同濟大學

TONGJI UNIVERSITY

COLLEGE OF ELECTRONICS AND INFORMATION ENGINEERING

Bachelor of Science
in
CONTROL THEORY AND CONTROL ENGINEERING

Design and Optimization of a semiautomated Assembly Line for Axial Flux Drives

Internship Thesis Project in Automatic Machines

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Abstract

Due to the high torque and power density, Axial Flux Permanent Magnet (AFPM) machines are a promising solution for electric vehicles (EVs) and high-efficiency applications. However, the so-called pancake motor poses significant challenges to the manufacturing process due to its unusual stator design and the high precision needed for proper rotor placement. This results in high cost and poor volume scalability. In this thesis, a design case study is presented, drafting possible solutions to the mentioned problems. A prototype assembly process is analyzed and its scale-up to a semi-automated low-capacity assembly line is designed. In particular, the manufacturing and testing steps are reduced and optimized, applying lean line design techniques. Among the most important issues, resolver-calibration, rotor's spacer-ring dimensioning and the design of an ergonomic standard workbench are addressed. The experimental results obtained in design verification tests are presented and discussed.

Keywords: axial flux machines, lean manufacturing, assembly line design

Abstract (Chinese)

由于高转矩和功率密度，轴向(AF)永磁(PM)电机是一种很有前途的电动汽车和高效应用的解决方案。然而，所谓的盘式电机设计，由于其独特的定子设计和转子所需的高精度，给制造工艺带来了重大挑战。这导致了高成本和低产量可扩展性。在本论文中，我们提出了一个设计案例研究，并对上述问题提出了可能的解决方案。分析了样机装配工艺，设计了半自动低产能装配线。特别是，采用精益生产线设计技术，减少和优化了制造和测试步骤。其中最重要的问题是旋转变压器的标定、转子隔环的尺寸确定和人机工程学标准工作台的设计。给出并讨论了设计验证试验的实验和仿真结果。[1]

关键词： 轴流电机；精益制造；装配线设计；工效学工作台

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[1] 完整摘要见第87页附录B。

Acronyms

AC Alternating Current. 9, 93

AF Axial Flux. vii, 3, 4, 6, 7, 9, 93, *Glossary:* Axial Flux

AFPM Axial Flux Permanent Magnet. iii, 2–4, 6, 9, 10, 12, 83

AIDC Automatic Identification and Data Capture. 7, 59

AM Additive Manufacturing. 6, 84

BEV Full Battery Electric Vehicle. 4

DC Direct Current. 1

DSSR Double Stator Single Rotor. 3, 9, 10, 93

DUT Device Under Test. 35, 80

emf Electromotive Force. vii, 9, 35, 38, 78–80, *Glossary:* Electromotive Force

EOL End Of Line. 7, 31, 33, 35, 48, 65

EV Eletric Vehicle. iii, 3, 4, 9

HEV Hybrid Electric Vehicle. 4

IGBT Insulated-Gate Bipolar Transistor. vii, 3, *Glossary:* Insulated-Gate Bipolar Transistor

IIoT Industrial Internet of Things. 6

MES Manufacturing Execution System. 7, 84

mmf Magnetomotive Force. vii, 93, *Glossary:* Magnetomotive Force

MOSFET Metal-Oxide-Semiconductor Field-Effect Transistor. vii, 3, *Glossary:* Metal-Oxide-Semiconductor Field-Effect Transistor

ODE Ordinary Differential Equation. 37

PM Permanent Magnet. vii, 9, 20, 21, 23, 24, 39, *Glossary:* Permanent Magnet

RF	Radial Flux. viii, 3, 4, 9, 93, *Glossary:* Radial Flux
RFPM	Radial Flux Permanent Magnet. 2, 9
RMS	Root Mean Square. 79, 80
SMC	Soft Magnetic Composite. 6
SSDR	Single Stator Double Rotor. 6, 93

