ELECTRICALLY ASSISTED CALIBRATION OF PERMANENT MAGNET SYNCHRONOUS MOTOR'S RESOLVER

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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Electrically assisted calibration of permanent magnet synchronous motor's resolver

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Keywords: PMSM, resolver, calibration, alignment

This master's thesis sought to develop a production friendly methodology for aligning resolver with respect to the electrical a-phase of permanent magnet synchronous motor. Motivation for the research emerged from the lack of comprehensive calibration methodology, though individual methods have been studied. To explore the fundamentals of the resolvers and electric motors, literature review was first conducted.

The subject was researched through three viewpoints – design, mechanical methods and electrical methods. Different methods within these definitions were recognized with the support of literature review. Design was considered through the tolerancing of the motor's components and mechanical methods introduced principles for positioning the resolver, aided by jigs. Furthermore, electrical methods were studied through an experimental test setup to compare their accuracy and usability.

Results of both qualitative and quantitative nature were obtained in the research. Considering the design of the motor was seen as a necessary stage of the calibration and varying advantages were recognized for different mechanical methods. For electrical methods rotor alignment with direct current was observed as the most accurate option. However, inductance-based alignment done with an LCR meter was considered as a promising alternative in certain situations. Based on the results, topics for further research were discussed and strategies for implementing the methodology to production were given.

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Kestomagneettitahtimoottorin resolverin sähköavusteinen kalibrointi

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Tämä diplomityö pyrki kehittämään tuotantoystävällisen metodologian resolverin linjaamiseksi kestomagneettitahtimoottorin sähköisen a-vaiheen suhteen. Peruste tutkimuksen toteuttamiselle syntyi kattavan kalibrointimetodologian puutteesta, joskin yksittäisiä menetelmiä on tutkittu. Resolvereiden ja sähkömoottoreiden perusteiden tutkimiseksi suoritettiin ensin kirjallisuuskatsaus.

Aihetta tutkittiin kolmesta näkökulmasta – suunnittelu, mekaaniset menetelmät sekä sähköiset menetelmät. Erilaisia menetelmiä tunnistettiin näiden määritelmien puitteissa kirjallisuuskatsauksen tukemana. Suunnittelu käsiteltiin moottorin komponenttien toleroinnin kautta ja mekaaniset menetelmät toivat esiin periaatteita resolverin paikoittamiseksi, jigien avustamana. Lisäksi sähköisiä menetelmiä tutkittiin kokeellisen testijärjestelyn avulla niiden tarkkuuden ja käytettävyyden arvioimiseksi.

Tutkimuksessa saavutettiin sekä laadullisia että määrällisiä tuloksia. Moottorin suunnittelun huomioiminen nähtiin välttämättömänä vaiheena kalibrointia, ja vaihtelevia hyötyjä tunnistettiin erilaisille mekaanisille menetelmille. Sähköisistä menetelmistä roottorin linjaaminen tasavirtaa käyttäen havaittiin tarkimmaksi vaihtoehdoksi. Kuitenkin, induktanssiperusteinen linjaus LCR-mittarilla tehtynä katsottiin lupaavaksi vaihtoehdoksi tietyissä olosuhteissa. Tuloksiin pohjautuen, aiheita jatkotutkimukselle pohdittiin ja strategioita metodologian toimeenpanemiseksi tuotannossa esitettiin.

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Like most great achievements, this thesis too reflects not only the author's efforts but the contribution of many others as well. While I'm sincerely grateful to several people for their assistance with this work, recognition for certain individuals is at place.

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SYMBOLS AND ABBREVIATIONS

Roman characters

f	reference frame axis	
I	current	A
K_i	resolver constant	
t	time	s
V_{cos}	cosine winding voltage	V
V_m	excitation voltage	V
V_{sin}	sine winding voltage	V

Greek characters

θ	resolver angle	°, rev
ω	angular velocity	°/s, rev/s
ω_e	excitation frequency	rad/s

Subscripts

d	direct axis
q	quadrature axis

Abbreviations

AC	Alternating Current
DC	Direct Current
DOF	Degrees of Freedom

elec.	Electrical
HF	High Frequency
IPMSM	Interior Permanent Magnet Synchronous Motor
MTPA	Maximum Torque Per Ampere
mech.	Mechanical
m.m.f.	Magneto-Motive Force
PM	Permanent Magnet
PMSM	Permanent Magnet Synchronous Motor
PSO	Position Sensor Offset
SPMSM	Surface mounted Permanent Magnet Synchronous Motor
VRR	Variable Reluctance Resolver

Table of contents

Abstract

Tiivistelmä

Acknowledgements

Symbols and abbreviations

1 Introduction 10
1.1 Objective 10
1.2 Scope 11
1.3 Contribution 12
2 Background 13
2.1 Electricity and magnetism 13
2.2 Electric motors 14
2.2.1 Permanent magnet synchronous motor 16
2.3 Resolvers 19
2.4 Electrical reference frames 21
2.5 Existing methods for calibration 24
3 Calibration methods 27
3.1 Equipment 27
3.2 Tolerance analysis 30
3.3 Mechanical calibration 32
3.3.1 Absolute alignment 33
3.3.2 Relative alignment 36
3.3.3 Combined alignment 37
3.4 Electrical calibration 38
3.4.1 LCR alignment 38
3.4.2 DC alignment 41
3.4.3 High frequency injection 41
4 Results 43

4.1 New information 43
4.1.1 Positioning the resolver 43
4.1.2 Identifying the position sensor offset 45
4.2 Analysis 47
4.3 Concrete applications and generalized results 49
5 Discussion 51
5.1 Reliability and validity 51
5.2 Key findings 52
5.3 Novelty value of the results 53
5.4 Topics for future research 54
6 Conclusions 55
References 56

Appendices

Appendix 1. Results of the LCR alignment

Appendix 2. Impact of current in DC alignment

Appendix 3. Impact of initial rotor position in DC alignment

Figures

Figure 1: Classification of electric motors (Kim 2017, 2).

Figure 2: Simplified operation of a brushed DC motor (Kim 2017, 41).

Figure 3: Simplified structure of PMSM (Erkol 2019, 52).

Figure 4: Stator and rotor structure configurations of a PMSM (Kim 2017, 164).

Figure 5: Three pole pair variable reluctance resolver (Celikel et al. 2023, 3).

Figure 6: Transformation from abc to dq-coordinate system (Vidlak, Makys & Gorel 2022, 4).

Figure 7: Current and magnetic flux in dq-reference frame (adapted from Kim 2017, 239).

Figure 8: PMI375-T800 electric motor (Danfoss 2024b).

Figure 9: The resolver utilized in the motor.

Figure 10: Wiring diagram of the setup.

Figure 11: Rotor jig concept.

Figure 12: Stator jig concept.

Figure 13: Assembly jig concept.

Figure 14: Circuit connection for measuring the a-phase inductance (adapted from Rallabandi et al. 2019, 4).

Figure 15: Setup for LCR measurement.

Figure 16: Impact of current in DC alignment.

Figure 17: Impact of initial rotor position in DC alignment.

Tables

Table 1: Tolerance stack-up analysis (values in mechanical degrees).

1 Introduction

The world is rapidly electrifying and many applications that used to operate on fossil fuels now utilize electric motors in some way. In fact, around half of the electricity produced globally today is consumed by electric motors (European Commission 2024). An electric car often serves as a symbol of this transition, but progress can also be seen in other mobile solutions such as working machinery and marine industry (Danfoss 2024a; International Energy Agency 2024). To meet the requirements of these fields, reliable and efficient production of electric motors will be increasingly valuable in the future.

One typical component of an electric motor is the resolver, which is used to measure the angular position of the motor's rotor. Information about the position is needed for controlling the motor, and faulty measurements typically undermine the motor's torque and efficiency characteristics. While resolvers themselves are sturdy and reliable devices, their installation process can contribute to measurement inaccuracies in the form of position sensor offset (PSO). (Kim 2017, 373–375.)

The term position sensor offset is used to describe the misalignment between the resolver's electrical output and the real position of the motor's rotor (Kuruppu, Abeyratne & Hettiarachchi 2023, 1–2). By calibration, the offset between the two can be reduced to tolerable limits. In a three-phase motor, this is typically done by aligning the resolver with respect to the stationary electrical a-phase of the motor's stator. Resolvers with higher pole count must be adjusted with greater precision, however, and this task is generally too challenging to be done solely by hand. Additionally, the real position of the rotor is defined by the orientation of the magnetic fields inside the motor, complicating visual evaluation of the alignment. To overcome these challenges in a production environment, comprehensive calibration methodology is needed.

1.1 Objective

The objective of this research is to develop a cost-effective methodology by which the resolver of a permanent magnet synchronous motor (PMSM) can be calibrated with respect to its electrical a-phase. Emphasis is placed on considering the methods' applicability to a

production environment. The research is begun by conducting a literature review to study the fundamentals of electric motors and resolvers as well as existing calibration methodology. After this, the objective is sought to be filled by the means of method triangulation, consisting of three different practical viewpoints for the calibration: design, mechanical methods, and electrical methods.

From the objective of the research, two research questions were derived. First of the questions is the main research question, while the second is a sub-question.

1. How can a resolver be calibrated with respect to the electrical a-phase of a PMSM during production?
2. Can sufficient calibration accuracy be achieved without an electric inverter as a power supply?

The hypothesis for the research is that the calibration methodology needs to be constructed based on all methods. Design can be utilized for tolerancing the components in a way that the calibration is possible and practical while mechanical methods can be used for manual adjustment of the resolver. Electrical methods, however, may be needed for supporting the mechanical ones and for making finer adjustments.

As a result of the research, qualitative information about the feasibility and functionality of the methods is expected to be achieved. The qualitative results particularly cover the design and mechanical aspects of the methodology. However, quantitative results are sought for evaluating the accuracy and precision of the electrical methods.

1.2 Scope

The resolvers investigated in this research are commercial off-the-shelf products and thus the product development related to them is not included in the scope. In general, the assumption is made that the resolvers' quality is sufficiently consistent outside the announced measurement accuracy. Additionally, the development of assembly tools and production processes is limited to generating concept stage solutions up to the level that the developed methods can be verified and compared. In other words, this research seeks to provide guidelines and principles for the calibration rather than concretely implementing them in production.

1.3 Contribution

As stated, the increasing utilization of electric motors greatly advocates the importance of the subject. While research about the phenomena themselves exists, lack of information can be found in terms of comprehensive and integrated production applications as well as in comparing the accuracy of different methods. Additionally, many studies focus on mitigating the offset on software-level rather than fixing it.

Through this research, methodology for the manufacturers of electric motors is sought to be developed to advance cost effective and reliable production. A customer of such company is likely to benefit from the properly calibrated machines in the form of shorter set up times and accurate control possibilities. Furthermore, the research can be seen to promote sustainable values through facilitating electrification of mobile solutions.

2 Background

In this chapter a systematic literature review of the subject is conducted based on scientific articles and literature. The review covers the fundamentals and theories related to functioning of electric motors and resolvers, and studies how these can be applied in practice. Basics of controlling the motors are also discussed and finally existing methods for eliminating the PSO is researched. The sources mainly consist of scientific articles but also books and online resources have been utilized.

