, commercial SynRMs usually don't achieve such low saliency ratios and therefore need to be over-engineered to reach comparable nominal torque.

2.2 Power factor

The power factor of a SynRM is calculated as follows. Losses are omitted.

$$\cos\varphi = \frac{\frac{3}{2}\omega_\mathrm{s} \cdot (L_\mathrm{d} - L_\mathrm{q}) \cdot I_\mathrm{d} \cdot I_\mathrm{q}}{3 \cdot \frac{|\mathbf{U}_\mathrm{s}|}{\sqrt{2}} \cdot \frac{|\mathbf{I}_\mathrm{s}|}{\sqrt{2}}}$$

$$\cos\varphi = \frac{(L_\mathrm{d} - L_\mathrm{q}) \cdot I_\mathrm{d} \cdot I_\mathrm{q}}{\sqrt{(L_\mathrm{d} \cdot I_\mathrm{d})^2 + (L_\mathrm{q} \cdot I_\mathrm{q})^2} \cdot \sqrt{I_\mathrm{d}^2 + I_\mathrm{q}^2}} \tag{2.3}$$

By partially derivating this equation by the ratio $\frac{I_\mathrm{d}}{I_\mathrm{q}}$ and looking for the extreme of this function, the condition for MPF (Maximum power factor) is obtained (2.4). When applied to (2.3), MPF is determined (2.5). [2]

$$\frac{I_\mathrm{dC}}{I_\mathrm{qC}} = \sqrt{\frac{L_\mathrm{q}}{L_\mathrm{d}}} \tag{2.4}$$

$$\cos\varphi_\mathrm{C} = \frac{1 - \frac{L_\mathrm{q}}{L_\mathrm{d}}}{1 + \frac{L_\mathrm{q}}{L_\mathrm{d}}} \tag{2.5}$$

Therefore, lower saliency ratio improves the power factor. However, as with torque, SynRMs currently suffer from insufficiently low ratios and cause a higher inductive load on the power system. By consuming more reactive current, they create a higher load, that the converter must supply, thus the need to over-engineer the converter arises, increasing the cost and size of the drive system.

2.3 Efficiency

SynRMs achieve very high efficiencies, as losses only occur in the stator. Conversely, IMs suffer from high Joule and iron losses in the rotor with increased loads, especially when overloaded. This is caused by increased motor slip, which causes greater difference in stator and rotor frequencies, resulting in higher iron and joule losses in the rotor. SynRMs can be significantly overloaded for a larger period of time without notable losses, apart from the increased temperature of the stator winding.

In consequence of this advantage, weaker SynRMs can be used in applications, which require IMs to be over-engineered, thus decreasing the cost of the drive system.

However, efficiency should not be mistaken for power losses. Low saliency ratio results in lower maximum torque and power factor for comparable shaft sizes of IMs should be considered, as it increases the input cost of the drive system and losses. On the contrary, it offers high efficiencies, which results in quick investment returns.

2.4 Dynamics

The dynamic properties of electric drives are determined mainly by two factors: time constant τ and moment of inertia I. [2]

The time constant is only dependent on the quadrature axis current, as it is the part that affects torque generation in the motor and can cause quick torque changes. [2]

$$\tau = \frac{L_\mathrm{q}}{R_\mathrm{s}} \tag{2.6}$$

Moment of inertia depends on the rotor size and mass. For comparable rotor sizes of SynRMs and IMs, SynRMs generally achieve lower mass, which is caused by the lack of copper and the addition of air gaps. [2]

Chapter 3

Methods of controlling a SynRM

This chapter describes different principles and methods of controlling a synchronous reluctance motor. Firstly, it explains how to achieve a certain behaviour of the drive and then covers two widely used control methods - Field Oriented Control (FOC) and Direct Torque Control (DTC).

3.1 General

In order to achieve high stability during high speeds, control with a constant angle between stator current space vector $\mathbf{I}_\mathrm{s}$ and d-axis is often used. Only the vector size is changed in response to different torque requirements. [2]

The fastest response is achieved by using the criteria of maximum torque (1.25) for a constant field-generating flux Ψ_d. This type of control is used where high dynamic response is required. [2]

Where high dynamics or high stability are not needed, it is possible to use the criteria for maximum power factor (2.4) to reduce stress on the converter. [2]

Rotor position is estimated by measuring inductance in both axes and searching for the largest difference without using a separate sensor. From there, appropriate starting speed and torque can be calculated. [3]

3.2 Field Oriented Control (FOC)

FOC is a control method that regulates the angle and size of the stator current space vector. The measured current is transformed to the d-q system using Park transform and then each component is regulated separately. Different ratios and values affect the way the drive system behaves, so the parameters have to be chosen correctly to optimise drive control. The d-axis current component creates a magnetic field and the q-axis component generates electromagnetic torque. Subsequently, the regulated values are converted back to the abc system and processed by a gate driver which controls the inverter module. The block diagram of FOC with a speed sensor can be seen in Fig. 3.1. [4]

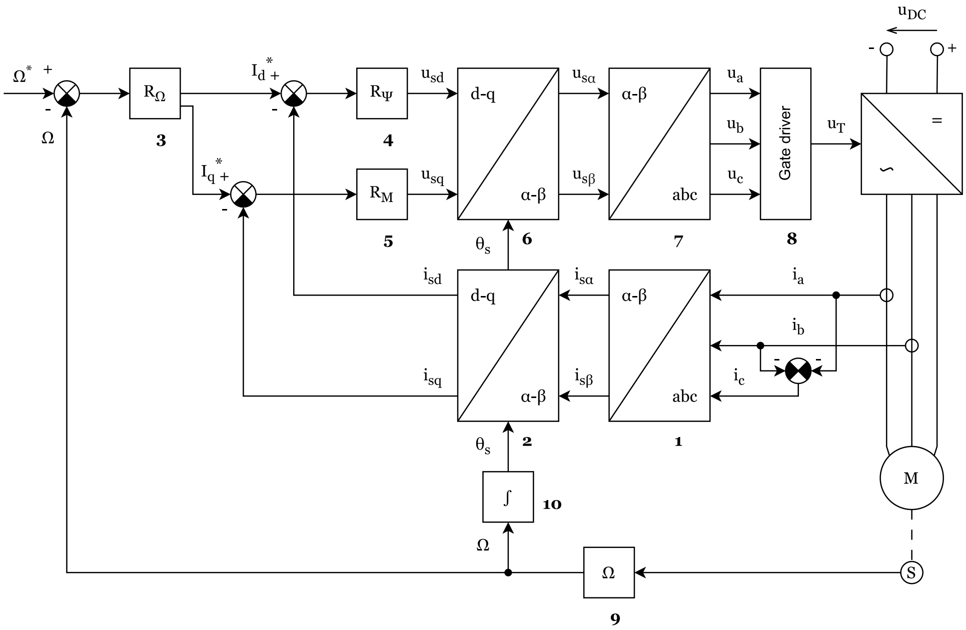


Figure 3.1: Block diagram of FOC

Sensorless vector control calculates angle θ_s from a mathematical model by also measuring stator voltage. It puts higher computational stress on the system, so it is not recommended for applications with uneven load distribution because the dynamic response may not be fast enough and the drive could act unpredictably.

Stator current is measured and transformed to the α-β and d-q system in blocks **1** and **2** respectively. Required field-generating current I_d^* and torque-generating current I_q^* are outputs of the superior regulator of velocity **3**. Regulated voltages from blocks **4** and **5** are inversely transformed back to the abc system in blocks **6** and **7** respectively and lead into the gate driver **8**, which controls semiconductors in the inverter module. Block **9** converts data from a velocity/position sensor to velocity and block **10** integrates it over time to stator d-axis angle. [4]

3.3 Direct torque control (DTC)

In preference to regulating each current component of the d-q system, DTC controls torque directly by changing the position and size of the space vector of stator magnetic flux Ψ_s on a given trajectory. Current and voltage is converted into a stationary system called the α-β system, which is tied to the stator position. Current torque is calculated from the mathematical model of the motor and converted values of voltage, current and flux. According to (3.1), the flux Φ_s position difference has the same direction (aside from a small difference caused by stator current) as the stator voltage U_s difference, and is proportional to time difference. Therefore, trajectory and size of magnetic flux and its rotational speed can be controlled by a switching sequence of the

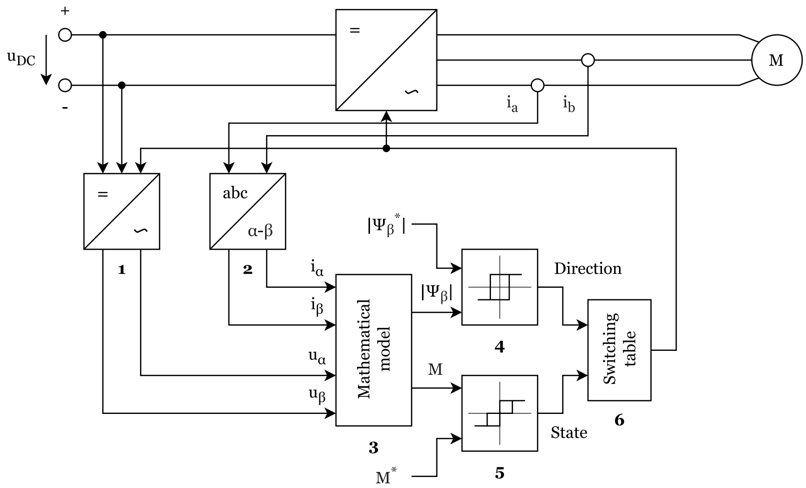


Figure 3.2: Block diagram of DTC

inverter module, enabling direct torque control, as the name suggests. The block diagram of DTC can be seen in Fig. 3.2. [4]

$$\Delta \boldsymbol{\Psi}_{\mathrm{s}} = (\mathbf{U}_{\mathrm{s}} - R_{\mathrm{s}} \cdot \mathbf{I}_{\mathrm{s}}) \cdot \Delta t \tag{3.1}$$

Magnetic flux Ψ_β and torque is calculated from the mathematical model **3** of the motor - voltage is obtained from the DC link voltage and known switching state of the inverter, and currents are measured and converted to the α-β system. If the actual flux Ψ_β is smaller than the required value Ψ_β^*, the current switched state is held. Otherwise, the next switching state is activated - realised by block **4**. Torque is maintained in a certain range by switching active and passive states if the actual torque is smaller than required and vice versa - block **5**. The torque band range is determined by the switching frequency. [4]

Chapter 4

Description of components used

The assembled workstation consists of three core objects - the drive, a PLC and an HMI panel. The drive is responsible for motor control based on set parameters and setpoints communicated from the master system, which in this case is the PLC. The operator sets inputs and reads outputs via an appropriate interface - HMI panel. All components must be correctly chosen to ensure compatibility of the whole system. For this reason, every component is shortly described in this chapter. For the list of components, see table 4.1.

4.1 Drive

The SINAMICS S120 is part of the SINAMICS drive family from Siemens. It is a universal modular drive system for high-performance applications and

Article number	Description
6SL3040-1MA01-0AA0	Control unit
6SL3054-0FB10-1BA0	Compactflash card
6SL3055-0AA00-2TA0	Terminal board
6SL3055-0AA00-4BA0	Basic operator panel
6SL3060-4AK00-0AA0	Drive-cliq cable 0.31 m
6SL3060-4AU00-0AA0	Drive-cliq cable 0.6 m
6EP1333-3BA10	Power Supply
6SL3130-7TE23-6AA3	Active line module
6SL3100-0BE23-6AB0	Active interface module
6SL3120-1TE24-5AC0	Motor module
6FX5008-1BB41-1BF0	Power cable
6SL3055-0AA00-5CA2	Sensor module
6SL3060-4AW00-0AA0	Drive-cliq cable 1.2 m
6FX5002-2CA12-1BF0	Signal cable
1FP1014-1DB42-1AK4-ZG11+L05,	Synchronous reluctance motor
6ES7511-1TK01-0AB0	PLC CPU
6AV2128-3QB06-0AX1	Operator panel

Table 4.1: List of components

can be used as a single-axis or multi-axis drive designed for higher motion control.