Contents

Chapter I

Introduction

THE need for finished manufactured goods in large quantities is steadily increasing since the 19th century. Technological improvements in manufacturing plants play an essential role in reducing costs and allowing a high standard of living for more people. Indeed, as discussed in [1], most of the products produced are related to the latter:

> The most advanced consumer products of today are associated with high standards of living, such as vehicles for transportation, electronic equipment for communication, business and leisure, and products for recreation and amusement. [1, p. 2]

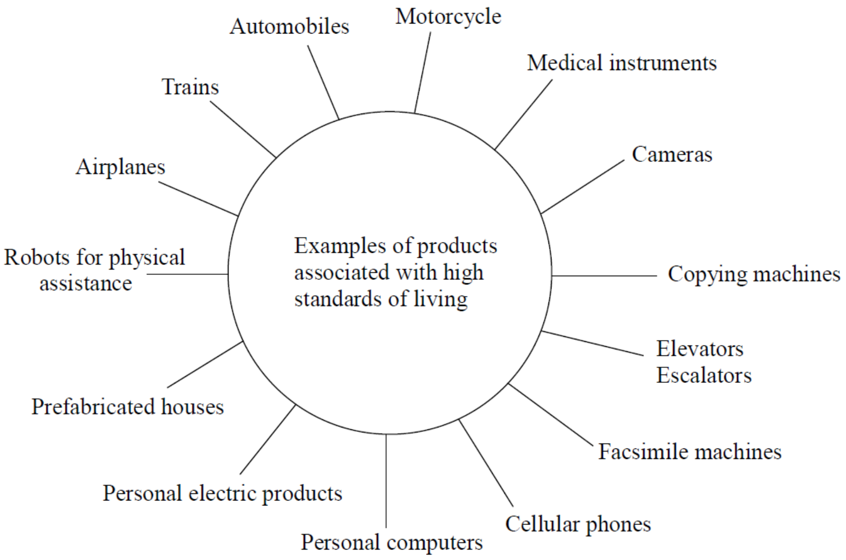

Figure 1.1: Products associated with a high living standard[1]

Figure 1.1, shows some common examples of products associated with a high living standard. It is interesting to note, that almost all of them *include electrical drives* in a power range varying in several orders of magnitude, from the tiny vibration Direct Current (DC) motors to high power asynchronous induction machines in trains. It is needless to mention that in order to satisfy this demand, smoothly working production systems are needed.

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[1] Taken from [1, p. 2]

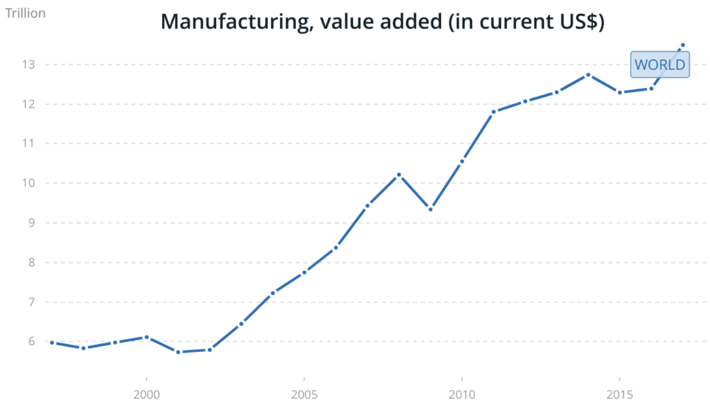

Figure 1.2: Value added in manufacturing worldwide[2]

Figure 1.2 points out the steady increase and incredible value in the order of trillion US dollars, which is added in manufacturing industries worldwide. Especially for small companies and innovation-driven startups the given dimension of the markets can be a true challenge. It is therefore a common approach for startups to choose a niche market first, avoiding high-volume demands. When the innovation gains market acceptance though, the production system needs to be adapted accordingly.