2.1 Electricity and magnetism

Practically all electric motors utilize the interaction between magnetic fields to produce rotation. In addition to permanent magnets (PM), a magnetic field can be produced by applying current through a coil. While the magnetic field produced by a single coil isn't necessarily sufficient for producing motion, grouping several as a winding enables the generation of a stronger magnetic field. The field's magnitude can also be increased by increasing the current. (Hughes & Drury 2019, 1-2.) Thus, the magnetomotive force (m.m.f.) can be defined by multiplying the current with the number of windings (Hacker & Sumereder 2020, 93).

An analogy between a magnetic and an electric circuit can be made, where the m.m.f. is compared to voltage. In such analogy, resistance can be replaced with reluctance and current with flux. Reluctance describes how difficult it is for the flux to complete the magnetic circuit, and is dependent on the permeability, or the magnetic conductivity. Flux on the other hand can be used to derive flux density by dividing it with the area it flows through. Flux density acts as a quantity for evaluating the intensity of a magnetic field. (Hacker & Sumereder 2020, 94–95; Hughes & Drury 2019, 9–10.)

Inductance is another concept that is important for understanding the functioning of electric motors. It represents a coil's capability to produce flux when current flows through it and therefore contributes to the m.m.f (Pyrhönen, Jokinen & Hrabovcova 2013, 36). The amount of inductance is defined by factors such as coil's material, dimensions and number of turns. On the other hand, when a coil is subjected to an external alternating magnetic field, current

is induced in it with the magnitude depending on the inductance. (Hacker & Sumereder 2020, 103–106.)

Many electric motors utilize permanent magnets alongside the windings for producing the magnetic fields. Not only can the structure of a motor be simplified with PMs, but they often provide higher torque density and easier controllability. (Vaez-Zadeh 2018, 7-19.) When a current carrying winding is placed in a PM's magnetic field, a deflecting force is produced as a product of the interaction of two magnetic fields. The direction of the force is dependent on the direction of the current. Similarly, this interaction can be produced with the magnetic fields of two windings. (Hacker & Sumereder 2020, 100–102.)

2.2 Electric motors

Electric motors are in no way a recent invention. In fact, the first developments were made already in the 1800s (Kim 2017, 1). Hence electric motors are now seen in many industrial applications as well as in household appliances, and the basic principle of producing rotation with electricity is familiar to many. Characterized more profoundly however, the mechanical force is produced by the previously described interaction between magnetic fields, which can be created by energized windings, permanent magnets, or induced currents (Kim 2017, 4).

In terms of the mechanical structure, an electric motor consists of the stationary part, stator, and the rotating part, rotor. The rotor is fixed to the shaft of the motor which provides the rotational output. The stator and rotor have their own respective magnetic fields that seek to align with each other. (Engelmann & Middendorf 1995, 32–33.) Since the magnetic flux is carried through both components, the motor can be said to represent a magnetic circuit. In this circuit, however, an air gap is needed between the components to allow for the rotor to move. Air has poor permeability and thus the size of the air gap should be optimized to maintain the strength of the magnetic field. (Hughes & Drury 2019, 10–15.)

When classifying electric motors, a distinction is often made between direct current (DC) and alternating current (AC) motors (figure 1). Of these, a brushed DC motor can be seen as the simplest variant since electrical phases don't need to be considered and speed control is

done by simply adjusting the voltage. Thus, it is a good example for studying the fundamentals of electric motors. (Beaty & Kirtley 1998, 2–278.)

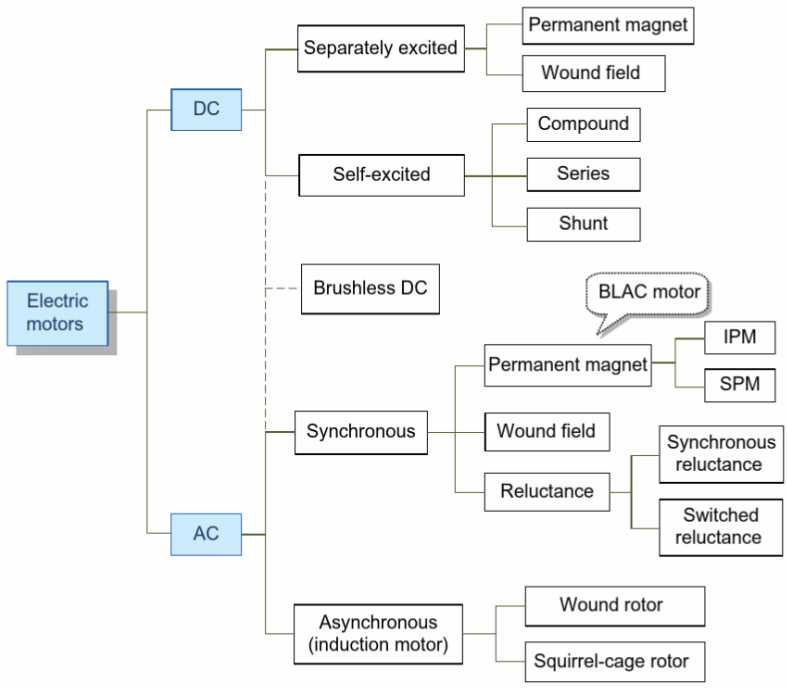

Figure 1. Classification of electric motors (Kim 2017, 2).

In a brushed DC motor, the rotor's magnetic field is formed by the armature winding. When current is fed through it, a magnetic field for the rotor is formed which seeks to align itself with the magnetic field of the stator. Stator's magnetic field, on the other hand, is created by the field winding or by permanent magnets. (Beaty & Kirtley 1998, 277–278.) However, only up to half a rotation can be achieved this way, which is why a commutator is used in this motor type to reverse the direction of the armature current and the orientation of the rotor's magnetic field with it. Commutator can be, at simplest, characterized as curved plates connected to the armature winding. As it rotates along with the rotor, the plates contacting the current supplying components, or brushes, change periodically. (Kim 2017, 39–42.)

In figure 2 a schematic depicting the operation of the motor is presented. In this representation the armature winding consists of only one coil attached to the two commutator plates. Additionally, one pair of permanent magnets form the stator's magnetic field. Due to this uneven geometry the torque of the motor varies greatly depending on the orientation of

the coil, which is why in real applications the armature consists of multiple coils. This is done by symmetrically placing additional coils in the armature winding. (Kim 2017, 40–41.)

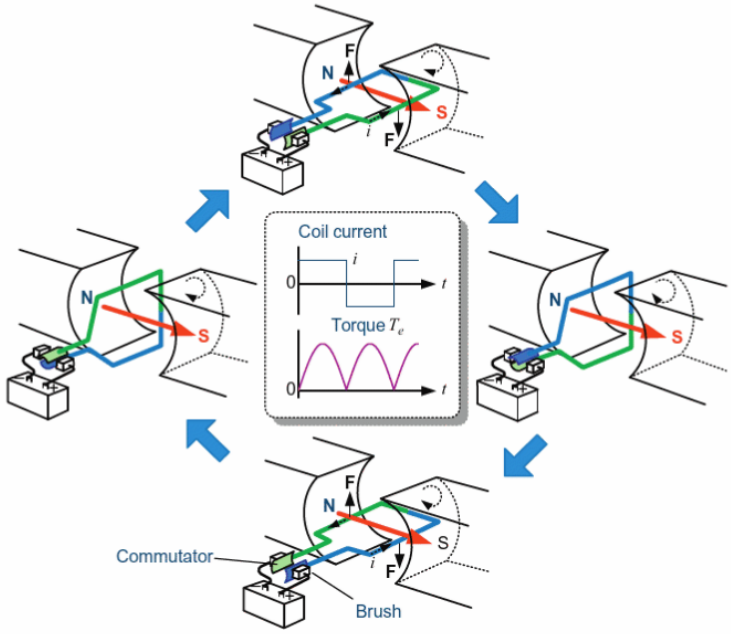

Figure 2. Simplified operation of a brushed DC motor (Kim 2017, 41).

Further classification of DC motors can be done to self-excited DC motors where the rotation is used for producing a magnetic field, making them suitable as generators (Hughes & Drury 2019, 124–125). However, brushless DC motor is a variant that is often seen as separate from DC motors in general. While direct current is utilized in its operation, the structure and operation principle share more similarities with AC motors. (Kim 2017, 389.)

2.2.1 Permanent magnet synchronous motor

The AC motors can further be divided into synchronous and asynchronous motors, from which the former is mainly focused on in this research. While the driving magnetic field was formed for the rotor in brushed DC motor, synchronous AC motor utilizes a rotating magnetic field of the stator to generate torque. The rotor's rotation is in phase with the stator's field, hence the name. (Hughes & Drury 2019, 308–309.)

Permanent magnet synchronous motor is a subtype of synchronous AC motor that uses permanent magnets for the rotor and three phase alternating current for the stator to generate its magnetic fields. While the rotor's magnetic field can also be produced with a winding excited by DC, usage of PMs removes the need for additional power source. This simplifies the motor's structure and provides lower operating temperatures due to no copper losses, but often increases the price. (Vaez-Zadeh 2018, 18–25.)

In general, PMSMs can reach very high efficiencies and energy densities. This is typically seen as energy savings, compensating the high initial purchase price. (Vaez-Zadeh 2018, 18–19.) Due to these properties PMSMs are often utilized in applications such as electric cars, but also in industrial actuators and pumps, for example (Müller, See, Ghani, Bati & Thiemann 2017). Furthermore, they can be used as generators by applying a driving torque to the shaft. This way the rotor induces a current to the stator windings, feeding it to the supply instead. (Hughes & Drury 2019, 288–289.)

The structure of a PMSM (figure 3) resembles the brushed DC motor's (figure 2) in many ways but the place of the winding and PMs is reversed between the rotor and the stator. For this reason, the commutator is also unnecessary. The stator winding of PMSM is divided into three-phases where the conductors are displaced by 120 degrees. (Kim 2017, 143–144.) While a one pole pair structure is used as an example here, it is worth noting that typically several pole pairs are utilized by increasing the number of magnets and by introducing additional sets of windings (Hughes & Drury 2019, 308–311).

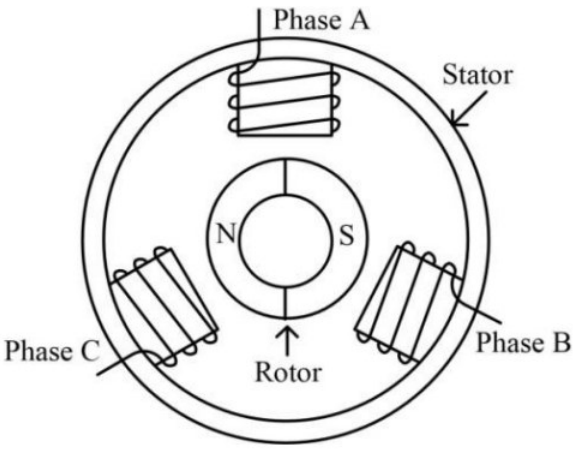

Figure 3. Simplified structure of PMSM (Erkol 2019, 52).

For energizing the windings of a PMSM, three-phase current is used. In three-phase electric current, the system is divided into three separate AC circuits, each with the same magnitude of voltage but with a phase difference of 120 degrees relative to each other. (Hacker & Sumereder 2020, 158.) In the stator in figure 3, one winding corresponds to an electrical phase, essentially forming an independent AC circuit. As the windings are energized one at a time, the polarity of the stator's magnetic field re-orients continuously, producing torque through the rotor that synchronously seeks to align itself with it. (Kim 2017, 5–146.)