These units are capable of, among many others, the following functions:

- Vector, Servo, V/f control
- Closed-loop and open-loop control
- Positioning
- Integrated safety functions
- Regenerative feedback

I will be using the multi-axis system (S120 Booksize series), which uses each drive part as a separate, centrally controlled unit. Each of these units have to be configured and commissioned separately, as they include a variety of functions which will be discussed in later chapters. They are connected using Drive-cliq communication interface specially designed for drives. [5]

4.1.1 Control unit

The Control unit (CU in short) is responsible for drive control and communication with other units or devices. It is also used to commission the drive as a whole. Every CU must contain a sufficient number of I/O and communication ports.

For this application, I am using the SINAMICS S120 CU320-PN Control unit - article number 6SL3040-1MA01-0AA0. For the operation of the CU, a CompactFlash card and operator panel are mandatory. The CF card contains the drive firmware - article number 6SL3054-0FB10-1BA0.

4.1.2 Active line module

The active line module (ALM) is an actively pulsed regulated rectifier/regenerative unit for four-quadrant operation that generates a controlled DC link voltage using pulse-width modulation. Permissible fluctuations on the line voltage have no effect on the motor voltage. It comprises of a self-commutated IGBT inverter, which operates on the supply system via an Active interface module. [6]

I am using an ALM with article number 6SL3130-7TE23-6AA3 - Input: 3AC 380-480 V, 50/60 Hz; Output: DC 600 V, 60 A; Power 36 kW; Internal air cooling

4.1.3 Active interface module

The active interface module (AIM) is mandatory for the use of an ALM. It contains a clean power filter, which protects the power supply from switching-frequency harmonics and smooths the current to a sinusoidal wave. Interference suppression to ensure compliance with category C3 and cosφ control is

also present.
[6]

I am using an AIM - article number 6SL3100-0BE23-6AB0 - For 36 kW ALM; Input/Output: 3AC 380-480 V, 50/60 Hz; Internal air cooling

4.1.4 Motor module single-axis

The motor module (MM) is an inverter unit. It uses the DC link voltage to generate a variable-voltage and variable-frequency signal to supply a 3-phase motor. Motor modules contain IBGTs as power semiconductors and operate using pulse-width modulation. Two variants are available - single/double motor module to control one or two motors at a time. [6]

Motor module used for my application: 6SL3120-1TE24-5AC0 - Single motor module; Input: DC 600 V; Output: 3AC 400 V, 45 A; Internal air cooling; Optimized pulse sample and support of the extended safety integrated functions

4.1.5 Sensor module cabinet-mounted

The sensor module cabinet-mounted (SMC) is used to evaluate encoder signals and in some cases motor temperature. [5]

My application uses a SMC30 - article number 6SL3055-0AA00-5CA2 - evaluation of HTL/TTL, SSI encoders and PTC, KTY-84, Pt1000 and PTC temperature sensors.

4.1.6 Encoder

Encoders are used to evaluate the speed or position of a motor. I am using the Sendix HTL 5020 incremental encoder with A, B, R tracks, provided with the motor as option G11.

4.1.7 Terminal board

The TB30 terminal board provides additional I/O ports to a control unit - article number 6SL3055-0AA00-2TA0.

4.1.8 Basic operator panel

The basic operator panel (BOP) can be used for setting parameters, reading diagnostic information and faults - article number 6SL3055-0AA00-4BA0.

4.2 Other hardware components

4.2.1 Power supply

The power supply is connected to line voltage and supplies other hardware components with stabilized DC voltage. [7]

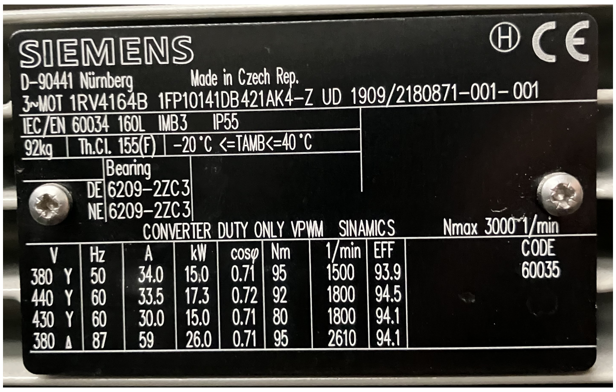


Figure 4.1: Synchronous reluctance motor rating plate

SITOP PSU200M (article number 6EP1333-3BA10) can be connected to both single-phase or 3-phase (2-phase) line networks up to 500 VAC. It supplies stable DC voltage and can withstand high fluctuations in supply voltage and has integrated safety functions. Input: 120/230-500 V AC; Output: 24 V DC/5 A

4.2.2 PLC

A programmable logic computer (PLC) is an industrial PC used for controlling manufacturing processes. For that reason, I/O ports are used. Communication with other devices is achieved via communication protocols such as Profinet, USS, Modbus and Profibus etc. [8]

I use the CPU 1511T-1PN (article number 6ES7511-1TK01-0AB0) in this application because of its specialised motion control functions. Work memory 225 KB for program and 1 MB for data, 1st interface: PROFINET IRT with 2-port switch, 60 ns bit performance.

4.2.3 HMI panel

The HMI panel is a monitoring/control device used to connect a user to a system in the form of a screen or tablet. [9]

The panel used in my application: SIMATIC HMI MTP1500, Unified Comfort Panel, touch operation, 15.6" widescreen TFT display, 16 million colours and a PROFInet interface. Article number: 6AV2128-3QB06-0AX1

4.3 Synchronous reluctance motor

The principle workings of a synchronous reluctance motor is explained in chapter 1. This part only describes the specific motor used.

This motor is from the SIMOTICS GP/SD VSD4000 line motor series from Siemens and was developed for converter operation with a focus on high dynamic performance. For motor rating plate, see Fig. 4.1.

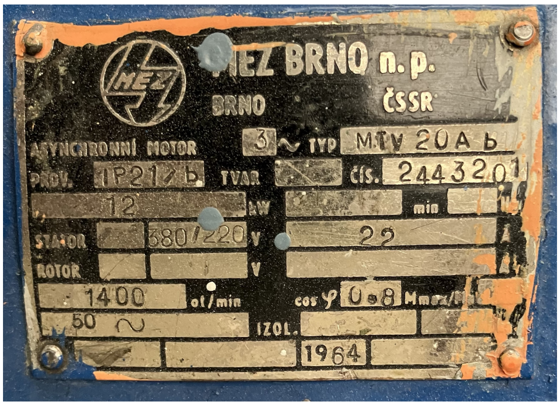


Figure 4.2: Induction motor rating plate

4.4 Induction motor

The induction motor used is a part of a Ward Leonard system and is about 60 years old. Moreover, the motor values that are punched out on the rating plate are suspected of being incorrect because testing shows different results. For motor rating plate, see Fig. 4.2

Chapter 5

Connection diagram

Every component must be properly wired to the supply system and other devices if needed. Connection diagrams are given in the respective catalogues (refer to bibliography) and for greater detail in manuals. Communication is connected with cables appropriate for the type of interface.

5.1 Power connection

Power connection can be seen in Fig. 5.1. It consists of a 24 V supply system for electronics, a three-phase 400 VAC power system and other wiring.

5.2 Communication topology

Communication topology can be seen in Fig. 5.2.

5.3 Encoder and temperature sensor connection

Encoder and temperature sensor connection can be seen in table 5.1. This table only shows used pins, others have been omitted.

Conn.	Pin	Designation	Technical data	Cable clr.
X521	1	A	Incremental signal A	Yellow
X521	2	A*	Inverse incremental signal A	Green
X521	3	B	Incremental signal B	Black
X521	4	B*	Inverse incremental signal B	Brown
X521	5	R	Reference signal R	Blue
X521	6	R*	Inverse reference signal R	Purple
X531	1	P Encoder 24V	Encoder power supply	Black/white
X531	2	M Encoder	Ground, encoder power supply	Yellow/white
X531	3	-Temp	PT1000 temperature sensor	Separate
X531	4	+Temp	PT1000 temperature sensor	Separate

Table 5.1: Encoder connection

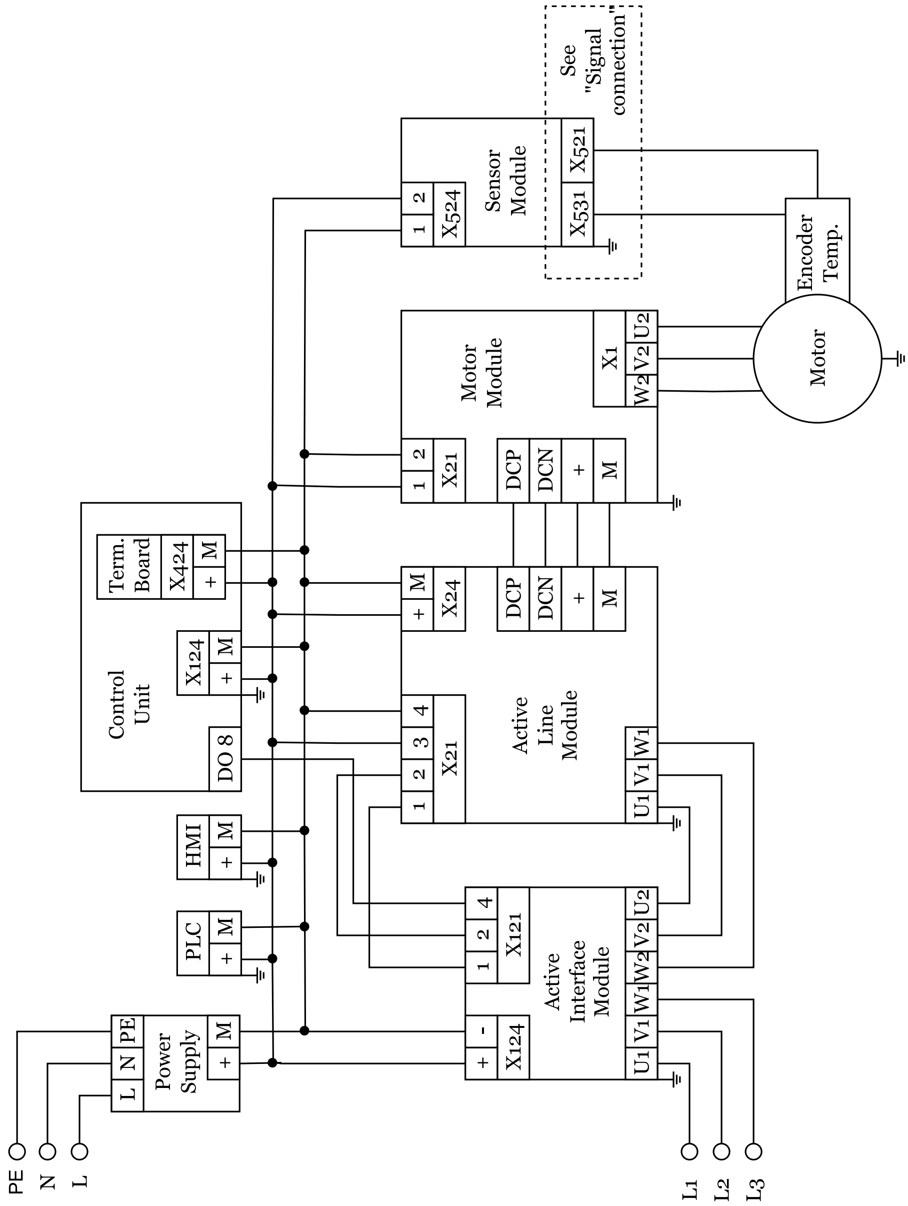


Figure 5.1: Power connection

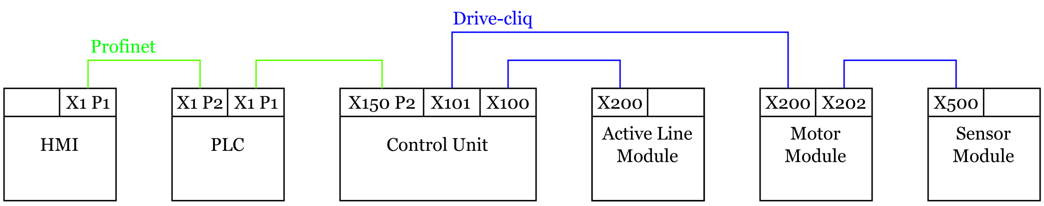


Figure 5.2: Communication topology

Chapter 6

User program in TIA Portal

Each device was configured and commissioned in TIA Portal V18, which integrates multiple tools for the digitalisation of automation services e.g. STEP7 to create programs in PLCs, Simatic WinCC for visualisation, Startdrive to commission drives, etc.