This kind of scale-up from prototype to mass production requires crucial design decisions, often paired with a high risk. Some of the most important trade-offs involved are:

- maintaining customer-tailored product design while standardizing a simplified production process
- maximizing production volumes while maintaining costs low

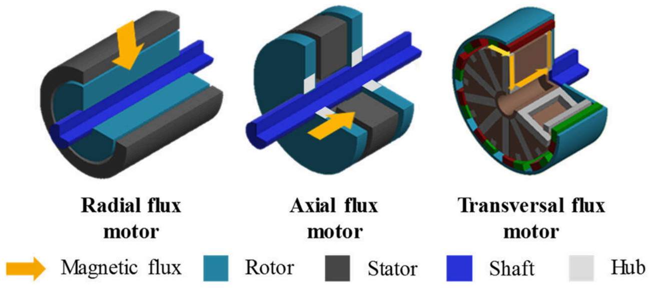

Figure 1.3: Electric drive flux topologies[3]

This thesis addresses those issues in a particular case study on Axial Flux Permanent Magnet (AFPM) synchronous motors, see fig. 1.3. Compared to the widely adopted Radial Flux Permanent Magnet (RFPM) motors, they offer many significant advantages from a performance point of view, such as higher power density and compact design. However, *several issues in part fabrication and final assembly* kept production and development costs too high to compete. This project tries to overcome those drawbacks by analyzing an *existing prototype production* and designing the scale-up to a semiautomated, low-capacity assembly line, primarily focusing on production process solutions without compromising the existing motor design.

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[2] See [2]

[3] Taken from [3]

1 Industrial Context

Figure 1.4: Magelec Propulsion LTD

This thesis is based on an internship project carried out in the R&D department of **Magelec Propulsion LTD** in Shanghai. Magelec is an integrated manufacturer of electric powertrains that produces AFPM synchronous drives, IGBT and MOSFET based engine control systems and transmissions.

The core product is the AFPM synchronous electric motor in Double Stator Single Rotor (DSSR) topology, which is a well performing product especially in Eletric Vehicle (EV) applications. Prototypes have already been used successfully in the highly competitive Formula E car racing circuit. The successful implementation of the prototypes even in a more widespread range of powertrain solutions, led to requests for higher volume productions of several models.

In the following chapters, the prototype assembly process will be analyzed and optimized for a first low-capacity assembly line. More details on the product range will be provided in section 1 on page 9.

The internship project extends to a group of three students, in which other two thesis works have been carried out. They treat details about a measurement station, see [4], and the end of line testing, [5], both integral part of the assembly line design. Therefore, they will be discussed in their basic approaches in their respective sections in section 4 on page 33.

2 Motivation

As discussed in [6, p. 3], AFPM drives, are difficult to handle from a manufacturing point of view. The main issues are:

uniform airgap The axial flux design implies to put the airgap parallel to the shaft direction. The airgap thickness has a large impact on performance, since it directly affects the flux path's reluctance. In order to keep it as small as possible, stator and rotor must be placed as close as possible. This requires them to have a smooth and uniform surface, i.e. *small manufacturing tolerances*. Furthermore, it must be guaranteed that the small distance is uniformly kept during the whole product life cycle under any operating condition.

laminated stator cores The unusual stator design makes it difficult to laminate the core. Several techniques have been developed such as cutting slots later or wind the stator from thin layered material. However, they are still expensive with respect to widely adopted techniques used for radial flux (RF) motors.

A good solution to those issues could cut down the cost and unleash the potential of better performing AFPM synchronous drives. From the company's point of view this would translate to a significant competitive advantage.

2.1 Electric Vehicle Revolution

According to [7], the EV revolution is predicted to hit the market in the near future. As fig. 1.5 shows, the current trend is more directed towards hybrid electric vehicles(HEV), but full battery electric vehicles (BEVs) will play a significant role with over 35 % market share in 2040. Also the trend of falling battery prices, investigated in [8], underlines this market direction.