Differences among PMSM designs can be found, for example, in the rotor and stator structure (figure 4). Often a distinction is made between surface mounted permanent magnet motors (SPMSM) and interior permanent magnet synchronous motor (IPMSM) depending on the location of the magnets in the rotor. Commonly the IPMSM offers better speed range for the motor, but several magnet topologies exist inside this definition, impacting the characteristics. (Zhou, Huang, Fang & Wu 2018, 609–610.) Furthermore, the stator can be constructed with distributed or concentrated winding as seen in the two leftmost and rightmost illustrations in figure 4, respectively. This affects the stator's efficiency and manufacturability, for example. (Kim 2017, 164–165.) A shared characteristic between the rotor and the stator, however, is their laminate structure, produced by laying several thin sheets on top of each other. Typically, a steel of good magnetic conductivity is used as the material. (Pyrhönen et al. 2013, 456–458.)

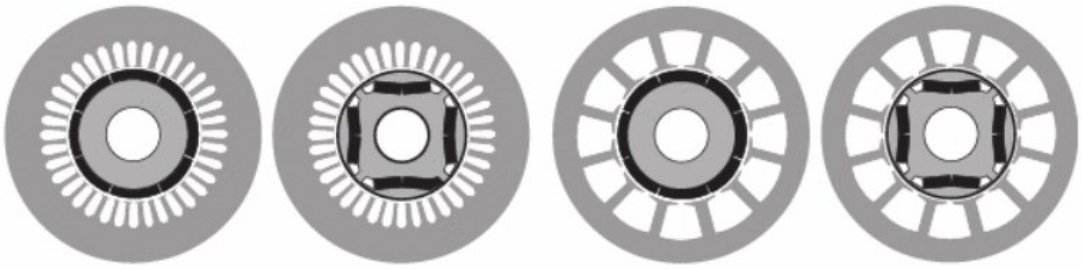

Figure 4. Stator and rotor structure configurations of a PMSM (Kim 2017, 164).

Rotor structure can also be designed to utilize reluctance torque which is formed by the rotor's tendency to align itself in a way that the reluctance in the magnetic circuit is minimized. (Hughes & Drury 2019, 320–321.) While motors whose operation is based solely

on reluctance exist, it is commonly implemented as a part of IPMSMs. If rotor's reluctance is high in between the magnets, this will further push them to align with the magnetic flux. Thus, the IPMSM's torque is formed by two terms, magnetic and reluctance torque. However, since the current for utilizing the magnets and reluctance must be supplied from different directions with respect to the rotor, the orientation of the supplied current must be optimized to provide the best torque to current ratio, or maximum torque per ampere (MTPA). (Kim 2017, 163–239.)

While the angular speed of the DC motor is controlled with voltage, PMSM's speed is dependent on the frequency of the stator's current. A higher frequency shortens the time between exciting adjacent coils, resulting in faster rotation of the stator's magnetic field. In addition to frequency, the number of pole pairs in the motor affects the speed of the motor and by dividing the frequency with it, the angular speed can be calculated. (Giri 2013, 1–2.)

2.3 Resolvers

Information about the orientation of the motor's shaft is often needed for control solutions, as will be seen in later chapters, and resolvers can be utilized for this purpose. While other solutions such as rotary encoders exist, the rugged, stable, and accurate resolvers are commonly used in electric motors where such features are needed. (Ni, Cai, Gu, Nie & Wu 2022, 1–2.) Resolvers are analogue devices and provide an absolute value of the orientation, often converted to digital form. Interestingly, their structure and functioning share a lot of resemblance with electric motors. (Celikel, Boztas & Aydogmus 2023, 1.)

A resolver too consists of two components, stator and rotor. The rotor of the resolver is mounted to the motor's shaft, and the stator is typically fixed to the frame of the motor. Different designs for the resolvers have been developed but a distinction is often made based on the rotor structure. Variable reluctance resolver (VRR) has a permanent magnet as its rotor and the stator contains three windings: one primary or excitation winding and two secondary windings, sine and cosine winding. On the other hand, a wound rotor resolver has the primary winding located in the rotor in place of the PM though this somewhat complicates the design. (Celikel et al. 2023, 1–4.) In both designs however, the secondary windings are mechanically displaced by 90 degrees in relation to each other (Kim 2017, 373–375).

Resolvers' operation is based on comparing the magnitude of the induced voltages in the secondary windings. A high frequency AC excitation voltage is supplied through the primary winding which is induced in the secondary windings. As the rotor rotates, the magnitude of the induced voltage changes sinusoidally. In a VRR, this change is caused by the variation in the air gap. When the air gap geometry changes, the reluctance of the magnetic circuit changes with it, impacting the inductance. (Saneie, Nasiri-Gheidari & Tootoonchian 2018, 4323–4324.) As discussed, the current and therefore the voltage induced to the secondary windings is dependent on the inductance.

The type of VRR studied in this research, variable air gap length resolver, achieves the reluctance variation through the length of the air gap. This variation results from the shape of the rotor (figure 5), where the outer radius changes sinusoidally. (Saneie et al. 2018, 4323–4324.) On the other hand, classification to a radial flux resolver can be made since the magnetic field is formed radially between the components, instead of axially where the rotor and stator would be placed on top of each other (Celikel et al. 2023, 4–5).

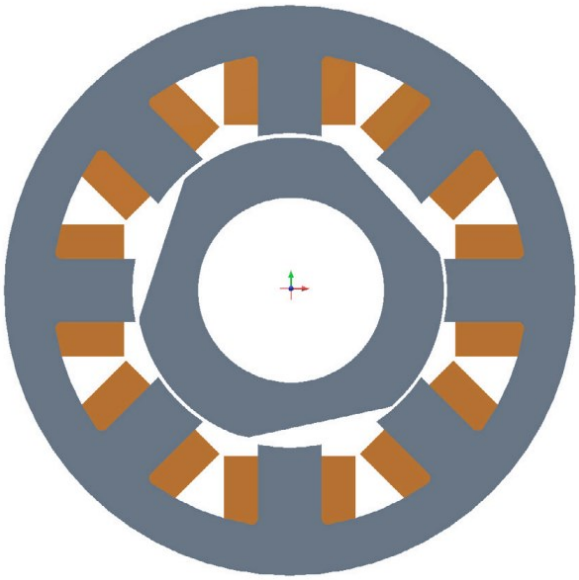

Figure 5. Three pole pair variable reluctance resolver (Celikel et al. 2023, 3).

The voltages in the secondary windings ($V_{\sin}$ and $V_{\cos}$) of a resolver a be calculated from the excitation waveform (Celikel et al. 2023, 1–3):

$$V_{\sin} = K_i V_m \sin(\omega_e t) \sin(\theta) \quad (1)$$

$$V_{\cos} = K_i V_m \sin(\omega_e t) \cos(\theta) \quad (2)$$

In the equations 1 and 2, V_m is the amplitude, t is the time, and ω_e the angular frequency of the excitation signal (Celikel et al. 2023, 1–3). θ is the resolver's angle, while K_i is a resolver specific constant, often left out of the equation (Saneie et al. 2018, 4324). As can be interpreted from the equations, the voltages have a 90-degree phase shift between them, a result of the mechanical displacement (Celikel et al. 2023, 2).

While the voltages in the secondary windings can be analytically examined, practical applications typically measure them in some way (Saneie et al. 2018, 4324):

$$\theta = \tan^{-1}\left(\frac{V_{\sin}}{V_{\cos}}\right) \quad (3)$$

Equation 3 can be used to calculate the angle of the resolver based on the ratio between the induced voltages (Saneie et al. 2018, 4324). However, the calculated value represents the resolver's electrical angle rather than the mechanical, a concept that will be further discussed in the next chapter.

2.4 Electrical reference frames

With the two-pole rotor PMSM (figure 3) one mechanical revolution is performed per electrical cycle. Real applications, however, typically utilize multiple pole pairs by increasing the number of magnets and windings, as discussed in the case of the DC motor. In such situation several electrical cycles, or rotations of the stator's magnetic field, are needed for a full mechanical revolution. The term electrical angle is often used to make a distinction to the mechanical orientation, and it can be better described through the electrical reference frames. (Hughes & Drury 2019, 262–265.)

The three-phase winding of the motor's stator can be initially expressed as the abc-reference frame (figure 6). This is often called the stationary reference frame, and it consists of three axes representing the electrical phases in a 120-degree angle with respect to each other. (Hughes & Drury 2019, 262–265.) After establishing the coordinate system, vectors representing the magnitude of each phase can be drawn. By forming their resultant vector, the phase of the current can be displayed in the abc-frame. (Sul 2011, 117–118.)

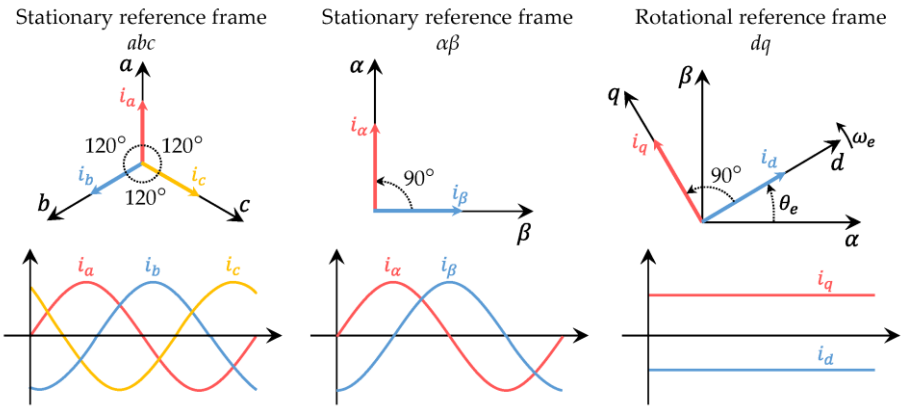

Figure 6. Transformation from abc to dq-coordinate system (Vidlak, Makys & Gorel 2022, 4).

The abc-representation can be further transformed into a two-axis coordinate system by utilizing Clarke transformation (Kim 2017, 178-181):

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad (4)$$

In equation 4, f represents the axes in the denoted direction (Kim 2017, 178–181). This new coordinate system, the αβ-stationary reference frame is oriented in way that the α-axis is aligned with the a-axis and the β-axis is perpendicular to them. It is noteworthy that Clarke transformation typically serves as an intermediate stage and is often integrated with the next one. (Hughes & Drury 2019, 265.)

The second transformation, Park transformation, can be used to convert the αβ-stationary reference frame to a rotating dq-reference frame (Giri 2013, 44–45):

$$\begin{bmatrix} f_{\mathrm{d}} \\ f_{\mathrm{q}} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} f_{\alpha} \\ f_{\beta} \end{bmatrix} \tag{5}$$

This reference frame also consists of two axes but rotates at angular speed ω. While the speed can be arbitrarily defined, the dq-frame's orientation is typically seen to be synchronized with the motor's rotor and denoted by θ. (Kim 2017, 175–176.) This is the interpretation that the dq-frame is utilized for in this research.