6.1 Device configuration

After creating a project in TIA Portal, each device has to be selected and added to the Devices & networks section. To ensure that the devices are compatible with their counterpart, correct firmware versions have to be selected. In my case, it is V5.2.3 for the drive CU, V2.8 for the PLC and V17.0.0.0 for the HMI panel. If the firmware version is not known, it can be checked in Online access under Diagnostics. When all devices are selected, they must be connected with an appropriate communication interface connection in the same subnet and subnet mask. Subsequently, IP addresses and device names of each device have to be selected. The chosen ports, IP addresses, device names and subnet in the project must align with the physical setting. They can be directly configured in the device in Online access under Functions. Here, the master is the PLC and other devices are slaves. The device configuration network overview for this project can be seen in Fig. 6.1.

6.2 Drive configuration

As was explained in chapter 4, the S120 booksize drive system is formed from multiple modules, which communicate with each other using a special communication interface designed for Siemens drives, Drive-cliq. The psychical layer of Drive-cliq is Ethernet, but it has specially designed connectors to secure data flow without interference, even in close proximity to power cables. Moreover, the communication protocol is adjusted to ensure quick data transfer with other modules or measuring systems. For encoders and temperature sensors designed for Drive-cliq, the cables can carry supply cables too.

Each module is selected from the hardware catalogue and drag-dropped

Device	Type	Address in subnet	Subnet
SINAMICS S_1	SINAMICS S		
Drive unit_1	CU320-2 PN		
PROFINET interface	PROFINET interface	192.168.0.1	PN/IE_1
Ethernet commissio...	Ethernet commissionin...	169.254.11.22	Not connected
DRIVE-CLiQ interface	DRIVE-CLiQ interface		
S7-1500/ET200MP station_1	S7-1500/ET200MP stati...		
PLC_1	CPU 1511T-1 PN		
PROFINET interface_1	PROFINET interface	192.168.0.3	PN/IE_1
HMI_2	MTP1500 Unified Comf...		
HMI_RT_2	MTP1500 Unified Comf...		
HMI_2.IE_CP_1	PROFINET Interface		
PROFINET Interface_1	PROFINET Interface	192.168.0.2	PN/IE_1
HMI_2.IE_CP_2	PROFINET Interface		

Figure 6.1: Device configuration network overview

into the graphical overview page, where they are appropriately laid out and connected. The project must align with the physical connection, otherwise faults will occur. Order numbers have to be specified in the selection panel afterwards. Sensor modules and motors are assigned to their corresponding motor modules, which represent individual drive axes. In the case of this project, two motors are selected for a single motor module because they can be freely switched out. Drive object type of the MM must be selected as universal (vector), otherwise appropriate motor types won't be available. The drive system configuration can be seen in Fig 6.2 and 6.3.

6.2.1 Parametrization

After selection is complete, every module has to be separately set up. This is achieved by selecting parametrization of a certain drive object in the left panel. Each module has a number of functions that can be activated and set up. But for the purposes of this thesis, only used functions will be described.

Drive control represents the Control unit. The only change will be to the I/O ports - Bidirectional digital input/output 8 is set as an output, which is connected to the AIM and controls the internal fan, see Fig. 5.1. p738 of Drive control is connected to source r2091.0, which is a PROFIdrive source. Communication will be explained in a later section.

Infeed represents the rectifier unit of the converter, i.e. the ALM. Factory setting for this object is sufficient, but after the first download, the infeed commissioning parameter filter must be set as ready via parameter view. p10 must be changed to [0] Ready.

Drive Axis represents a single driven axis and corresponds to a MM, in case of a double MM - two drive axes are created. This object defines motor data, control type, limitations, setpoints, ramp-function generator, drive and technology functions, safety integrated etc. Firstly, in Data sets, create a second drive data set and assign the second motor data set to the drive data set. The motor data sets were automatically created when individual motors were added. This way, each drive data set corresponds to a different motor, which can be freely switched when needed. The following settings of Drive

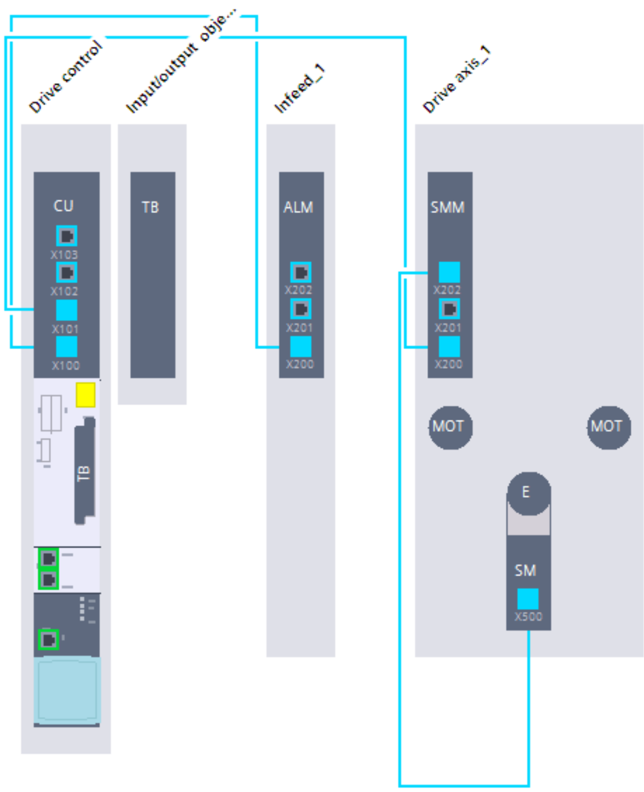


Figure 6.2: Drive configuration overview - graphical

axis apply to both data sets:

- Function modules: set Speed/torque control
- Control type: [21] Speed control (with encoder)
- Reference parameters: to make processing data later easier, set the reference parameters the same for both motors (it is better to choose the motor with higher nominal values, table 6.1)
- Optimizations: Motor data identification as [2] Identify motor data at standstill - must be manually set as [0] after first download
- Actual value processing: both motors use the same encoder, so fine resolution for both data sets G1_XIST1 is 11 bit

Limitations for each motor are calculated separately. Then under Drive functions -> Messaged / monitoring -> Motor temperature, appropriate sensor monitoring and type must be selected for each data set. Temperature of the SynRM is measured by a Pt1000 resistance sensor via SMC and the IM does not have a temperature sensor.

Module	...	Type	Article no	Drive object ..	Firmw..
Drive control				1	
Drive unit_1		CU320-2 PN	6SL3040-1MA01-0Axx	1	V5.2.3
Input/output object_1				2	
Terminal Board_1		Terminal Board TB30	6SL3055-0AA00-2Txx	2	
Infeed_1				3	
Line Module_1		Active Line Module Booksize	6SL3130-7TE23-6Axx	3	
Drive axis_1				4	
Motor Module_1		Single Motor Module Booksize C/D types	6SL3120-1TE24-5ACx	4	
Encoder evaluation_1		Sensor Module Cabinet SMC30	6SL3055-0AA00-5Cxx	6	
Measuring system_1		HTL/TTL encoder	XExxxxx-xxxxx-xxxx	5	
Motor_1		1FP1 standard reluctance motor	1FP1x14-1DB42-1xxx	7	
Motor_2		Induction motors	XMxxxxx-xxxxx-xxxx	8	

Figure 6.3: Drive configuration overview - table

6.2.2 Communication with the PLC

Communication between the drive and PLC is implemented using PROFIdrive, an application profile from PROFIBUS and PROFINET International (PI) and is focused on drives. Data is exchanged cyclically or acyclically in the form of Telegrams. Telegrams consist of a configurable sequence of control/status words that can be sent and received by the drive. Each drive unit has a standardised Siemens telegram with predefined data sequences that comply with function blocks in the PLC program from Siemens motion control libraries, which in most cases eliminates the need to manually set up communication. If more values are needed, additional Free telegrams can be added to the Drive axis telegrams as an extension. The list of used telegrams with their respective addresses can be seen in Fig. 6.4.

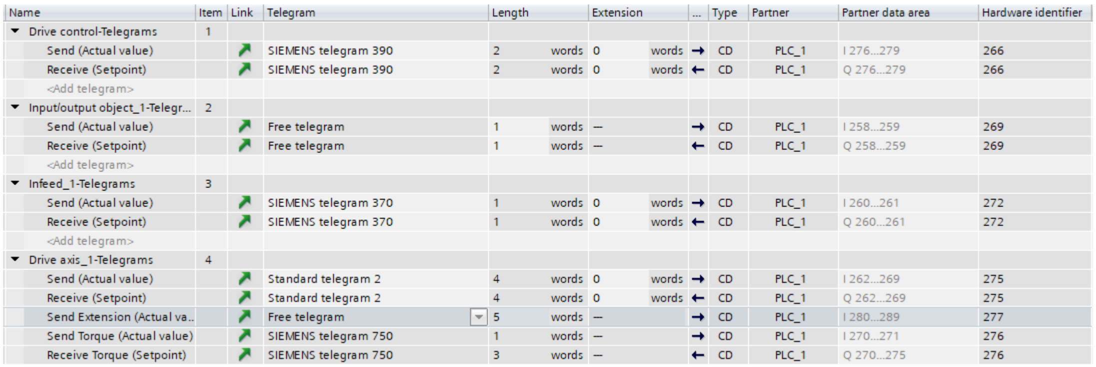
The aforementioned AIM fan control is sourced from one of the control words of telegram 390 of the Drive control object and is controlled via HMI panel. In the same way, drive data set sellection bit 0 p820[0] is sourced from r2091.9 (of Telegram 390). It was originally sourced via telegram 2 of the Drive axis object, but since it is directly controlled by a Technology object (later section), it could not be accessed, therefore, it was reconnected to another telegram.

By setting up control via telegrams, many sources for drive parameters are automatically changed to accommodate this type of control. The affected parameters correspond to predefined telegram structures and are a part of control/status words of the selected telegram.

In order to process more values, a 5-word telegram extension was added.

Number	Parameter text	Value	Unit
p2000	Ref. speed	1500.00	rpm
p2002	Ref. current	49.58	Arms
p2003	Ref. torque	190.99	Nm
p2004	Ref. power	30.00	kW
p2007	Ref. acceleration	25.00	rev/s^2

Table 6.1: Configured drive parameters



Name	Item	Link	Telegram	Length	Extension	...	Type	Partner	Partner data area	Hardware identifier
Drive control-Telegrams	1									
Send (Actual value)			SIEMENS telegram 390	2 words	0 words	→	CD	PLC_1	I 276...279	266
Receive (Setpoint)			SIEMENS telegram 390	2 words	0 words	←	CD	PLC_1	Q 276...279	266
<Add telegram>										
Input/output object_1-Telegr...	2									
Send (Actual value)			Free telegram	1 words	—	→	CD	PLC_1	I 258...259	269
Receive (Setpoint)			Free telegram	1 words	—	←	CD	PLC_1	Q 258...259	269
<Add telegram>										
Infeed_1-Telegrams	3									
Send (Actual value)			SIEMENS telegram 370	1 words	0 words	→	CD	PLC_1	I 260...261	272
Receive (Setpoint)			SIEMENS telegram 370	1 words	0 words	←	CD	PLC_1	Q 260...261	272
<Add telegram>										
Drive axis_1-Telegrams	4									
Send (Actual value)			Standard telegram 2	4 words	0 words	→	CD	PLC_1	I 262...269	275
Receive (Setpoint)			Standard telegram 2	4 words	0 words	←	CD	PLC_1	Q 262...269	275
Send Extension (Actual va...			Free telegram	5 words	—	→	CD	PLC_1	I 280...289	277
Send Torque (Actual value)			SIEMENS telegram 750	1 words	—	→	CD	PLC_1	I 270...271	276
Receive Torque (Setpoint)			SIEMENS telegram 750	3 words	—	←	CD	PLC_1	Q 270...275	276

Figure 6.4: Telegrams

See table 6.2.