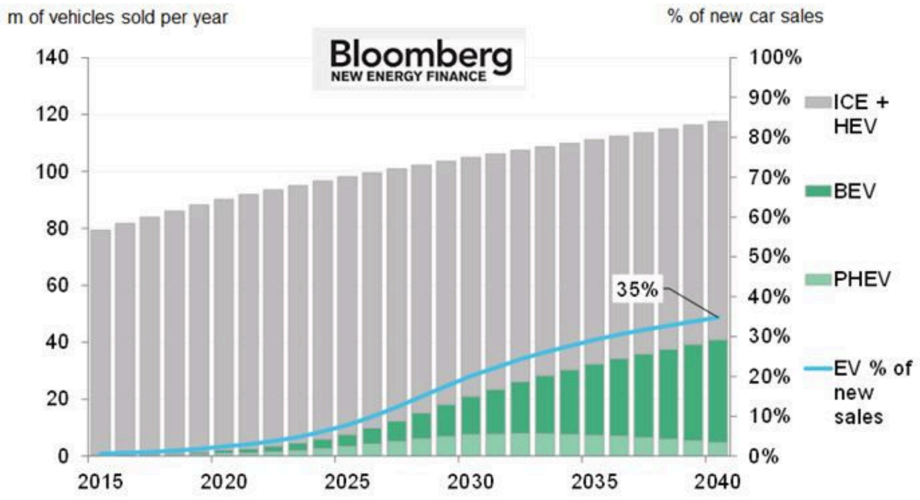

Figure 1.5: EV Revolution[4]

From a technical point of view, in the most common case both HEVs and BEVs will rely on electrical drives in their powertrains. Therefore it can be expected that the market around electric motors will increase in any case.

From an ecological point of view, this ongoing development towards EVs can be seen as beneficial for the efforts to mitigate climate change. Without going into details, BEVs are known to perform much better in terms of energy efficiency on the road. One of the most import factors in the overall product-life-cycle eco-balance remains therefore the battery. Recent studies[5] show that the eco-efficiency of Lithium battery packs production is mostly governed by the electricity mix available to the production facility. The energy sources can be improved and turned into regenerative options over time, whereas vehicles ones on the road are difficult to change. This means that in any case, removing air polluting combustion engines from the transport systems is an important and *necessary* first step.

In this context, the AFPM synchronous motor with its high-power density could reduce raw material consumption and further increase efficiency. However, as fig. 1.5 drafts, the disruption in the automotive industry with EV technology will happen soon. So for axial flux (AF) motors to make an impact, production volumes need to increase significantly to lower the costs. Only in this way the technology can offer a valid alternative to conventional RF machines.

2.2 Ergonomic Workplace

As pointed out inter alia in [10], an ergonomic design of the workstations can reduce injuries and improve productivity. In the early stages of development, design decisions define the level

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[4] Taken from [7]

[5] see [9]

of safety and quality in the workstations. Subtle differences such as work table height or floor mats can heavily impact the life and health quality of operators for many years. So besides the increased productivity, this directly impacts safety and job quality for future operators.

3 State of the art

Automated manufacturing systems can be divided into different categories, see fig. 1.6, explained in [11].