Since the direct and quadrature axes are time-invariant, the resultant vector of the current can be controlled with just the constant values of its components, i_{d} and i_{q} (figure 7), without considering the sinusoidal characteristics in the other reference frames – assuming constant rotation is needed from the motor (Krause, Wasynczuk & Sudhoff 2002, 110). Additionally, through dq-frame the stator currents can be controlled with respect to the rotor. The d-axis is typically aligned with the pole flux of the rotor, meaning that the angle between it and the current vector dictates how much the current precedes the rotor. In many applications an ideal value for this angle would be 90° (aligned with the q-axis) but utilizing the previously discussed reluctance torque through MTPA requires involving the d-axis current as well. (Kim 2017, 234–239; Quang & Dittrich 2015, 3–5.)

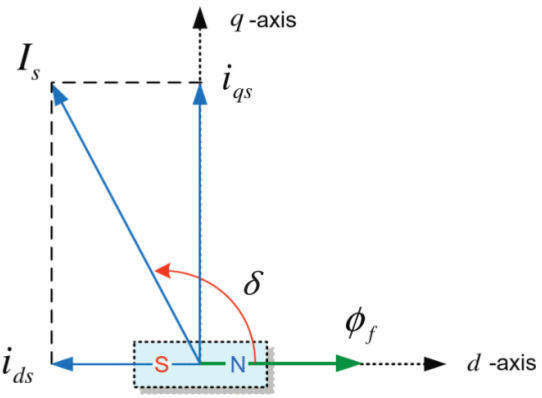

Figure 7. Current and magnetic flux in dq-reference frame (adapted from Kim 2017, 239).

Understanding of the vector control provides a justification for researching the resolver calibration. The orientation of the rotor is needed for obtaining the dq-frame and controlling the stator current according to the desired strategy. This is especially important at low speeds where PMSM's torque significantly decreases without accurate position information. In motors where the orientation is determined with a resolver, excessive PSO may lead to sub-optimal performance. (Wang, Tong, Wang & Tian 2023, 1–2.)

2.5 Existing methods for calibration

Several methods have been developed for the calibration of a resolver in PMSMs. Especially the acquisition of the initial rotor position is a frequently researched topic since the real position of the rotor is needed to align the resolver with it. These range all the way from mechanical to algorithm-based electrical methods, usually with increasing complexity. This added complexity does not guarantee a better calibration result in every case however, and the selection of the method should be made based on the needs and attributes of the individual motor and system.

At the earliest, the PSO can be impacted during the production stages preceding the resolver's assembly. While the offset is usually seen to be caused by angular displacement, radial eccentricity of resolver's stator and rotor can also cause errors due to uneven air gap size (Wang, Hao, Wang, Zhang & Li 2024, 1–3). Thus, the motor's components should be designed with tight enough tolerances to provide more accurate initial alignment between the resolver's mounting surfaces. This requires considering tolerance stack-up, since the cumulative variation in the assemblies can often lead to inadequate dimensional accuracy. (Wang, Li, Hartman & Sutherland 2019, 1–2.) On the other hand, specialized jigs can be used when assembling the resolver to control the angular displacement. Depending on the needed accuracy however, these measures are often insufficient for controlling the PSO and other methods should be considered too. (Wu, Li, Wang & Yin 2024, 2.)

Popa, Kreindler, Giuclea & Sarca (2007, 1–2) describe a solution for the initial rotor position detection where the rotor is rotated to electrical zero position by applying DC voltage to the a-phase of the stator winding. The current creates a stationary magnetic field that forces the rotor to orient accordingly. The resolver can then be mechanically adjusted to its zero position while reading the position measurement (Kuruppu 2021a, 1–2). This DC alignment

is recognized as the simplest way to obtain the initial position of the rotor by other researchers as well but applicability for on-load applications can be questioned (Wu et al. 2024, 1–3).

This challenge was further researched by Zossak, Stulraiter, Makys & Sumega (2018, 4–6) who concluded that increasing the load noticeably affected the steady state position offset when constant current was used. While the effect of the load can be mitigated by supplying greater current, unwanted overshoot is typically produced, leading to longer settling times. This is also impacted by the rotor's initial position. However, the steady state offset generally disappears in a no-load environment, although the used current must still be optimized for the above reasons. In any case, these results confirm the statements made by Wu et al. (2024, 2). The DC alignment method involves some unpredictability and may be affected by different motor and set up parameters.

A back emf based approach is another possible way for determining the PSO, where the voltages induced in the three-phase windings, the back electromotive force, are utilized instead of the input current (Lin, Jiang, Zhang, Yue & Li 2022, 134–135). The method is performed by driving the motor that is being calibrated with another one while measuring the voltages in the windings (Kuruppu 2021b, 1–2). The back emf is then compared to the resolver signal and the offset is determined from their phase difference (Kuruppu 2021a, 2). However, the requirement for external machine complicates the test set up (Lin et al. 2022, 135). The same can be said of the methods based on dynamo setups which have also been suggested. (Wu et al. 2024, 3–4).

Further research related to determining the rotor initial position includes, for example, high frequency injection methods, where external voltage is used to differentiate the position of a rotor based on its saliencies. While this includes methods where square-wave and pulse waveforms are used, concentrating on the sinusoidal methods will be sufficient here. In rotating sinusoidal injection two orthogonal high frequency signals are supplied to the stator in a rotating manner. The current components induced on the α- and β-axis differ due to the saliency of the rotor and can be used to estimate the rotor position. (Wang, Gaolin, Zhang & Xu 2020, 37–41.) Similarly, the pulsating sinusoidal injection relies on analyzing the difference in the induced currents. However, its functioning is based on one signal, injected along the initially estimated d- or q-axis. (Liu, Tseng, Lin & Chen 2016, 1–2.) The

advantages of HF injection are especially seen in on-load situations as well as when the rotor is not freely movable (Zossak et al. 2018, 2–6).

Since many producers of electric motors lack the processes or capability to utilize these methods, the calibration of the resolver is often left to the end user (Lin et al. 2022, 135). Software level solutions typically use closed loop algorithms to define and correct the error between the real and measured resolver position (Mori, Kojima, Kimpara & Nakano 2017, 23–25). These methods, however, do not respond well to the objective of this research since calibration is needed for the needs of the motor production.

3 Calibration methods

The methods developed for the calibration procedure are presented in this chapter. The methodology is formed through method triangulation which consists of three viewpoints. First, the design of the motor's components and assembly needs to be considered through tolerancing to help evaluate the viability and limitations of the calibration. Second, the mechanical means are studied due to their potential for simple and cost-efficient calibration with minimal equipment. Third and foremost, the need for repeatable and sufficiently accurate calibration is sought to be ensured with electrical methods where a dedicated experimental setup is utilized.

An important consideration in generating the methods is their applicability to the production of the PMSMs. Thus, the methods apply the principles introduced in the review in the context of the specified hardware and their production processes. The most important consideration derived from this is the desired calibration accuracy, which was defined to be ± 0,2° (mech.).

3.1 Equipment

To validate the applicability of the methods an experimental setup was assembled. The setup consisted of, most importantly, the electric motor and the resolver but also of the inverter which was utilized for control and measurement purposes. The development of the methodology was supported by the technical documentation of the equipment, especially regarding the design and mechanical viewpoints.

The motor utilized for the study was a PMI375-T800-2300+RES1 manufactured by Danfoss (figure 8). With its 191 kW power (continuous) it is able to provide a torque of 796 Nm. The motor is based on synchronous reluctance assisted permanent magnet technology, which utilizes the rotor's reluctance for improving its torque and speed capabilities. (Danfoss 2024b.) The motor has six pole pairs, meaning that one electrical revolution equals to $\frac{1}{6} \approx$ 0,1667 mechanical revolutions. It's also noteworthy that each of its magnetic poles consists of two adjacent blocks of permanent magnets.

Figure 8. PMI375-T800 electric motor (Danfoss 2024b).

The resolver utilized in the motor is a commercial off the shelf product with six pole pairs (figure 9). It functions through the variable reluctance technology and has connections for excitation, sine, and cosine signals as well as the ground connection. The stator of the resolver houses the covered winding, and it utilizes mounting slots for positioning and installation. The rotor, however, is mounted to the shaft with an interference fit and can be placed freely in any orientation.

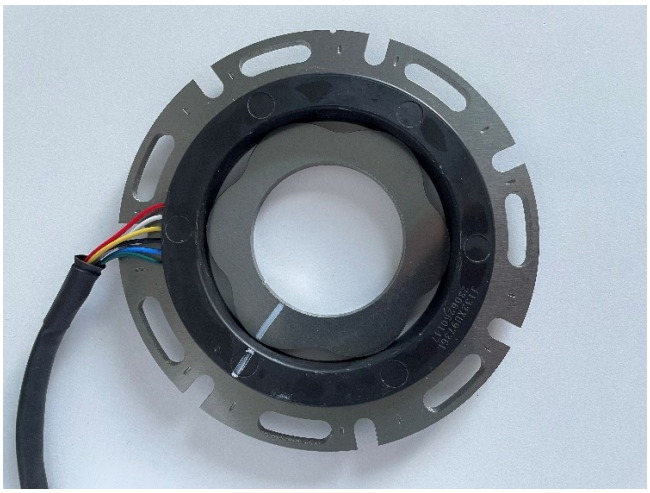

Figure 9. The resolver utilized in the motor.

For driving and controlling the motor, an electric inverter was connected to it with three-phase cabling and low voltage connector. The inverter was powered by two power supplies,

one being 24 V and intended for powering the low voltage connections, and the other 50 V for driving the motor. While the latter would not be usable for real operation, it was observed to be sufficient here since the required features worked reliably in the no-load environment. The wiring diagram of the setup can be seen in figure 10.

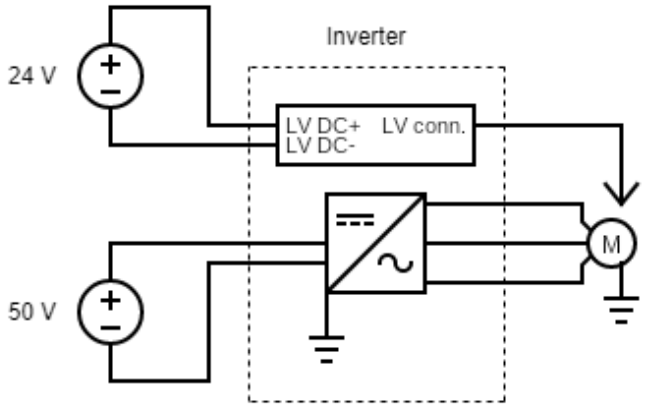

Figure 10. Wiring diagram of the setup.

The inverter was controlled through the PowerUSER-software which also provided tools for signal processing and plotting. For example, the resolver output was read through the software. The output is given in revolutions, as a value between zero and one, and is calculated by the software based on the ratio of the sine and cosine voltages as seen in equation 3. Furthermore, the logged measurement data was exported from the software for post processing with other tools.

Additionally, an LCR meter was used for inductance measurements. Since a handheld meter was observed to be too unreliable due to the instability of the reading, a tabletop model with four terminal pair connection was used. The connections and utilization of the LCR meter will be further discussed in the coming chapters.