6.2.3 Torque control

Torque control isn't implemented by directly switching control types but by applying torque limiting to standard vector speed control. That way, it is impossible to overshoot the torque setpoint and spin the motor out of control because the speed setpoint essentially becomes a speed limiter for torque control; since the speed regulator is still superior to the torque regulator. When a torque limit is applied, the speed adjusts to comply with the limit. Torque control with a speed limiter is achieved.

By activating the supplementary torque telegram 750 to Drive axis telegrams, in Parametrization -> Open-looped/closed loop control -> Torque limiting, upper and lower torque limits are sourced from the control words of this telegram. The upper torque limiter chooses the minimum from this value and a predefined maximum torque p1520[0] and uses it as the set limit. The same applies to the lower torque limiter.

In order to bypass faults occurring from reaching the torque limit, parameter p2144[0] must be activated.

Source	Text	Data type
r27	Absolute actual current smoothed	Double word
r35	Motor temperature	Word
r82[2]	Active power actual value, Electric power	Word
r32	Active power actual value smoothed	Word

Table 6.2: Telegram extension

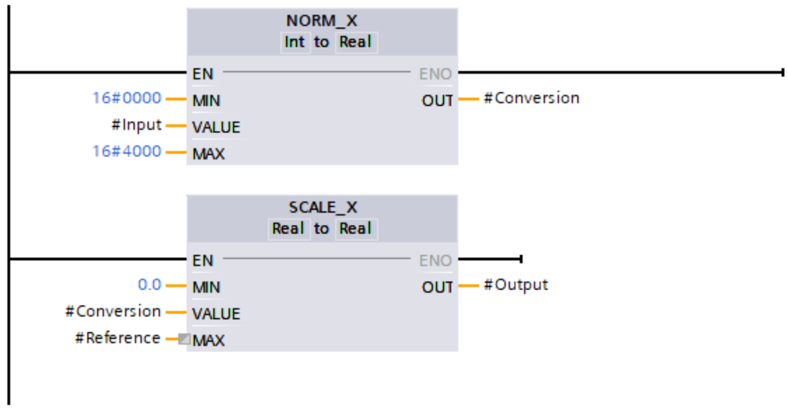


Figure 6.5: Data type conversion - example

6.3 PLC program

6.3.1 Data type conversion

In order to read and write data to the drive via telegrams, data type conversions are necessary since the values are typically exchanged in the form of words or double words. This process is repeated for multiple values, so function blocks are created for this purpose. Function blocks are created by adding a block to Program blocks and selecting Function blocks. Input, output and static variables are then defined and connected to the appropriate block ports. Firstly, the value is normalised in the range from 0 to 1 while being converted to a Real data type. Then, it is scaled using an appropriate reference value (see Fig. 6.1). An example of a conversion function can be seen in Fig.. 6.5 - Word to Real. A positive Word value scales from 0x0000 to 0x4000. A similar approach is done for other type conversions. Note: negative Word values scale from 0x8000 to 0xC000 from 0 to negative values (in Real format). Converted values are further processed or displayed via HMI.

6.3.2 Technology object (TO)

Technology objects act as an interface between hardware and software. In motion control applications, they map a physical drive in the controller and issue commands to the drive by means of the user program from motion control instructions. For the purposes of this thesis a Speed axis TO was selected. In the configuration, the desired telegram of the respective drive unit is selected. Then, dynamic defaults and limits are set. In this case, telegram 2 of the Drive axis was selected with dynamic defaults and limits set per table 6.3. Other settings can stay set as default. The use of a technology object is explained further.

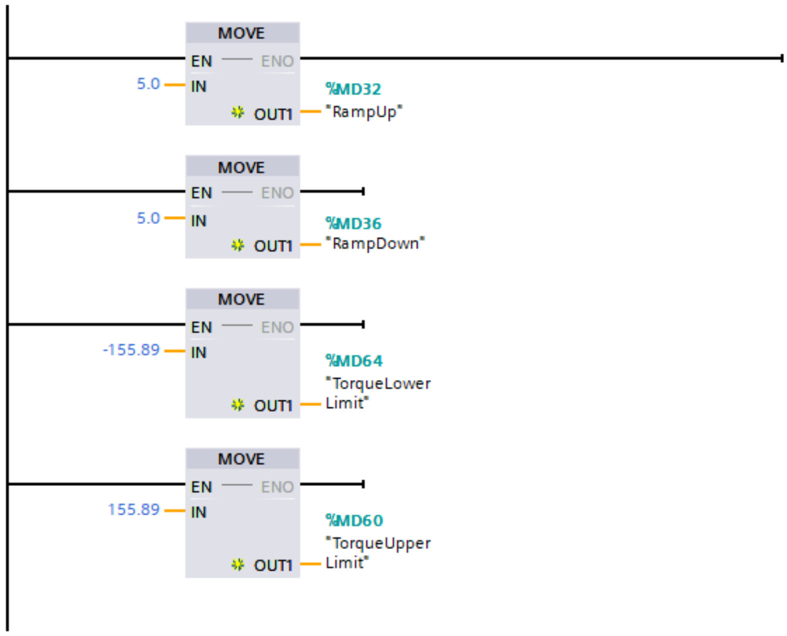


Figure 6.6: Startup sequence

6.3.3 Startup

To avoid early faults, essential values are defined during startup. By adding a new block and selecting Organisation block -> Startup, a block that runs only a single time during startup is created. The program can be seen in Fig 6.6. The meaning of each value is evident from the tag name.

6.3.4 Motion control

All subsequent sections of the PLC program are a part of the Main Organisation block and are cyclically repeated indefinitely. The first topic are Motion control function blocks, which are linked to a certain TO and used to control a physical drive through a telegram specified during the configuration of a TO. To enable drive control, function block MC_POWER is used. It powers up the drive and outputs the required frequency and voltage. However, in this case, the drive is only switched to standby mode without a speed setpoint.

Section	Name	Value	Unit
Defaults	Speed	1500.0	1/min
Defaults	Ramp-up time	5.0	s
Defaults	Ramp-down time	5.0	s
Limits	Speed	3000.0	1/min
Limits	Ramp-up time	0.1	s
Limits	Ramp-down time	0.1	s

Table 6.3: Dynamic defaults and limits of the TO

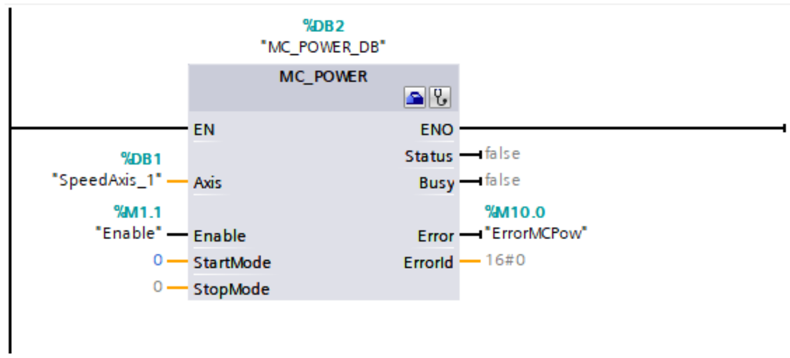


Figure 6.7: MC_POWER function block

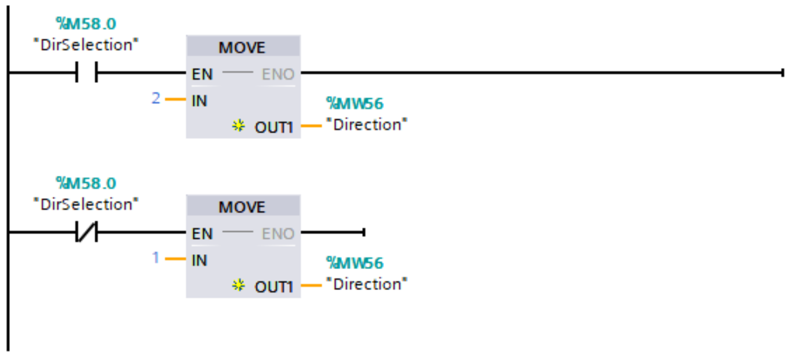


Figure 6.8: Direction of rotation

The block can be seen in Fig. 6.7, description of used inputs and outputs are in table 6.4, and others are irrelevant for this application.

The next function block is MC_MOVEVELOCITY. It is used to set the speed setpoint of the motor as well as to specify ramp times or acceleration values. Direction of rotation is determined by switching a single bit, which changes the value of a tag that represents direction. See Fig. 6.8. Acceleration is calculated from speed and ramp times using equation (6.1), deceleration is calculated similarly. Reference speed (1500 1/min or 25 1/s) is always used to keep acceleration and deceleration constant for required ramp times. The program can be seen on Fig. 6.9, MC_MOVEVELOCITY on Fig. 6.10, and port descriptions in table 6.5.

$$Acceleration = \frac{Speed}{Ramp\ up\ time} \tag{6.1}$$

Type	Parameter	Description
Input	Axis	Specifies the respective TO
Input	Enable	Switches the drive into ON mode
Output	Error	True - An error occurred in this instruction

Table 6.4: Description of used ports of MC_POWER function block

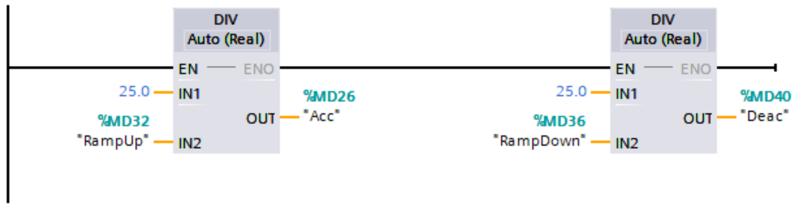


Figure 6.9: Acceleration and deceleration calculation

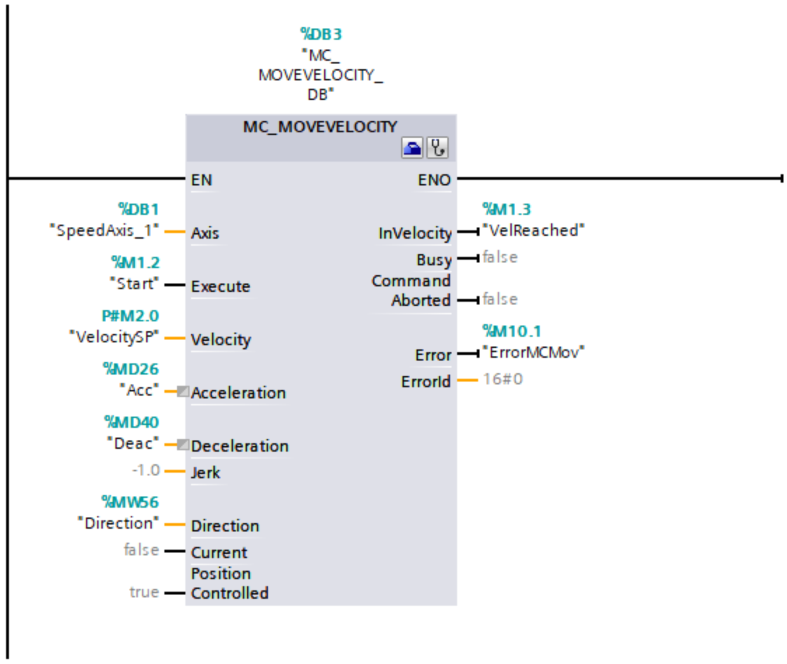


Figure 6.10: MC_MOVEVELOCITY function block

In order to acknowledge faults and restart the drive, block MC_RESET is used. The restart input has two functions when executed:

- True - Reinitialization of the drive and acknowledgement of pending faults and alarms.