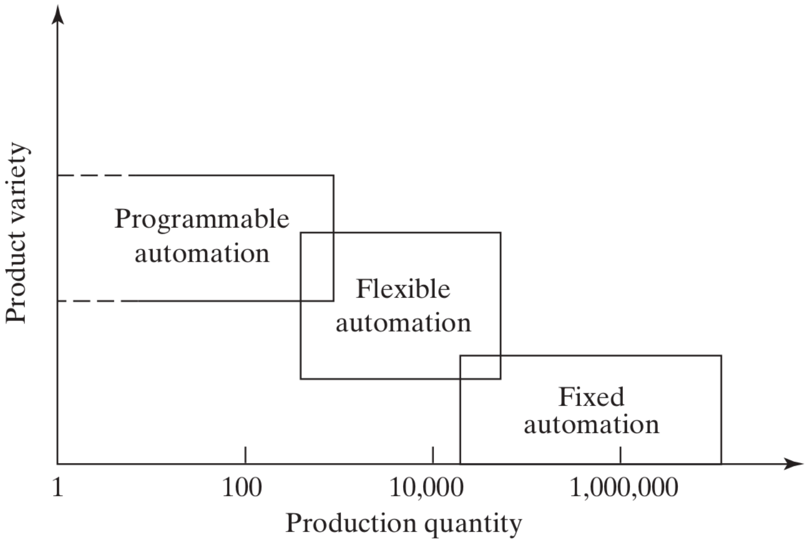

Figure 1.6: Types of automation

The most suitable system for the project's needs would be *flexible automation*, capable of producing different models with negligible changeover time. However, scaling-up a *prototype* production directly to an automated system is unfeasible in most cases. Flexible automation shall therefore be used just in some workstations to implement a semiautomated process.

This human machine interaction is typical for a worker-machine system where *collaboration* guarantees rapid adaption to changing workflows. A high-end state-of-the-art approach is *collaborative robotics*.

3.1 Collaborative Robotics

A more recent trend in robotics is to offer collaborative solutions, where machines interact directly with the operators. E.g. in [12], a heterogeneous assembly line layout is pictured, where workers of any age can ergonomically work *together* with collaborative robots. However, the adoption in the industry is still at an early stage and the actual feasibility of such flexible learning systems in production environments needs yet to be demonstrated.

3.2 Lean Production

A nowadays established industry standard is lean manufacturing, see inter alia [13]. It is basically a systematic approach for minimizing waste and inventory by establishing a continuously improving flexible production system. The lean technique has evolved to a mindset used also in management and organizational tasks. Core concepts include worker involvement and customer focus. An overview can be found in [11, p. 751].

3.3 Made in China 2025 and Industry 4.0

Both China, and Europe, in particular Germany, promote the application of IT-technologies in manufacturing environments. Keywords such as Industrial Internet of Things (IIoT) have become important drivers for better connected and interfaced devices. In [14] Li compares the two plans with each other and the country's capabilities in terms of human capital, manufacturing capability and Research&Development. According to Li both plans chase smart manufacturing systems employing digital networking within and beyond the factory to both customers and suppliers.

3.4 Axial Flux Machines Production

Regarding the specific production issues with AFPM machines, [3] proposes interesting new approaches. In particular, the use of innovative materials such as Soft Magnetic Composites (SMCs) or high-performance thermoplastics to further increase power density is suggested. For what concerns the stator core lamination, SMCs is proposed to make an ironless stator. Beyond reducing weight, this simplifies also the final assembly process due to reduced magnetic interactions. However, the approach is limited to the Single Stator Double Rotor (SSDR) topology.

Furthermore, Kampker, Treichel, Kreisköther, *et al.* suggest to apply Additive Manufacturing (AM) for stator fabrication. Special materials can be created directly in the required shape, without the need for expensive and inflexible casting processes.

In the industry, recently a Belgian startup called Magnax[6] showcased a new SSDR motor design. According to their claims, several issues have been solved, allowing sustainable mass production of a high performance AF machine.

3.5 Related Publications

As a general reference for manufacturing systems [11] is recommended. [16] contributes with a quick overview on AFPM, whereas a more sophisticated reference is given with [6].

A future outlook of how collaborative robotics can be applied to assembly lines is provided in [12]. New innovations for AFPM manufacturing are proposed in [3]. new typologies of electric drives without air gap are studied in [17]. Detailed studies on resolver impact on motor performance are given in [18].

3.6 Summary

The currently available solutions regarding AFPM motor manufacturing are rather widespread and their usage and performance yet to be proofed in real world scenarios. New manufacturing trends, such as Industry 4.0 or collaborative robotics open up new possibilities for early-adopters. However, for this cost-critical production ramp-up to a low capacity assembly line, their implementation would be unsuitable and too risky. Interesting approaches with AM and new innovative plastic compounds are proposed, which nourish the overall exciting developments in the industry.

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[6] see `www.magnax.com`, accessed on , or more specifically [15]

From a general manufacturing point of view, a well established approach to manufacturing remains the *lean* technique. The industry-wide adoption makes it a common language for key elements in assembly line design.