3.2 Tolerance analysis

Tolerancing is used to control the variation of dimensions and geometry of components and assemblies in production (Henzold 2021, 5–7). In terms of calibrating the resolver, the issue of tolerancing can be seen relevant for two reasons. First, the PSO may be controlled to some extent by the means of tolerancing, supporting other calibration methodology. Second, the eventual calibration may not be possible if the variation of the components causes too great deviations from their designed positions. In any case, considering the motor design through tolerancing can be seen as an inevitable step in the resolver calibration.

Tolerances in assemblies must generally be investigated through tolerance stack-up. When multiple components are fixed into each other, their dimensional variations add up and may result in greater variations in the assembly level. On the other hand, the variations can happen in both ways and may cancel each other out from the point of view of the assembly. Tolerance stack-up is often studied through statistical methods where the likelihood of faulty assemblies is evaluated through the statistical variations of individual components. In terms of this research, however, a worst-case model is more relevant since the calibration of the resolver is done at the end of the assembly process where defects are likely to be costly. (Wang, Li, Hartman & Sutherland 2019, 13–14.)

When inspecting the tolerances of the specified assembly it can quickly be seen that controlling the PSO through mere tolerancing cannot be considered practical since the allowed variation is consumed by certain single tolerances alone. The internal accuracy of the resolver belongs to this group with a value of ± 0,2° (mech.). This is notable because even if the resolver was positioned exactly in the correct orientation every time, the resolver's error could still exceed the desired PSO.

The resolver is located in the non-drive end of the studied motor. Its stator is mounted to the bearing shield, which in turn connects to the end shield. The end shield is fixed to the frame of the motor. Resolver's rotor on the other hand is mounted to the shaft via interference fit and can be freely adjusted unlike the other components.

For positioning the resolver, mainly angular tolerances are of importance. The axis of rotation for these tolerances is the axial centerline of the shaft and the orientation of the components can be expressed with respect to the frame. Since the stator of the resolver can

only be adjusted on a range of 15,5° (mech.) due to the clearance of the mounting slots (see figure 9), the total range of variation due to the tolerances should be limited to ± 7,75° (mech.). If this condition is not met, the intended mounting slots may not be used during assembly, leading to inconsistencies in the production.

A tolerance stack-up analysis is presented in table 1. In the table, the upper and lower tolerance of a component's mounting feature are listed. Majority of the values result from machining tolerances defined either individually in the components' documentation or through the general tolerance (ISO 2768-1:1989). Some tolerances, specifically the interference fits, have not been defined and are therefore marked with a value of zero. Additionally, the internal error of the resolver is considered on last row of the table.

Table 1. Tolerance stack-up analysis (values in mechanical degrees).

	Component	**Mounted to**	**Tolerance (+)**	**Tolerance (-)**
Rotor	Shaft	Rotor laminate stack	0	0
	Resolver rotor	Shaft	0	0
Stator	Stator laminate stack	Frame	0	0
	Frame	N-end shield	0,05	-0,05
	N-end shield	Frame	0,05	-0,05
	N-end shield	Bearing shield	0,1	-0,1
	Bearing shield	N-end shield	0,1	-0,1
	Bearing shield	Resolver stator	0,2	-0,2
	Resolver stator	Bearing shield	0,2	-0,2
	Resolver stator	Resolver rotor	0,2	-0,2
		Total:	0,9	-0,9

By comparing the sum of tolerances to the allowed variation of ± 7,75° (mech.), two conclusions can be made. First, whether the variation caused by the tolerances remains within the allowed limits, and second, what requirements for the remaining interference fits must be assigned. Depending on the required accuracy, additional design features may need to be introduced for the interference fits. Furthermore, the winding of the stator must be begun from a standard location to maintain the position of the electrical phases.

3.3 Mechanical calibration

The assembly of the studied PMSM is primarily done with manual, handheld tools. Integrating resolver calibration to this process can be assumed to be the simplest and most cost-efficient approach since no specialized assembly cells are needed. Mechanical calibration can therefore be defined as the principles, according to which the components' position is mechanically controlled during the assembly. Additionally, all adjustments to the orientation of the motor are done mechanically. In practice, the easiest way to implement mechanical calibration is through the usage of jigs and fixtures.

Different kinds of fixtures are commonly used to hold and support components during manufacturing and assembly. This effectively means constraining the components' degrees of freedom, transitional or rotational (Venkataraman 2022, 3–9). In general, their purpose is to increase the quality and efficiency while also foolproofing production steps. Especially machining fixtures typically incorporate some kind of clamping mechanisms to better constrain the work part. (Hoffman 2004, 1–8.)

A distinction is often made with jigs which are used to guide the movement of a tool or component interacting with the workpiece (Venkataraman 2022, 4–5). In other words, while also intended for constraining the movement of the workpiece, jigs often accomplish this with respect to the tool rather than in the global coordinates (Fiedler, Ehrenstein, Höltgen, Blondrath, Schäper, Göppert & Schmitt 2024, 1–2). In this research the definition of a tool is seen to also include marking tools.

Adapted from Nee, Tao & Senthil Kumar (2004, 8) the design process of a jig can be divided to three parts. First, the requirements of the process and geometry of the workpiece is considered. This way the design requirements for the jig are formed and its usability is ensured. After the important datum features are identified, the second stage is performed by deciding the utilized locating principles based on the observations. This consists of determining the position and location of the used locator. In the third and final stage, the jig body is designed to connect the functional features together. Sufficient rigidity for the body is required to maintain the correct dimensional relationships between the features.

In the context of assembling the resolver, fixtures and jigs can be used to control the angular position of its parts and thus the electrical output. In other words, this requires constraining

the parts' rotation around the shaft's center axis. Theoretically the utilized datum features could be found in the rotor and stator.

However, the design of studied the motor presents some problems in this regard. In terms of the rotor, the laminate stack is not visible or accessible when the resolver is assembled. This means that it is not possible to utilize the geometry of the laminate stack for locating at this point of the assembly. Also, no tolerances for the alignment of the shaft are defined, meaning that the orientation of the rotor cannot be determined based on the features of the shaft.

Similarly, physically aligning correct stator windings of the resolver and motor would be possible if their locations were known, but same challenges are faced as with the rotor. The motor's stator cannot be seen from the outside and thus its orientation is unknown. On the other hand, utilizing the features of the frame isn't possible at present either since the angular tolerance of the interference fit between the frame and the stator is undefined.

By considering these limitations for the jigs, three suitable mechanical methods were recognized. Concept stage designs were created to qualitatively evaluate their viability for use based on required traits, cost efficiency and simplicity. For the methods where further potential was seen, prototyping and practical testing was applied by qualitatively inspecting the calibration results' range and accuracy. Additionally, impact of possible design changes was considered.

3.3.1 Absolute alignment

Following the principle of tolerancing, the resolver could theoretically be calibrated by placing every component of the motor to their designed, correct position. However, it should be noted that the resolver's alignment matters only with respect to the motor's stator and rotor, not the other components. This change in perspective enables the possibility for ignoring a long chain of components, reducing absolute alignment to a challenge about correctly positioning the stators and rotors.

As mentioned though, the geometry of the motor provides challenges for absolute positioning. Since the orientation of the motor's rotor and stator is unknown when mounting the resolver, alignment of the parts must be done based on visible indicators. For this

purpose, markings could be done during the production phases where the datum features are still visible.

Following the outlined jig design process, relevant features of the rotor should first be identified. Its laminate stack has a circular hole pattern, aligned with the permanent magnets. On the other hand, the shaft is located at the center of the pattern. These datums are sufficient for constructing the locating scheme. Applied from the common 3-2-1 -locating principle, the surface of the laminate stack constrains one translational and two rotational degrees of freedom (DOF) (Fiedler et al. 2024, 2). The remaining two translational DOF are constrained when the jig is located along the shaft and the rotation around it is eliminated with locators in the hole pattern.

With the information about the reference geometry, needed locators can be determined. The shaft can be seen as a locator itself and the jig body should be designed around it. For the hole pattern, cylindrical pins can be used. In general, the locators' edges should be chamfered to make them self-aligning. (Venkataraman 2022, 12–17.)

The designed jig can be seen in figure 11. The body is designed to connect the discussed features and it provides a slot for creating a marking to the shaft. The marking can be utilized through the geometry of the resolver's rotor to position it correctly. The jig can be classified as a template jig, since no clamping is used to hold it in place (Hoffman 2004, 9). However, due to the symmetricity of the rotor's hole pattern the jig cannot be completely foolproofed and it should be manually located towards the magnets of needed polarity.

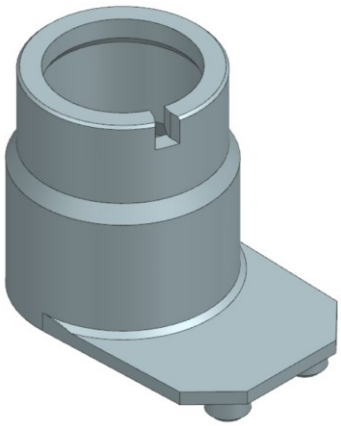

Figure 11. Rotor jig concept.

While the principle of utilizing markings can applied for the stator as well, the marking must be done first, and the jig located according to it. The marking should be done on the outer surface of the frame, over the a-phase winding. This way the datum reference can be obtained after the stator is covered. On the other hand, the datum features of the resolver's stator, the mounting holes, are visible during its assembly and can be directly utilized with cylindrical locators. If a liner was introduced between these, the marking could be utilized to align the two stators.

The stator jig consists of two bodies, designed to be connected to each other with a metallic ruler (figure 12). While considerable bending forces would occur in any liner due to the long distance between the marking and resolver, the ruler can be expected to have sufficient rigidity to withstand this in the needed direction. The leftmost body is intended for utilizing the resolver's geometry whereas the rightmost is used for alignment with respect to the marking.

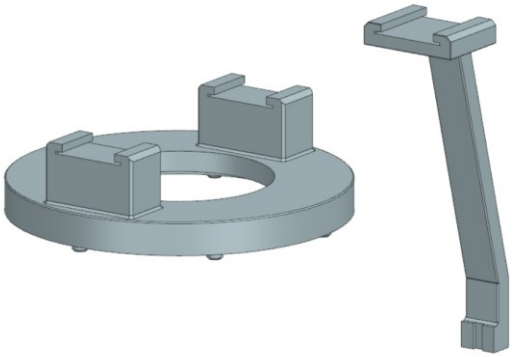

Figure 12. Stator jig concept.

Absolute alignment can be seen attractive due to its independence on electrical methods. However, its successful implementation requires actions in several production phases and the stator alignment over long distance creates some uncertainty to the process. Additionally, tolerancing is required to some extent due to the concerns presented in the last chapter. With that being said, the method could be made more reliable through design changes. For example, if the position of the motor's stator was standardized, features of the frame and end shield could be directly used instead of markings.

3.3.2 Relative alignment

While the purpose of the calibration is to gain a zero output from the resolver when the motor is aligned with its a-phase, this does not necessarily mean that the resolver must mechanically be aligned with the motor's components. Instead, the resolver's parts can have an offset to the motor's components – provided it is equal for rotor and stator. In this scenario, zero output for the resolver still occurs when the motor is aligned. It could be said that the resolver is relatively aligned.

The principle can be implemented by installing the resolver to its zero position when the motor is aligned with respect to its a-phase. This method removes the need for markings and alignments in several production stages. While the resolver's zero position can be obtained through manufacturers markings, or more accurately by measuring the output, utilizing an assembly jig in the process will likely advance accuracy and consistency in the production.