Type	Parameter	Description
Input	Axis	Specifies the respective TO
Input	Execute	Sets the speed setpoint
Input	Velocity	Speed setpoint value
Input	Acceleration	Acceleration value
Input	Deceleration	Deceleration value
Input	Direction	1 - clockwise, 2 - counter-clockwise
Output	InVelocity	True - Speed setpoint reached
Output	Error	True - An error occurred in this instruction

Table 6.5: Description of used ports of MC_POWER function block

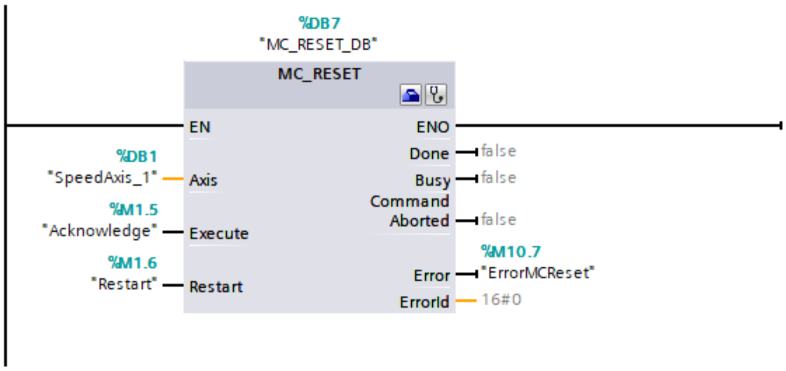


Figure 6.11: MC_RESET function block

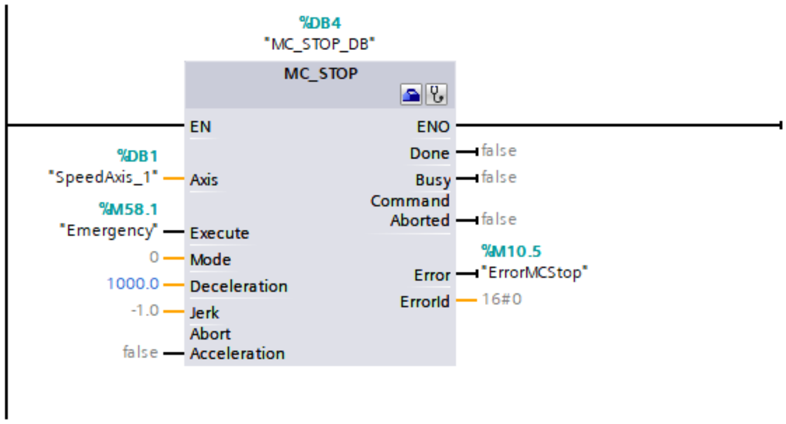


Figure 6.12: MC_STOP function block

- False - Acknowledgement of queued drive faults and alarms.

The block can be seen on Fig. 6.11.

An MC_STOP block is used to stop all movements of an axis and prevent new motion jobs for the drive. The axis brakes to a standstill and remains switched on. In mode 0, the dynamic response of the braking operation is determined by the configured emergency stop ramp, see Fig. 6.12.

The last drive control block is SinaInfeed from the SINAMICS library. The Sinamics S120 infeed control is not integrated into the TO and must be handled separately. It controls and evaluates the infeed unit via standard telegram 370. The precharging circuit must be activated first, and after a ready signal on the output, the infeed may be activated. This procedure is universal for infeed units of all sizes, even for units without a precharging circuit, in which case, the infeed may be activated immediately after enabling the precharging circuit. The block can be seen on Fig. 6.13 and port description is in table 6.6.

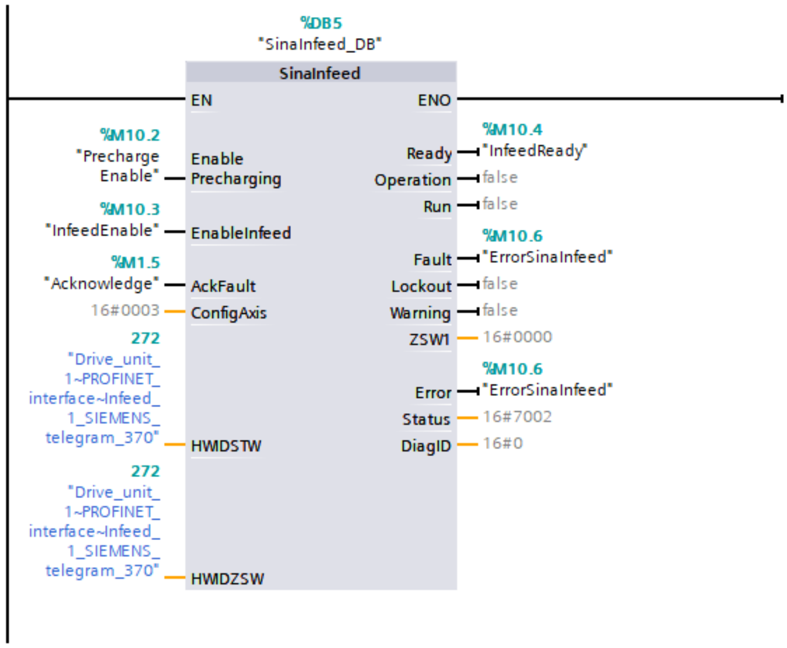


Figure 6.13: SinaInfeed function block

6.3.5 Drive data processing

In order to calculate important values such as efficiency and power utilisation, appropriate parameters must be read from the drive and converted to a readable data type - Real. Using the function blocks explained in section 6.3.1, torque, temperature, current and electrical power are read from the drive via their corresponding telegrams and addresses. An example of such a process can be seen on Fig. 6.14. Mechanical power is calculated with measured torque and speed. From that, power utilisation can be calculated too. Nominal mechanical power is determined in a similar way to rotation direction, but using the drive data set selection bit, see Fig. 6.15. Efficiency is calculated from electrical and mechanical power, see Fig. 6.16. Current and temperature are displayed as is.

Type	Parameter	Description
Input	EnablePrecharging	Precharge infeed
Input	EnableInfeed	Switch on infeed
Input	AckFault	Acknowledge faults
Input	HWIDSTW	Hardware identifier, setpoint slot
Input	HWIDZSW	Hardware identifier, actual value slot
Output	Ready	True - Ready to be switched on
Output	Error and Fault	True - Error infeed

Table 6.6: Description of used ports of MC_POWER function block

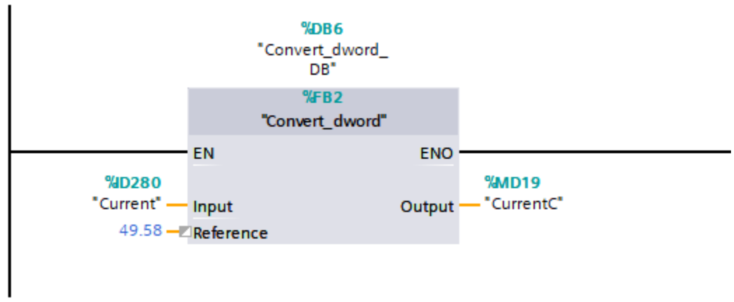


Figure 6.14: Reading drive parameters

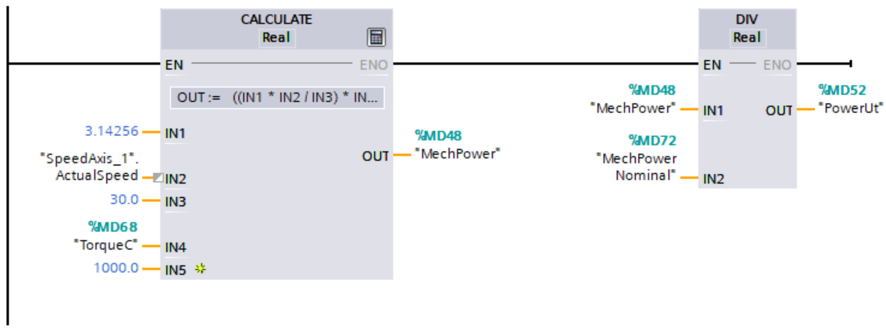


Figure 6.15: Mechanical power and power utilisation calculation

6.3.6 Torque limiting

Torque limiting is allowed only when the enable bit is activated. Otherwise standard torque limits are applied. The program works in such a way that when the limits are changed, depending on the enable bit, the values are either changed before sending or remain unchanged. The enable bit is sent to the drive via telegram and affects p2144[0] directly. See Fig. 6.17. Before the new limits are sent, they must be converted back to Word using the aforementioned conversion function blocks. See Fig. 6.18.

6.3.7 Error handling

Since every fault leads to the same process of acknowledgement, all faults are connected to a common output and handled together at one time. Acknowledgement is achieved by activating the Restart input of the MC_RESET function block and AckFault of the SinaInfeed block. If needed, maintenance must be done directly via TIA Portal.

6.4 HMI program - visualisation

The HMI panel is connected to the PLC via the PROFInet interface, which must be established as a partner in Connections. This way, an HMI tag can be linked to a PLC tag and then directly affect it - it works in both

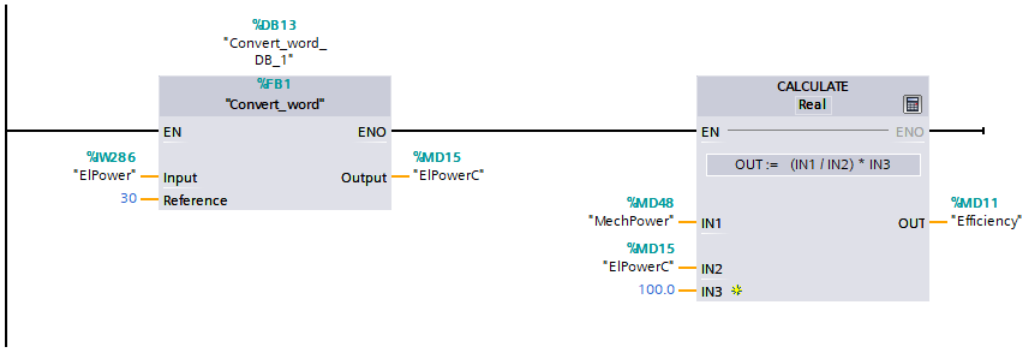


Figure 6.16: Efficiency calculation

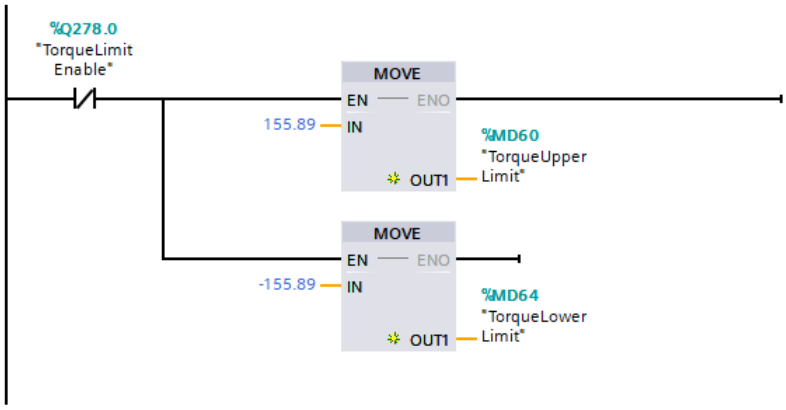


Figure 6.17: Torque limit determination

directions. If an HMI button changes it's state, the corresponding tag in the PLC changes too, thus creating a control interface for the system. The control elements consist of different input and output objects such as switches, buttons, gauges and IO fields etc. Each part of the control panel is further explained.

The first part is MOTOR SPEED, which is just a gauge that shows the motor speed in both directions. Even though the maximum speed of the motors is about 3000 rpm, 2000 rpm is chosen for the margin of error.

MAIN CONTROL includes all controls for switching the drive, or separate modules, on and off. Precharging activates the precharging circuit. Once the DC link is ready, a green light will appear to indicate that the infeed may be enabled too. Drive control is activated last by switching 'Enable axis' and the drive enters standby. To reduce noise when the drive is not operated, an AIM internal fan can be turned off. Switch motor type changes the drive data set to control the corresponding motor - the button changes colour, blue corresponds to SynRM and green to IM.