The jig needs to utilize the features of both resolver parts to constrain their rotation with respect to each other. For the stator, the previously used mounting holes are suitable datums here as well and cylindrical locators can be seen applicable. In terms of the rotor however, space is more limited, and no individual features are available. For the purpose, profile locating pins can be used to trace the part's geometry (Venkataraman 2022, 16).

The assembly jig's (figure 13) body has been designed with a recess between the locators, allowing for the resolver's stator to be firmly located against the jig. The angular relationship between the inner and outer locator pattern defines the position to which the jig aligns the resolver, effectively determining the resolver output. The jig incorporates foolproofing by having openings on its outer edge in locations where access to the resolver's mounting screws is needed. Due to the asymmetry of these openings, the resolver assembly is forced to correct orientation. Furthermore, ergonomics are considered with an extended handle around the shaft.

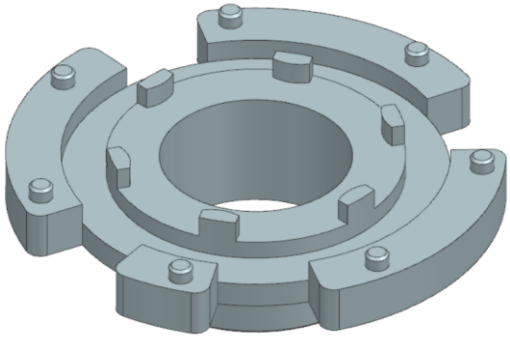

Figure 13. Assembly jig concept.

The greatest advantage of relative alignment is that it requires very little standardization for the assembly. As long as the motor is aligned with its a-phase, the resolver can be installed to its calibrated position. On the other hand, the need for motor alignment is a considerable prerequisite, one that will be further examined in the context of electrical methods. Also, possibility to re-orient both resolver components is required.

3.3.3 Combined alignment

Since the resolver's position in some motors is not freely adjustable, third method should be introduced. By utilizing a combination of the two previously presented methods the resolver can be positioned close to its intended position, but the procedure is still easily executed. In practice this means aligning one part of the resolver, rotor in this case, to its absolute correct position whereas the other part, here stator, is aligned relative to it.

For the studied motor, same tools and procedures can be used as with the previous two. First, the motor needs to be aligned with respect to its a-phase. Then the resolver's rotor is positioned absolutely by employing the markings done with the rotor jig (figure 11). Lastly, the stator is aligned using the assembly jig (figure 13). The requirements and datums for the jigs remain unchanged and hence they can be used with little further considerations.

Combined alignment can be seen as a necessary approach for the motors where constraints on adjusting the resolver are present. If, for example, resolver's rotor is fixed to the shaft with geometric features, the only way to impact its output is through rotating its stator. In such case however, the rotors' positioning would be based on design instead of mechanical

methods and sufficient adjustment range for the stator should be ensured through tolerancing. As with relative alignment, the resolver's stator could also be aligned based on the position measurement.

Instead, a motor where fewer limitations for positioning the resolver are present does not benefit similarly from the combined alignment. More tools and production stages are needed than with the relative alignment and pre-alignment of the motor is needed. Still, few practical advantages are gained, though it is noteworthy that the method reduces the impact of human error, since certain accuracy for the installation of the resolver's rotor is always required to ensure the sufficiency of the stator's adjustment range.

3.4 Electrical calibration

As discussed, certain mechanical methods require a pre-defined rotor position which is often reached by aligning the rotor with the a-phase. Additionally, verifying the PSO at the end of the production process must be done electrically. To meet these prerequisites and validation needs, it is appropriate to introduce electrical methods for resolver calibration. These methods are utilized through measurement devices or by powering and controlling the motor with an inverter. Having said that, the measurement of the resolver's output itself is not classified as an electrical method in this research as it provides no information about the resolver's orientation with respect to the motor.

Based on the existing methods presented earlier, it can be concluded that the electrical methods for obtaining the initial rotor position can be divided into two categories. The first consists of methods based on aligning the rotor with the a-phase whereas the second category relies on methods where the alignment is not needed. (Yang, Yang & Hu 2017, 1.) The first two of the three electrically assisted methods presented in this chapter utilize the alignment of the motor, but the last one seeks to detect the rotor position without rotating it.

3.4.1 LCR alignment

While Yeh & Yang (2021, 3–4) bring up the utilization of an LCR meter as the "conventional manual method" for measuring the inductance of a PMSM, research on using it for rotor

alignment is sparse. Inductance based alignment – aligning the motor through inductance measurement – requires manual operation in adjusting the rotor's position from the shaft, but it can be seen as an attractive option due to its cost efficiency and simplicity. No extensive setups or customized equipment are needed for the method, and electrical safety is more easily ensured since no voltage for driving the motor is utilized and manually turning the rotor induces only very low levels of voltage to the windings. However low saliency ratio of the rotor may decrease the accuracy to which the motor can be adjusted (Krishnan 2017, 312).

The circuit connection seen in figure 14 can be utilized to measure the inductance in the a-phase of the PMSM. The inductance measured between the points A and B, the line-line inductance, can be used to calculate the inductance for the rotor's d- and q-axis by aligning the desired axis with the a-phase and multiplying the line-line inductance by $\frac{2}{3}$. (Rallabandi, Taran, Ionel & Zhou 2019, 4–6.) However, for utilizing the LCR measurement the value of the inductances itself is of less importance. Instead, the maximum of the measured inductance needs to be identified for positioning the d-axis with the a-phase.

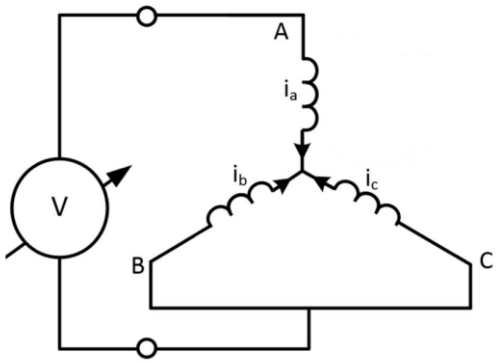

Figure 14. Circuit connection for measuring the a-phase inductance (adapted from Rallabandi et al. 2019, 4).

An experimental setup was assembled to study the viability of aligning the motor through the LCR measurement (figure 15). The setup was arranged according to the previously presented circuit (figure 14) and included a measurement of the resolver's position through

the inverter to evaluate the precision of the alignment afterwards. The inductance was continuously measured with an LCR meter. The current of the test signal was 20 mArms and a frequency of 10 kHz was used since it provided a good stability for the inductance measurement.

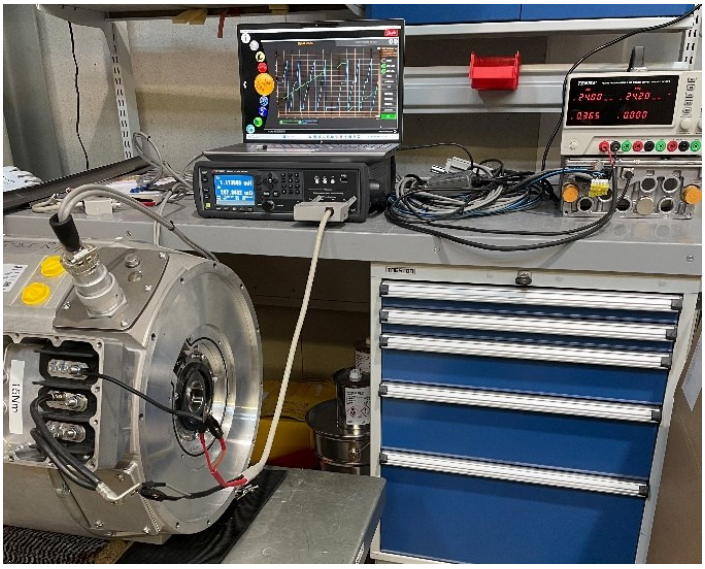

Figure 15. Setup for LCR measurement.

The shaft of the motor was slowly rotated and stopped at the peak inductance value. In the studied motor this position occurs every 30 degrees (mech.) due to the rotor's pole count of 12. It is important to note that an electrical revolution of the resolver corresponds to 60° (mech.), resulting in two electrical positions where the inductance peaks (0° and 180° (elec.)). Therefore, the zero position must first be differentiated by manually rotating the motor and measuring the direction of the induced current, either using the LCR meter or a multimeter.

The motor was rotated for three electrical revolutions, or half a mechanical revolution, and the output of the resolver was logged. By comparing the output at each alignment to the reference value – the value that the resolver should output – the PSO could be defined by the means of LCR measurement. To evaluate the correctness of these results, the true PSO value was defined as an average of several DC alignment runs.

3.4.2 DC alignment

As discussed previously, the alignment of a PMSM with respect to its a-phase is typically done through the previously discussed DC alignment. The method is straightforward to execute and should always provide close to zero orientation for the motor, making the alignment of the resolver simple. This is in contrary to LCR alignment where careful operation by hand was needed. While a more extensive setup including a power supply is needed for the DC alignment, incorporating the functionality with the end-of-line tester in the production of the studied motor creates a possibility for avoiding additional production steps. Therefore, studying the potential of electrical calibration through the method is well justified by the possible quality improvements.

The DC alignment was done by supplying the a-phase with a desired magnetizing current for the duration of six seconds. The effect of two parameters were studied: the used current and the initial rotor position. For the current, the rotor was positioned with an electrical offset of 45° with respect to the a-phase. The utilized current I was defined as a percentage of the base current 183,848 A. For testing the impact of the initial rotor position, constant current percentages of 10% and 40% were used. The initial position testing was performed from four different rotor positions: 15°, 45°, 90° and 135° (elec.).

By reading the resolver output in the aligned position, the PSO values could be defined as a difference to the zero position. While the evaluation of the PSO was done by the control software too, the calculation was redone oneself to ensure the consistency in the values. This was done by calculating the mean of the resolver output from the measurement data across the range of 5 to 6 s. To further evaluate the applicability of the DC alignment, the consistency of the PSO was studied when the alignment was done from different sides of the a-phase. Additionally, the movement of the rotor upon demagnetization was observed to see whether considerable deviations from the aligned position would occur.

3.4.3 High frequency injection

While the previous methods relied on aligning the rotor with the electrical a-phase, high frequency injection can be performed without physical rotation. This change comes with its advantages and disadvantages. On one hand, safety is more easily considered when no

moving components are involved and when the used electric current remains small. Additionally, the PSO identification is straightforward to execute since no mounting or manual adjustments are needed. On the other hand, the methods based on alignment prepare the motor's components for an easy resolver installation. In any case, HF injection should be seen as a viable alternative for determining the PSO, but its usability, accuracy, and precision must be evaluated in comparison to the other methods.

HF injection was performed using an existing feature through the inverter software. The feature is based on the previously discussed pulsating sinusoidal method and was tested for four different initial rotor positions: 15°, 45°, 90° and 135° (elec.). It was also investigated how consistent results the method would yield with constant rotor position.

4 Results

In this chapter, the results obtained in the research are described. These results can be classified by first considering, what new information has been produced. These findings serve as the basis for answering the research questions and fulfilling the goal of the research. On the other hand, analyzing these results is necessary in considering the production process perspective and in formulating the calibration methodology. Additionally, certain quantitative results require further investigation to better understand the properties of different methods. Finally, potential for generalizing the results must be considered to better evaluate what kinds of applications could benefit from the research.

4.1 New information

By applying the described research methods, results of both qualitative and quantitative nature were achieved. The results of tolerance inspection and mechanical methods are considered as information related to positioning the resolver and qualitative evaluation is emphasized. For the electrically assisted methods quantitative background was obtained instead and the results are reviewed from the perspective of identifying the position sensor offset.

4.1.1 Positioning the resolver

Considering the design of the motor through tolerances and calibration using mechanical methods was found useful in standardizing the assembly and providing the correct orientation for the resolver. However, the methods could not be proven sufficient for calibration by themselves, and their value is mainly evident in supporting the electrical methods. Despite these limitations, positioning the resolver can be seen as an integral part of the calibration methodology and the results provide information on utilizing the viewpoint.

By conducting the tolerance analysis, it was observed that the defined tolerances allowed for a variation of ± 0,9° (mech.) in the resolver's stator's mounting points. However, certain

tolerances for the motor were undefined, and by subtracting the stack-up value from the allowed variation of ± 7,75°, a tolerance stack-up of ± 6,85° was left to be assigned for the interference fits. Equally distributed, this would mean an allowed variation of ± 2,28° (mech.) for each of the fits, though further consideration may be necessary based on the size of each component. With these design improvements it could be ensured that the resolver's adjustment range always allows for the calibration and the resolver could be assembled to a standard orientation.

In terms of the mechanical methods, two of the alignment practices were rejected due to their inaccuracy, impracticality, and cost-ineffectiveness. While absolute alignment stood out as a calibration method where no electrical assistance was needed, practical viewpoints complicated its implementation. In addition to stricter tolerancing, its adoption would require design changes in the form of markings as well as several added production steps. Furthermore, the internal accuracy of the resolver makes it practically impossible to place it within the desired tolerances every time and further checkup would still be needed. It is difficult to justify the method's added value by the exclusion of the electrical methods when the cost-effectiveness of the whole production process significantly decreases – without a guarantee of successful calibration.

Combined alignment, on the other hand, was seen to create utility through a calibration, where the resolver's components would be aligned close to their designed positions with respect to the motor's stator and rotor. However, this method too requires stricter tolerancing along with changes deeper in the production process. Additionally, electrical methods would still be needed as a prerequisite. Finally, no value is gained from forcing the alignment to happen in one set position since both resolver's components are freely adjustable in the studied motor.

After these considerations, the relative alignment was selected as the preferred mechanical method. While requiring a motor alignment through electrical methods, the method itself can be executed in one simple step and is easily implemented in the production process. The jig's functioning was tested with a prototype, made by the means of additive manufacturing. It was observed that the resolver could be installed accurately with the jig allowing for a variation of ± 0,128° (mech.) in the resolver's output. However, systematic error occurred due to faulty positioning of the inner and outer locators with respect to each other. More

comprehensive documentation or further testing of the resolver would be needed to properly design the locator's position.

4.1.2 Identifying the position sensor offset

In total three suitable electrical methods were identified which could be used for finding the position sensor offset. Two of the methods relied on the rotor alignment, while one could be utilized without moving the rotor. The methods were tested according to the described arrangements. Due to the way the inverter's software processes the signals, mechanical position value was primarily utilized.

Two identification runs were performed by the means of LCR measurement. In both, six values for the resolver's position were obtained for the three electrical revolutions of the resolver. The PSO for each position was calculated by subtracting it from the reference position value, and an average of the PSOs was calculated. Finally, this average was compared to the known true PSO, yielding the accuracy to which the PSO could be defined using the LCR alignment

In the first run, the offset was calculated to be 3,78° (mech.) which translated to an error of 3,42° (mech.) with respect to the true PSO. In the second, the error decreased to 1,63° (mech.). Corresponding electrical values for the differences were 20,49° and 9,76°. While both results fall short of the desired calibration accuracy of ± 0,2° (mech.), the alignment could clearly be done with some reliability. It was also observed during the testing that short circuiting the b- and c- phases created a tendency for the rotor to align with the a-phase. This suggests that estimating the position of the a-phase could be possible without measurement devices, if done by a skilled operator. The complete results related to the method are presented in appendix 1.

DC alignment was conducted with different values of current and initial rotor position to study their effect to the alignment. For comparing the current, three of the resolver position measurement curves are presented in figure 16, which depict the mechanical response of the motor. The position sensor offset could be calculated by comparing the steady state mean to the closest sixth of a mechanical revolution (here $2 * \frac{1}{6}$). The results for other used currents are presented in appendix 2.

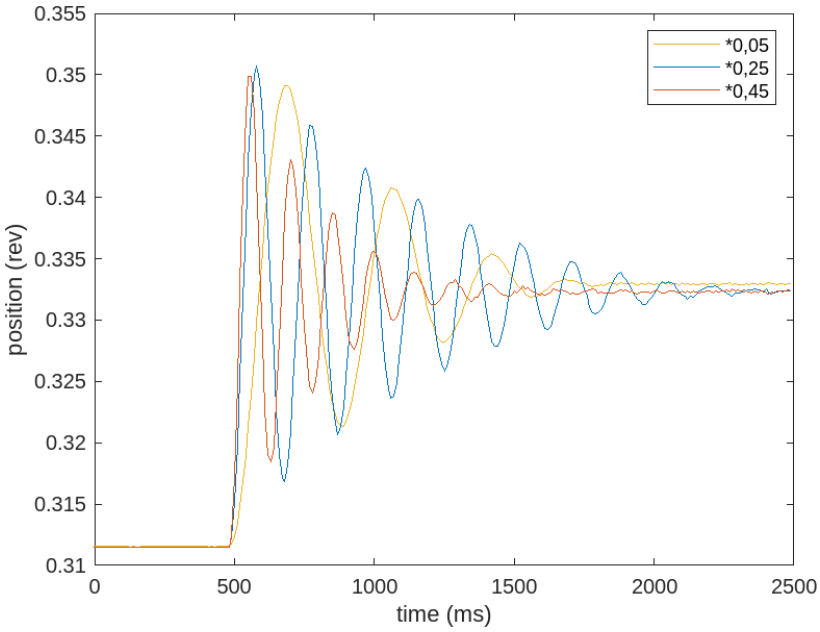

Figure 16. Impact of current in DC alignment.

The most divergent PSO value, 0,142° (mech.), was calculated for the 5% current, whereas offsets of 0,341° (mech.) and 0,374° (mech.) were derived for 25% and 45% currents, respectively. As the current was increased from 5% the offset values seemingly approached their limit with the 45% current providing a clean response but a small difference to adjacent measurements. While the rise time acted inversely proportional to increasing the current, greatest overshoot was achieved with the value 25%. This parabolic behavior was also observed in the settling time which was shortened by both increasing and decreasing the current from 25%. For raising the current beyond 55%, the power supply was deemed insufficient.

In figure 17 the mechanical response of the motor from three different initial rotor positions has been presented. The results were obtained for current multiplier of 10%. To clarify the figure, the response from 135° initial rotor position has been left out. However, complete results for the comparison are available in appendix 3.

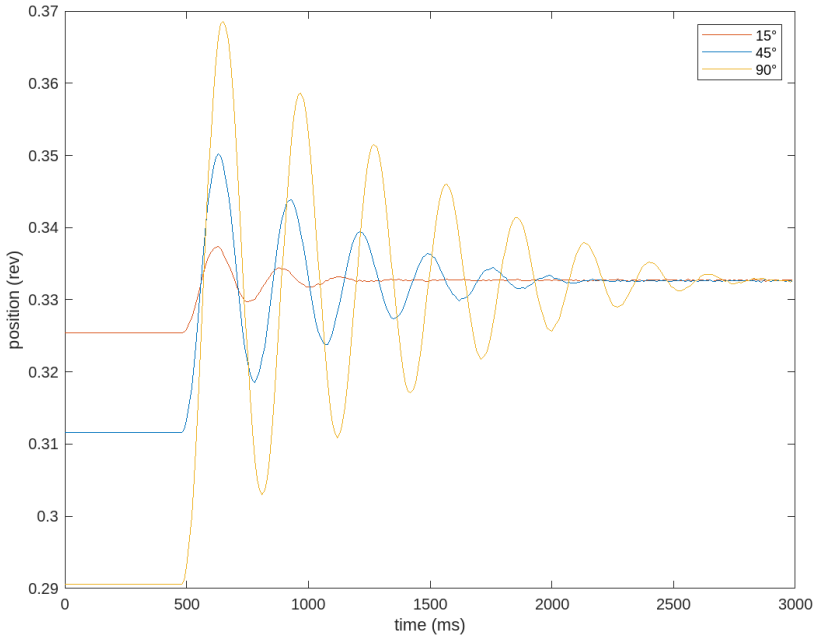

Figure 17. Impact of initial rotor position in DC alignment.

The PSOs defined for the 15°, 45°, 90°, and 135° (elec.) initial rotor positions were, respectively, 0,226°, 0,252°, 0,229°, and 0,217° (mech.). The magnitude of the overshoot and settling time increased with the initial rotor offset but the steady state value had little deviation between the cases. Increasing the current to 40% reduced the variation between the values further. However, the power supply could not produce sufficient power with the 40% current to reliably perform the alignment from initial rotor position of 135°.

Finally, high frequency injection was used to obtain PSOs for the same initial rotor positions. This provided offsets of 3,963°, 9,943°, 3,688°, and 4,411° (mech.). While the method was observed to be precise between consecutive measurements from constant rotor position, noticeable differences can be seen in the above PSOs. It can be stated that much uncertainty is related to PSO identification through HF injection, though refinements would likely be possible on software level.

4.2 Analysis

By considering the results of different viewpoints together through method triangulation, the calibration methodology can be formulated. The methodology consists of ensuring the

feasibility of the calibration through motor design considerations, utilizing mechanical locating principles – assisted by tools – in the production for correctly positioning the resolver's parts, and applying electrical methods to provide a standard orientation for assembly as well as for evaluating the success of the calibration. This electrically assisted calibration of a PMSM should be applied in the context of the equipment utilized at the time, as seen in this research.

Furthermore, the results related to determining the position sensor offset should be analyzed to compare the performance of the electrical methods. For the LCR alignment, consistent accuracy was achieved but the results deviated noticeably from the other methods. This suggests a lower precision for the LCR alignment, though still within the range where clear consistency could be seen. Similarly, some degree of variation could be seen in the results produced by high frequency injection. While the repeatability of the measurements was generally good with constant parameters, changes in the initial rotor position notably affected the PSO. Also, the values diverged from the ones obtained with DC alignment.

Since DC alignment's functioning is based on aligning the motor through the same electromagnetic properties that are utilized in the normal operation, DC alignment can be seen as the most reliable of the electrical methods. This is also advocated by its consistency in the defined PSO values, or inversely, in the uncertainties of the other methods. However, variations in the motor's response can also be observed in DC alignment when different parameters are compared, as seen in the results.

Increasing the magnetizing current can be seen first increasing the overshoot and settling time. After a certain threshold however, the impact of the current starts to reverse and further increases to it decrease the overshoot and settling time. This parabolic relationship could be caused by the current always adding to the acceleration from the initial rotor position but requiring a greater magnitude to introduce sufficient deceleration. However, the rise time acts in a more linear fashion, decreasing as the current is increased. The same can be perceived in the steady state value of the response, where a low current causes deviation from the values acquired with higher ones.