In SETPOINT, motor speed setpoint is selected using the sliding bar. Every new setpoint must be confirmed by pressing Start. Instead of having a long slider to encompass both negative and positive setpoints, direction is chosen by pressing Change direction. In case an emergency stop is needed,

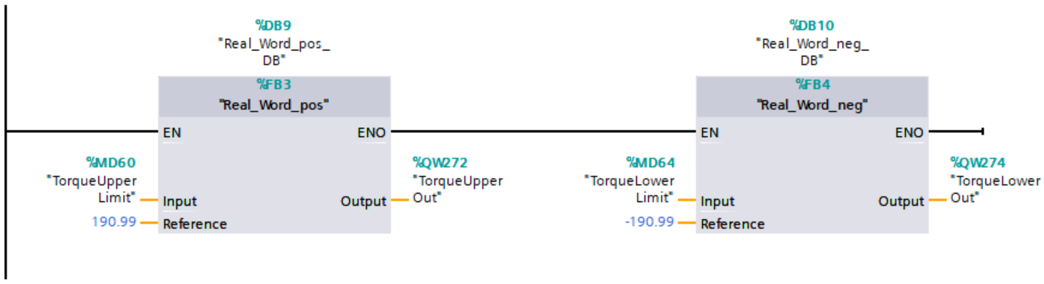


Figure 6.18: Torque limit conversion

pressing 'Stop' brakes the motor to a standstill in 0.1 s.

Important drive parameters and calculated values are displayed in the DIAGNOSTICS section.

New torque limits can be set in LIMITS. If they are not enabled, standard torque limits are applied, as explained in previous chapters. The lower (negative) torque limit must be entered with a "-" sign, otherwise drive faults may occur.

MAINTENANCE shows any active faults, which can be deleted by pressing 'Acknowledge faults'. To restart the drive, both 'Acknowledge faults' and 'Restart' must be pressed at once.

Ramp times are specified in the last block.

The whole design of the control panel can be seen on Fig. 6.19.

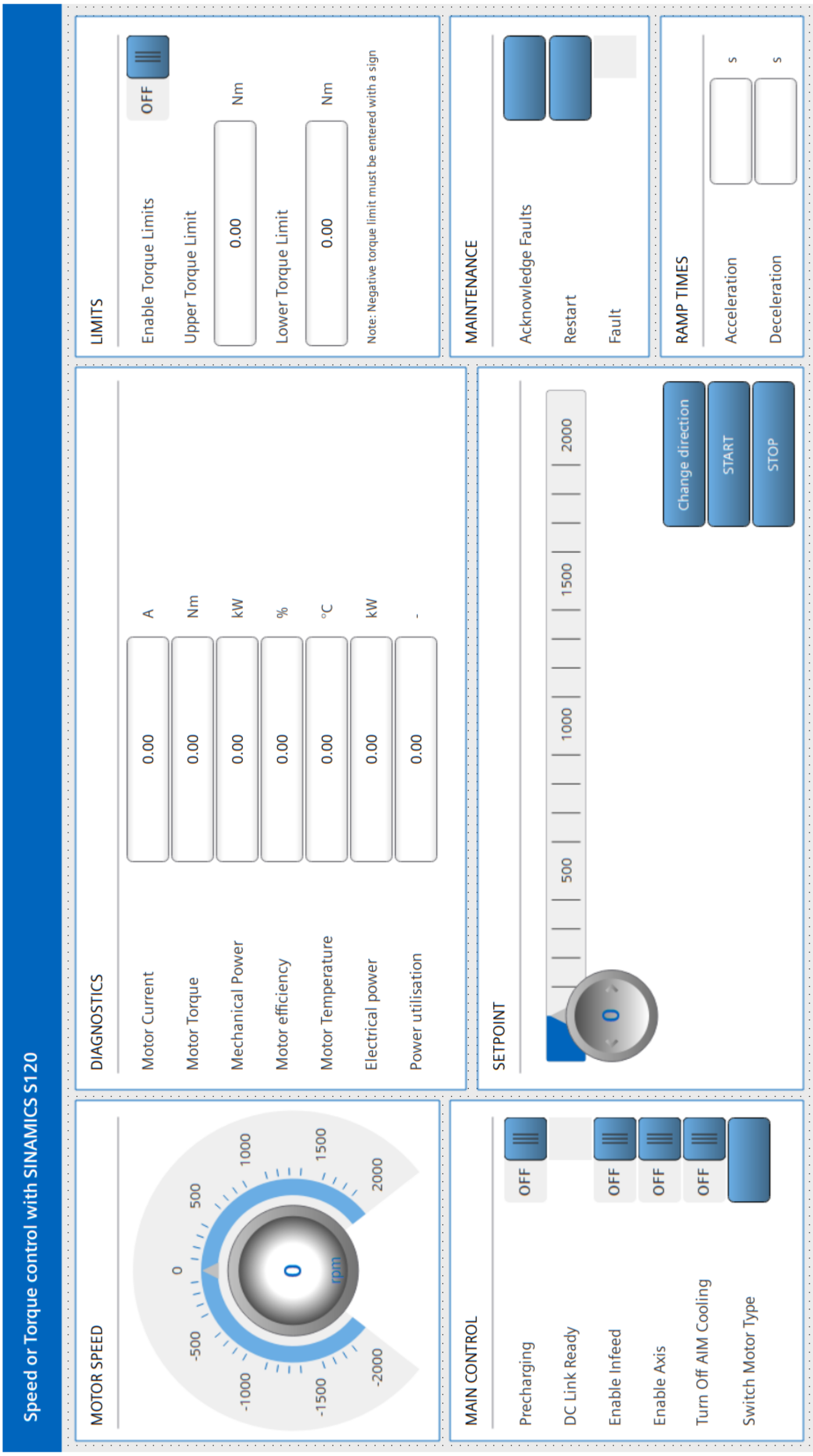


Figure 6.19: HMI panel screen

Chapter 7

Testing report

In order to test the performance of a Synchronous reluctance machine, it was connected to a source of variable load, i.e. another controllable electric machine. Efficiency of the motor was measured as a function of speed and torque, which was then compared to an induction machine with similar properties.

7.1 Workstation block diagram

The block diagram of the workstation can be seen on Fig. 7.1. The load consisted of a torque measuring gauge and a DC (direct current) machine that could act as a motor or dynamo, so the tested machine could be operated both in generator and motor modes. The DC machine is driven by a Ward Leonard system, which was operated by my thesis supervisor while I acquired data from and operated the tested drive. Torque was measured by a mechanical torque measuring gauge to ensure that the data was accurate. Other values, such as velocity and electrical active power of the motor etc. were measured by the tested drive.

7.2 Procedure

The used induction motor is a part of a 60+ years old Ward Leonard machine with very high moment of inertia and is suspected of having incorrect parameters punched out on the rating plate. Due to these facts, the converter was unable to drive the motor by normal means. The converter was reconfigured to control the motor with V/f and simulated digital inputs linked to fixed speed setpoints. Motor rated data had to be manually changed for clarity. This in turn created the possibility to continue with measuring and testing. The required values were read from the parameter list in online mode directly through TIA Portal on the PC in addition to the control of simulated digital inputs. Due to time limitations, the machine was only measured in motor mode. Therefore, please note that motor changeover has not been properly tested and may need further optimization.

1. The tested machine is set to a certain speed (frequency) setpoint).

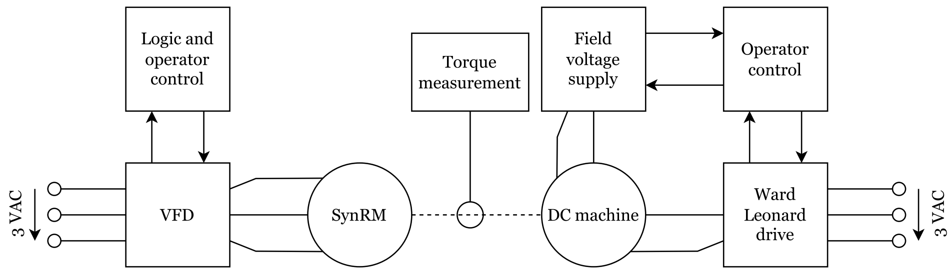


Figure 7.1: Block diagram of the workstation

2. Field current of the DC motor is switched on.
3. Armature voltage of the Ward Leonard DC generator is set to equal the armature voltage of the driven DC motor.
4. Both armatures are switched together.
5. Variable load is developed by changing the field current of the DC generator.
6. The selected torque value is set.
7. Speed, torque and efficiency are read.
8. Steps 5 to 7 are repeated for different torque values.
9. Steps 1 to 8 are repeated for different speed (frequency) setpoints.

7.3 Measured values

During the first part of testing, high torque values could not be achieved due to insufficient induced voltage in the DC machine caused by low speeds. A similar problem occurred during high speeds in regenerative operation of the tested motor, which was caused by the inability of the DC motor to create sufficient torque due to maximum armature voltage. The IM was unable to produce higher torque than 75 Nm and the converter tripped on overcurrent. Tables 7.2 and 7.1 show the results for the SynRm and IM respectively. Data for the IM had to be further segmented due to more values of velocity caused by motor slip.

It is important to note that the converter measuring system is not laboratory standard, so the values may slightly differ from reality. Nevertheless, the same error applies to both motors and therefore are still comparable.

7.4 Charts

The charts show motor efficiency as a function of speed and torque. Operation of the SynRM in both modes can be seen on Fig. 7.3). Since the IM wasn't tested in generator mode, comparisons can only be made in motor mode. See Fig. 7.2. Chart colour is scaled to reach the darkest point at a value of 100 % and lightest at 50 %. For a close-up, efficiency as a function of torque in the rated (or close to) operation frequency can be seen in Fig. 7.4.)

7.5 Discussion

Both motor types perform best in their rated operation point and lose efficiency with decreasing speed and/or torque. Based on the values and chart colours, it is evident that the SynRM reaches significantly higher efficiencies than the IM in the whole spectrum. Under lower loads, the IM performs much worse, while the SynRM stays above 90 % till about 10 Nm, which corresponds to about 10 % power utilisation. They perform similarly at lower speeds, but the IM may come to a standstill due to motor slip, as happened in this case. And that losses caused by motor slip hinder the performance even further. Interestingly, the highest measured value of efficiency was in generator mode close to the optimal operating point (about 80 - 90 % utilisation). The temperature of the SynRM didn't exceed 33°C and was

	η (%) for different velocities						
T (Nm)	99 rpm	301 rpm	499 rpm	749 rpm	998 rpm	1251 rpm	1505 rpm
-95	X	X	X	92.198	92.864	X	X
-90	X	X	X	X	X	96.689	X
-83	X	X	X	X	X	X	98.539
-75	X	X	X	95.025	92.367	98.216	97.375
-64	55.765	X	X	X	X	X	X
-60	X	87.773	X	X	X	X	X
-57	X	X	89.977	X	X	X	X
-55	54.367	85.370	91.509	96.664	94.641	97.290	98.175
-35	71.654	83.392	91.310	96.167	94.864	97.270	97.714
-20	62.697	87.244	92.814	96.895	98.076	97.325	95.493
-15	77.166	88.831	94.409	98.595	96.960	98.216	94.330
-10	57.875	92.003	89.943	94.346	96.641	96.180	95.810
-5	3.858	76.141	88.030	96.895	88.030	88.547	93.907
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	66.457	75.049	79.174	93.375	85.664	87.336	73.646
10	79.748	85.191	84.283	90.155	90.879	96.327	90.059
15	74.052	81.519	89.071	94.881	97.370	94.931	95.710
20	X	84.055	91.676	93.375	95.443	93.575	93.533
35	67.195	86.868	89.653	93.059	95.257	97.556	96.267
55	60.021	85.824	88.705	88.764	92.711	95.814	97.725
75	61.710	80.137	88.070	89.811	92.761	95.392	96.808
95	X	X	X	87.870	92.616	93.575	95.002

Table 7.1: SynRM efficiency data table

barely noticeable by touch. Conversely, the IM radiated significantly more heat.

$T = 0$ Nm		$T = 10$ Nm		$T = 20$ Nm		$T = 55$ Nm	
n (rpm)	η (%)	n (rpm)	η (%)	n (rpm)	η (%)	n (rpm)	η (%)
100	0.000	98	38.009	95	58.520	0	0.000
303	0.000	999	57.481	989	66.178	276	71.285
509	0.000	747	57.945	287	73.304	475	81.666
752	0.000	1248	60.786	1244	75.301	1484	85.132
1008	0.000	301	63.041	743	77.036	977	85.649
1257	0.000	501	68.136	491	79.104	736	85.985
1538	0.000	1503	69.953	1498	81.280	1221	86.500

$T = 5$ Nm		$T = 15$ Nm		$T = 35$ Nm		$T = 75$ Nm	
n (rpm)	η (%)	n (rpm)	η (%)	n (rpm)	η (%)	n (rpm)	η (%)
98	23.324	95	46.633	80	51.441	460	75.900
1234	46.151	991	63.279	282	74.359	718	82.444
1003	47.743	295	66.198	480	79.968	965	84.212
749	48.417	744	72.140	1484	82.662	1213	85.596
303	49.578	1494	72.881	986	84.044	1461	86.798
505	52.883	1236	73.821	1235	84.450		
1525	55.838	497	75.066	740	85.830		

Table 7.2: IM efficiency data table

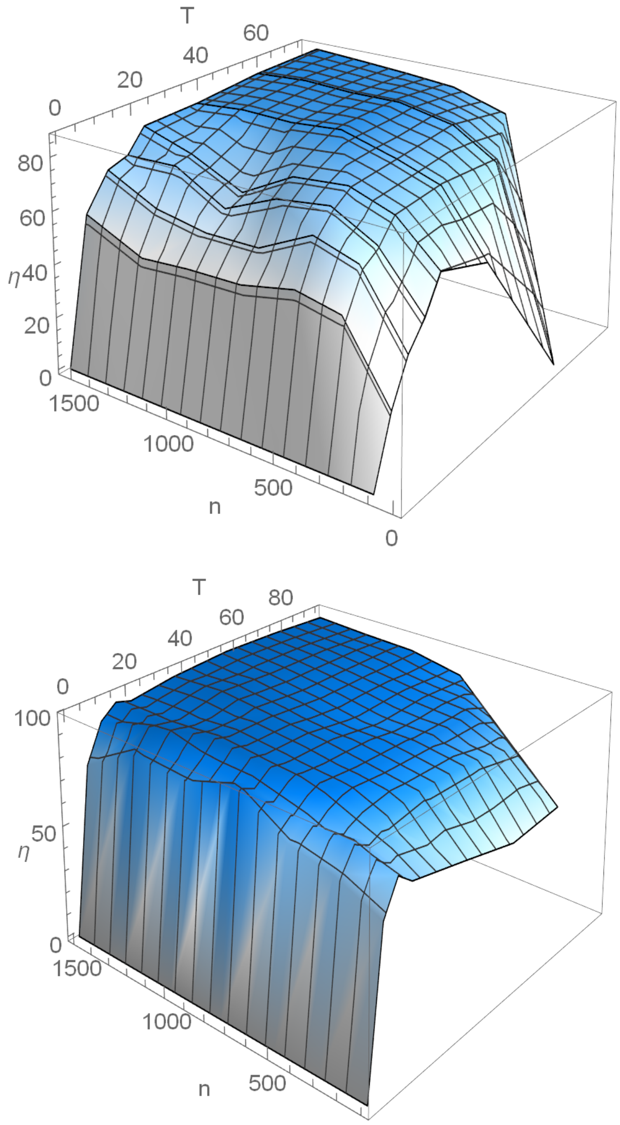


Figure 7.2: Comparison of efficiency charts between the IM (top) and SynRM (bottom)

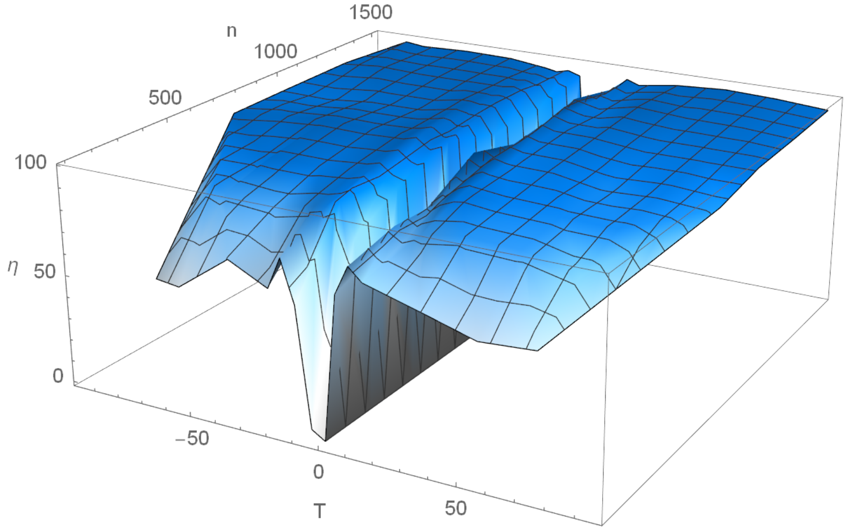


Figure 7.3: Efficiency chart of the SynRM in motor and generator mode

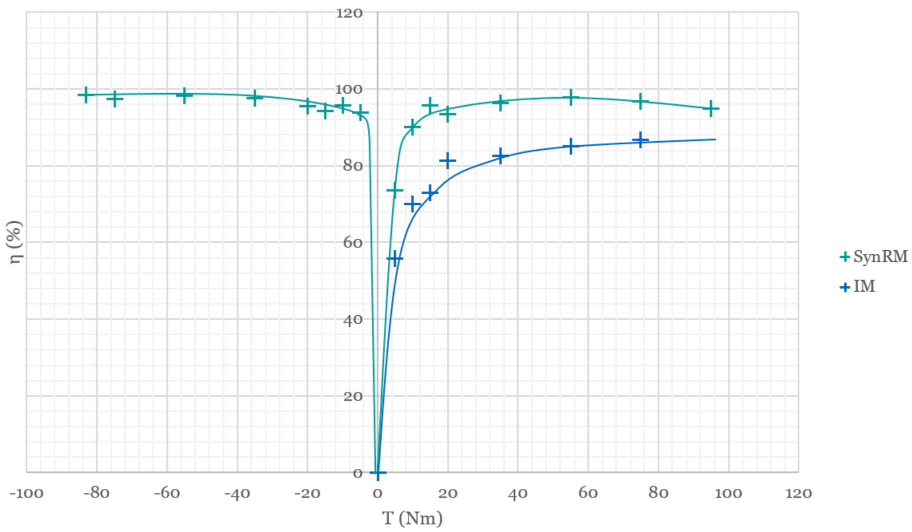


Figure 7.4: Efficiency as a function of torque with rated frequency

Chapter 8

Collection and visualisation of data from a Rotary Torque Sensor

This chapter has been included because the Synrm is planned to be used as a variable load, so an independent measurement of torque and speed is required. A rotary torque sensor meets these requirements.

There are two ways of measuring torque, one is to calculate it based on other values from a mathematical model of the system, or to measure it directly. The second method is described in this chapter. Moreover, an example of processing and visualising the data is also explained. Values are collected from a rotary torque sensor using a PLC and visualised with a HMI. For this purpose, I used a T20WN rotary torque sensor and VK20 junction box from HBN, then PLC 1212C, HMI panel KTP400 and signal board SB1221 from Siemens.

8.1 Basic working principles of a Rotary torque sensor

A strainable shaft is coupled with two other shafts from both sides. These shafts are fitted and mounted to the measured system. The strainable shaft is covered with a strain gauge, which changes its electrical resistance when force is applied - the path of resistive foil stretches out or shortens (the basic arrangement can be seen on Fig. 8.1). Resistance is measured via slip rings or a rotary transformer. Mechanical torque can then be evaluated from the measured data.

Rotary encoders are often used to measure angular velocity of the rotating system. This system uses an incremental quadrature encoder with A and B tracks. The rotating part has two outer rings, each being evenly segmented with translucent and opaque parts that release/block light of an optical sensor (Fig. 8.2 shows a basic example of 2 pulses per revolution).

The ring segments are distributed in such a way that the signals are phase shifted by 90° from the other ring, thus creating two square wave signals called A and B tracks (Fig. 8.3).

Angular velocity can be calculated from the frequency of this signal and direction is determined by the pulse sequence of the tracks.

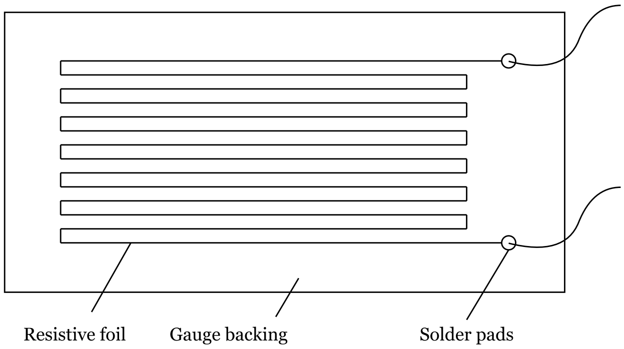


Figure 8.1: Strain gauge

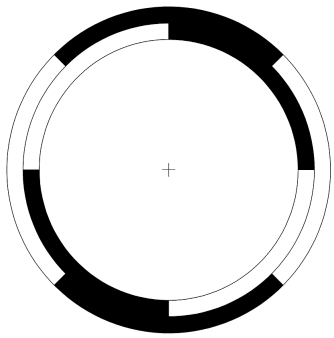


Figure 8.2: Model of a basic incremental encoder

8.2 Connection diagram

The connection diagram can be seen in Fig. 8.4. For specific connections, refer to the VK20 junction box manual.

8.3 Problem and solution

The torque output is a PWM signal with variable frequency ranged from 5 to 15 kHz, which corresponds to the torque value in both directions up to 50 Nm. Angular velocity is measured with an embedded incremental encoder 512 S/rev with A and B tracks. Both of these values must be sampled and evaluated using a PLC program.

SB1221 has fast digital inputs capable of reading signals with frequencies up to 200 kHz. They can be used as HSC - high speed counters and configured to work as counters or to measure frequency. The torque signal input is configured to measure frequency (Fig. 8.5), which is then normalised and scaled to show torque data (Fig. 8.6).

Tracks A and B are read by one input each and together configured as an A/B counter (Fig. 8.7).

Every 200 ms, the counter status is read and compared with the previous value, thus giving information about angular difference in time, which is then

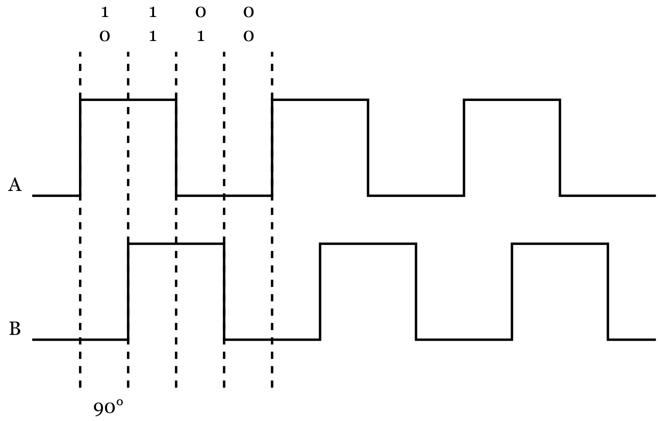


Figure 8.3: Output signal of an incremental encoder

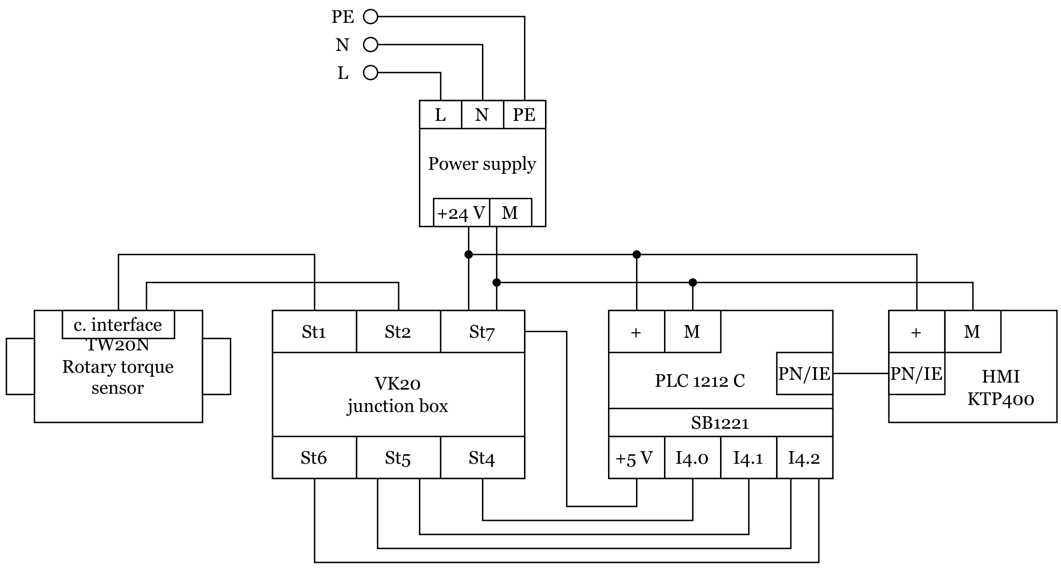


Figure 8.4: Connection diagram of a rotary torque sensor measuring system

converted to rpm using the formula below:

$$n = \frac{\Delta C}{0.2} \cdot \frac{60}{512}$$

where ΔC is the counter difference. Program in Fig. 8.8

Mechanical power of the driven system can then be calculated:

$$P_{\mathrm{m}} = \frac{\pi \cdot n}{30} \cdot T$$

where n is revolutions per minute (rpm) and T is applied torque. Program in Fig. 8.9