The effect of the initial rotor position was more linear and the rotor's offset to the a-phase predicted the magnitude of the overshoot and settling time. No significant steady state error was discovered as in comparing the different values of current. Limitations were seen in

using the 135° (elec.) initial angle, however, which was likely due to the insufficiency of the power supply when a greater current was drawn to match the required torque. It is also noteworthy that in some cases the position measurement was slightly altered after the current was shut off, though this phenomenon can be seen minor as its effect was estimated to fall in the range of 0,03° (mech.) max.

4.3 Concrete applications and generalized results

While the numerical results and the details regarding the methods are widely dependent on the used equipment and parameters, the qualitative aspects can be seen well generalizable. For example, in terms of the design and tolerance analysis significant reconsiderations would have to be done if different motor/resolver combination was to be calibrated. If the number of components is altered, the allowed variation of the components is likely to change. On the other hand, different design solutions can greatly impact the magnitude of individual tolerances.

Even though mechanical methods were seen applicable for the studied motor, their usability is heavily dependent on the specific design. If either of the resolver's parts is not sufficiently adjustable, it should be aligned with the motor's components through design choices. Additionally, the locating principles used with the tools are motor specific, meaning that they could be either easier or harder to implement in a motor with different geometrical features.

By contrast, the electrical methods can be expected to be well applicable with different PMSMs since the fundamentals of the electrical operation change little between models. Especially DC alignment can be expected to be a suitable method for finding the initial rotor position due to its simplicity and reliance on these fundamentals. However, the usability of LCR alignment and HF injection may suffer from low saliency ratio of the rotor. Also, changing the pole count of the motor or resolver could impact the accuracy of the calibration since a higher pole count would call for finer mechanical adjustments.

In terms of concrete applications, considering the results together can be seen to create a framework for the calibration process. This argument is promoted by the fact that the development and selection of the methods was done with an emphasis on a specific PMSM's

production. In context of the studied motor, the process could be easiest implemented around the end-of-line testing where the motor is connected and run with an inverter in any case. Nevertheless, the methodology would have to be considered earlier in the process too and utilizing the methods versatilely provides means for this – especially from the point of view of electrical safety.

5 Discussion

To evaluate the success of the research and correctness of the results, objective review is required. On the other hand, the results should be linked to the context of previous research and the possibilities for future studies must be considered. In this chapter, these viewpoints are discussed to provide deeper understanding of the results. Most importantly, strategies on implementing the methodology are provided as key findings.

5.1 Reliability and validity

The research was begun by conducting a literature review which was based on several scientific publications. The reliability of used articles was evaluated through the Field Weighted Citation Impact indicator in Scopus, which estimates how much an article is cited compared to similar ones. While some of the used sources held below average scores (less than 1) or the rating was missing, this was compensated with additional, better scored references (up to 3,72). Comparing the references with each other and building a dialogue between them can be expected to ensure the reliability of the literature review. Furthermore, the validity of the references was considered by classifying them in the used citation manager based on their subject area according to the chapters of this research.

Since the sample size for the quantitative results is relatively small, reliability evaluation of the data through distributions exposes it to oversensitivity. Hence, the random error is best considered through mean absolute deviation. Value of 0,051 for it was calculated from the PSO results of current comparison with DC alignment. Compared to the required accuracy of ± 0,2° (mech.) the deviation can be seen to promote method's reliability. For the LCR alignment, mean absolute deviations of 0,580 in the first and 0,292 in the second run were calculated. The figures indicate that much more uncertainty is related to the LCR measurement, even exceeding the allowed variation. Thus, LCR alignment should mainly be used by considering average of measurements, not through individual measurements. This principle was in fact utilized when defining the PSO with LCR alignment. The systematic error was considered in the comparison between the measured average and true PSO.

Furthermore, the validity of the methods has been ensured by continuously considering the theoretical background and requirements of the production.

The sensitivity of the results has been considered by conducting a sufficient number of measurements. Especially for the results of DC alignment, a sample of great size would be needed for invalidating the conclusions. For LCR alignment and HF injection this critical sample size is smaller, however. Changes in just a few numerical values could theoretically impact the conclusions. In response, the methods' consistency was qualitatively evaluated with successive measurements in addition to the recorded ones. The results are also in line with the theoretical background, decreasing their sensitivity. On the other hand, the research's objectivity is promoted by the combination of qualitative and quantitative viewpoints.

Finally, some considerations related to the testing conditions should be done. Since no standardized mounting was used, inaccuracies in the results could be caused by the vibration of the motor. While this effect was observed neglectable, it should be kept in mind in future research. Additionally, the accuracy of the utilized measurement devices should further be investigated to determine their reliability.

5.2 Key findings

The outlined methodology provides answers to the set research questions. Calibrating the resolver of a PMSM as a part of its production process is possible by the discussed means. Furthermore, it was shown that the calibration can be performed to a certain accuracy without powering the motor through a high voltage inverter.

The comparison of the qualitative and quantitative results provided information on the accuracy and usability of the methods. It was observed that the most consistent and straightforward rotor position identification was achieved with DC alignment. The method was seen reliable with different parameters if certain current threshold was exceeded. Furthermore, it could be paired with mechanical alignment, for which relative alignment was seen as the most appealing method.

Based on the findings, two strategies for utilizing the methodology can be formulated. On one hand, a simplified approach could be taken where the motor is DC aligned so that the

resolver can be installed according to the principle of relative alignment. Depending on the desired accuracy, LCR alignment could also be utilized here since the results remained within the resolver's adjustment range. Though, a second DC alignment would likely be needed to verify the PSO and to enable fine adjustments. Little design considerations would be needed with the strategy but sufficient adjustment range for the resolver's parts is required. This may be a limitation with motors where either of the resolver's parts is mounted to a fixed position.

On the other hand, a more sophisticated strategy could be utilized where design solutions and tolerancing are utilized through the principle of combined alignment to make sure that the resolver's parts can always be adjusted to their correct position. DC alignment would only be needed for checking the PSO and enabling fine adjustments. While the practice would require greater design considerations, it would reduce the effect of the human factors in the assembly process, likely improving the production consistency.

5.3 Novelty value of the results

As described, PMSMs and resolvers are common appliances nowadays and the scientific community has actively explored these topics for some time. Connections with former research can be made, for example, with Zossak et al. (2018) who studied the properties of DC alignment and compared the method to a form of HF injection. Many of their observations are in line with the results presented here. However, the conclusions on the benefits of the HF injection in this research are quite opposite to theirs, mainly because of the on-load conditions in their testing.

Still, research on resolver calibration to the extent of this study is scarce and the methodology provided here can be expected to comprise novel information. Additionally mechanical methods, often overlooked as a trivial part of the assembly and calibration process, were developed to greater depth in the research. This enables a more precise discourse on the subject in the future. Finally, rotor alignment using an LCR meter has not been widely considered in previous studies, suggesting that its comparison to better known methods has produced noteworthy results.

5.4 Topics for future research

An interesting continuum for the methodology would be its implementation to production. This would offer a possibility for monitoring the consistency of the methods through statistical analysis. Deviations could happen due to different human errors such as rotor movements during the resolver's assembly. Feedback on the usability of the methods, in turn, could be collected with surveys. Also, the LCR meter's applicability for measuring the d- and q- axis inductance values at the end of the production process could be tested.

Additionally, an important consideration would be the quality control of the utilized resolvers. If major mechanical variations in the component occur, limitations on using mechanical methods could be faced. Furthermore, the mechanical methods should be considered more profoundly from the design changes' perspective. While guidelines have been provided here, practical solutions should be presented for individual products.

To improve the motor's response in DC alignment, more complex inverter routines could be introduced. For example, overshoot could be reduced by changing to a ramp signal which would likely produce lower acceleration for the rotor but yield the benefits of the increased current going further in the routine. Also, including a second alignment from the other direction could give a better estimate of the PSO even though this difference was estimated minor.

6 Conclusions

The motivation for this research was drawn from the need for cost efficient and production friendly methodology for calibrating the resolver of a PMSM. Three viewpoints for methods were established and the calibration methodology was formed based on the design, mechanical methods and electrical methods. Based on a literature review different methods were formulated and compared within these viewpoints to provide reliable means for calibration. By analyzing the results, accuracy of the methods was considered and conclusions on their applicability were drawn. Finally, strategies for implementing the methodology were outlined.

While research on electrical calibration methods and software solutions has been done, framework for implementing the calibration as part of the production process is rarely presented. In this regard the research has produced novel information which a producer of electric motors could utilize – contributing to the global trend of electrification. However, future research should be conducted on implementing the methodology to production to evaluate the impact of human factors and other deviations.

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Appendix 1. Results of the LCR alignment

n (mech.)	deg (mech.)	Reference	Offset	
0,3441	123,87	120	3,87	
0,4252	153,07	150	3,07	
0,5128	184,59	180	4,59	
0,5962	214,62	210	4,62	
0,6750	243,01	240	3,01	
0,7598	273,52	270	3,52	
			3,78	° (mech.)
			0,0105	r (mech.)
		True offset:	0,0010	r (mech.)
		Difference:	0,0095	r (mech.)
			3,42	° (mech.)
			20,49	° (elec.)

(Resolver adjusted -> change in true offset)				
n (mech.)	deg (mech.)	Reference	Offset	
0,8609	309,92	330	20,08	
0,9451	340,24	0	19,76	
0,0278	10,01	30	19,99	
0,1109	39,92	60	20,08	
0,1970	70,92	90	19,08	
0,2790	100,44	120	19,56	
			19,76	° (mech.)
			0,0549	r (mech.)
		True offset:	0,0594	r (mech.)
		Difference:	0,0045	r (mech.)
			1,63	° (mech.)
			9,76	° (elec.)

Appendix 2. Impact of current in DC alignment

Multiplier	Current (A)	Calculated PSO (rev, mech.)	Complement (rev, mech.)	Final PSO (deg, mech.)
0,05	9,1924	0,16627	0,0004	0,142
0,1	18,3848	0,16597	0,0007	0,252
0,15	27,5772	0,16582	0,0008	0,304
0,2	36,7696	0,16576	0,0009	0,327
0,25	45,962	0,16572	0,0009	0,341
0,3	55,1544	0,16568	0,0010	0,356
0,35	64,3468	0,16564	0,0010	0,369
0,4	73,5392	0,16564	0,0010	0,369
0,45	82,7316	0,16563	0,0010	0,374
0,5	91,924	0,16561	0,0011	0,379
0,55	101,1164	0,16563	0,0010	0,375
0,6	110,3088	0,16556	0,0011	0,399

Appendix 3. Impact of initial rotor position in DC alignment

Multiplier	Position (deg, mech)	Calculated PSO (rev, mech.)	Complement (rev, mech.)	Final PSO (deg, mech.)
0,1	15	0,16604	0,0006	0,226
0,1	45	0,16597	0,0007	0,252
0,1	90	0,16603	0,0006	0,229
0,1	135	0,16606	0,0006	0,217
0,4	15	0,16567	0,0010	0,360
0,4	45	0,16564	0,0010	0,369
0,4	90	0,16565	0,0010	0,365
0,4	135	0,16029	0,0064	2,297