An average is calculated from the last 100 samples of each value and displayed together with raw samples on a HMI panel in the form of textboxes and time trends (Fig. 8.10). Time trends are shown on other screens (via screen selection).

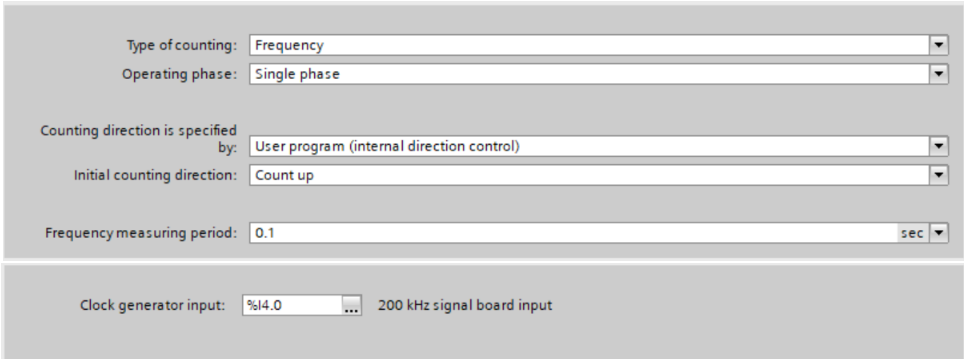


Figure 8.5: Configuration of a HSC to measure frequency

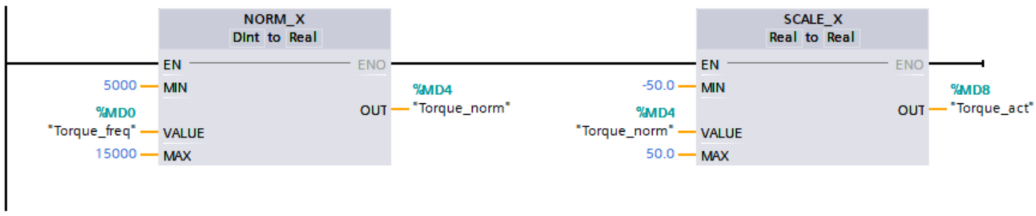


Figure 8.6: Torque calculation

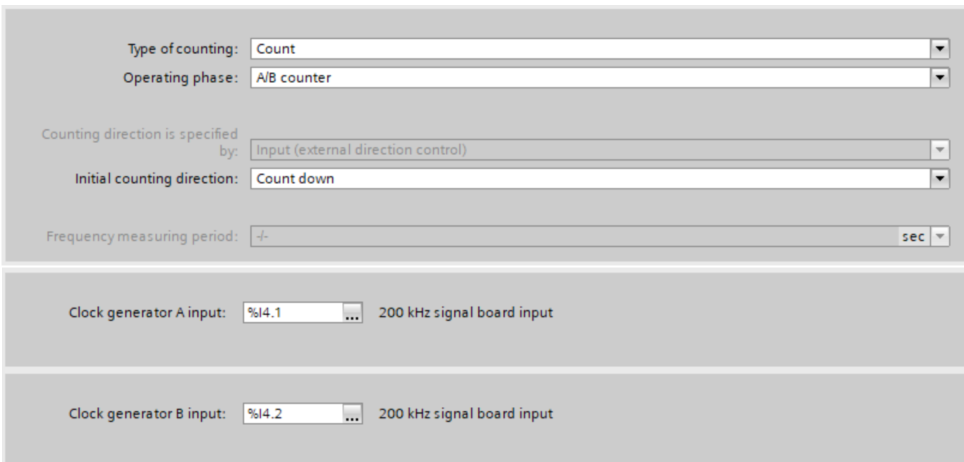


Figure 8.7: Configuration of a HSC as an A/B counter

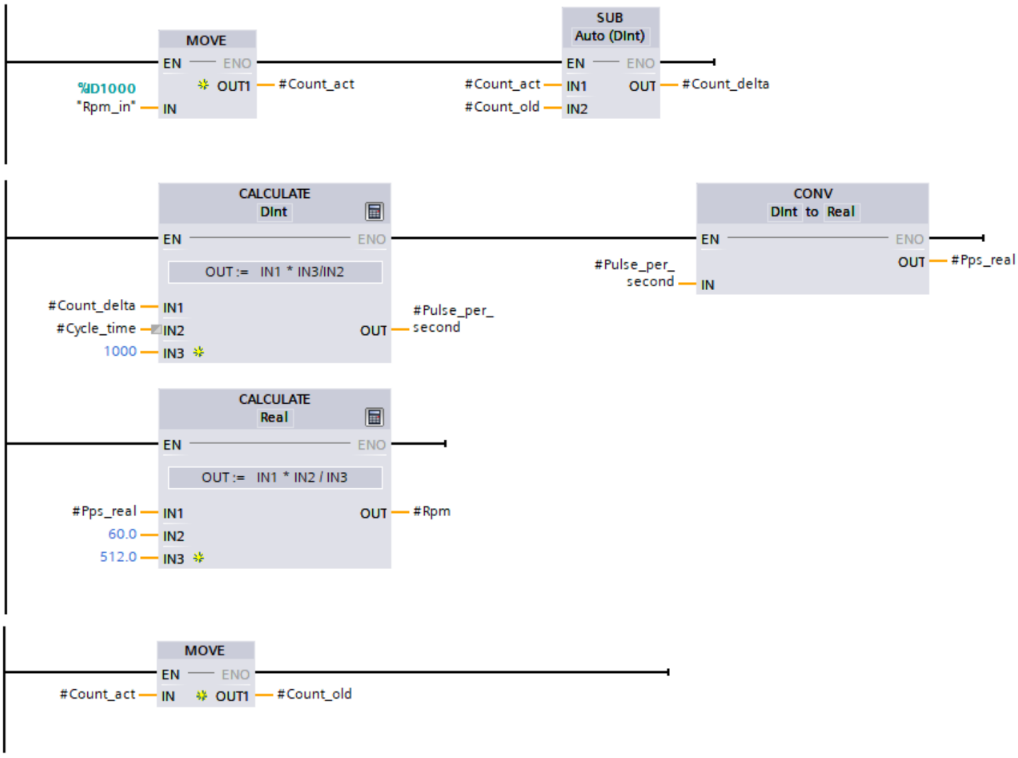


Figure 8.8: Rpm calculation

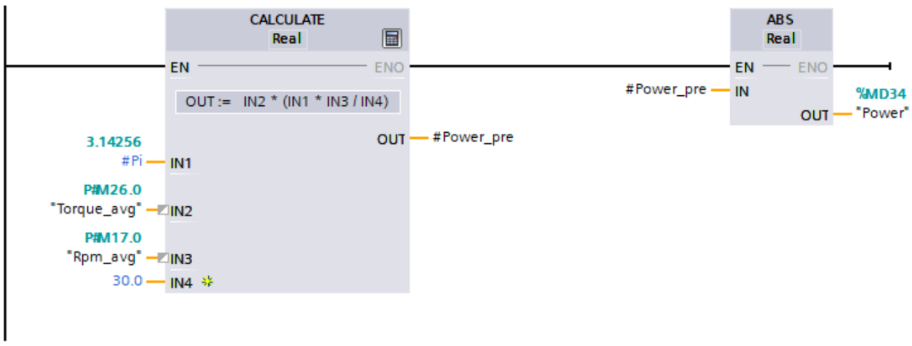


Figure 8.9: Mechanical power calculation

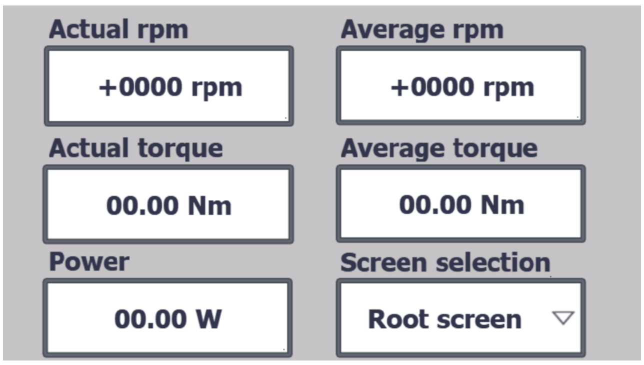


Figure 8.10: Rotary torque sensor data visualisation

Chapter 9
Conclusion

The first three chapters introduce the fundamental theory of Synchronous reluctance machines, their advantages and disadvantages from multiple points of view, and how to control them effectively in regards to the required operation.

The fourth chapter describes every component used to assemble the workstation and the following chapter arranges them into a working whole by creating a combined diagram.

The practical part shows how to create a user program that allows to directly control the speed and torque of a SynRM with a PLC and HMI panel. This control also includes display of important parameters, parameterizable ramp times, shutting down unit fans for noise reduction and motor switchover. Currently, the system can be used as a variable load to test other rotating machines even in high overload duty cycles. In the future, control could be expanded by creating a webserver from the HMI panel to access control and diagnostics from another location, Additionally, automatic data acquisition could also be implemented, which in combination with the webserver would allow download of measured data directly to a PC. As for the PLC program, set load characteristics could be created, which would make the drive seem like a different mechanism. For example, characteristics of pumps, fans, winders or conveyors could be implemented.

Measured data shows that the SynRM vastly overpowers the IM in terms of efficiency. However, it would be better to compare machines with identical nominal values, with the IM having an efficiency rating of at least IE4.

Finally, the last chapter demonstrates how to collect and visualise data from a rotary torque sensor with a PLC and HMI. The program is able to display the measured data both in real time and in the form of a chart.

Index

List of Notation

Symbol	Meaning
Ψ	Magnetic flux (Wb)
L	Inductance (H)
I	Current (A)
R	Resistance (Ω)
U	Voltage (V)
t	Time (s)
ω	Angular frequency (rad/s)
θ	Angle of the d-axis (rad)
σ	Angle between the space vector of stator voltage and d-axis (rad)
ϑ	Rotor offset (rad)
P	Power (W)
p	Number of pole pairs (-)
α	Saliency ratio (-)
β	Impedance ratio (-)
T	Torque (Nm)
$\cos\varphi$	Power factor (-)
τ	Time constant (t)
a (index)	a-axis
m (index)	mutual
s (index)	stator
k (index)	k system
q (index)	q-axis of the d-q system
d (index)	d-axis of the d-q system
max (index)	max value
j (index)	joule
e (index)	electrical
T (index)	corresponds to maximal torque
C (index)	corresponds to maximal power factor

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