4 Innovation

This thesis tries to apply the state of the art manufacturing concepts to a small capacity assembly line. The innovation lies thereby in the complex realization of mass production of AF drives in a real world scenario.

5 Thesis Outline

In chapter II, the existing production workflow is analyzed and bottlenecks are identified. The major planned improvements are presented and elaborated.

A possible solution to a special subproblem is treated in chapter III on page 39: the mechanical resolver calibration. Besides of simplifying the End Of Line (EOL) test, this additional procedure constitutes also a significant benefit in terms of interchangeability at the customer's side.

Chapter IV on page 47 designs the assembly line, defining the new process flowchart and a balanced production step allocation. Moreover, the design of the standard workbench is carried out, satisfying both ergonomic and technological needs. Finally, the assembly line layout is presented.

In chapter V on page 59, the manufacturing system design is completed by integrating a possible software system, i.e. Manufacturing Execution System (MES) for Automatic Identification and Data Capture (AIDC).

Chapter VI on page 77 presents some experimental results of test that have been carried out to evaluate the feasibility of the design.

Finally, chapter VII on page 83 comments the accomplished work and gives an outlook on future improvements and developments.

Chapter II

Workflow Analysis and Requirement Definition

In this chapter, the product to be manufactured is shortly introduced and the existing assembly workflow for the prototypes is analyzed. Afterwards, the main bottlenecks are identified and the major changes regarding crucial process parts are presented.

1 Product to be manufactured

As already outlined in chapter I, the product to be manufactured is an AFPM synchronous machine, in different kind of sizes and power ranges.

1.1 Axial flux PM machines

AF drives, also called disc-type machines, have a compact pancake shape with a reduced axial dimension with respect to a RF machine. With their high power density they are suited for various different applications, among which, EVs, machine tools, robots, pumps and fans. Due to their shape they can carry a large number of poles and can therefore also be used for high-torque – low-speed applications such as wind turbines.

In conventional RF machines, the air gap is directed in the radial direction, while in AF machines, the flow is directed axially. The active parts for generating the torsion surfaces, i.e. the surfaces on which conductors and permanent magnets (PMs) are arranged, are perpendicular to the axis.

AFPM machines have been invented in the early 1830s[1], however due to the lack of good quality ferromagnetic materials and the challenging fabrication process, they have not been used until the late 20th century. Even with the rise of good quality and low-price PMs, RFPM machines have dominated the market because of the more robust manufacturing process.

There are several types of AFPM drives. Magelec focuses on the DSSR AFPM Alternating Current (AC) synchronous machine. The AC synchronous machine generates a sinusoidal Electromotive Force (emf) waveform and is operated with sinewave currents, just like its RF equivalent.

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[1] see [6]

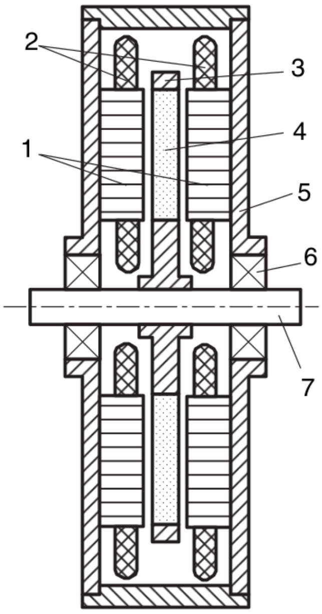

Figure 2.1: Double Stator Single Rotor Topology. 1 — stator core, 2 — stator winding, 3 — rotor, 4 — PM, 5 — frame, 6 — bearing, 7 — shaft.[2]

Figure 2.1 illustrates the topology. The single rotor is located in between the two stators. With the laminated stator cores the air gap can be reduced to a minimum which enhances performance.

1.2 Product models

Magelec's AFPM drives satisfy a power range from 20 kW to 180 kW, considering the models M17 up to M34. The models names come from the active machine diameter.

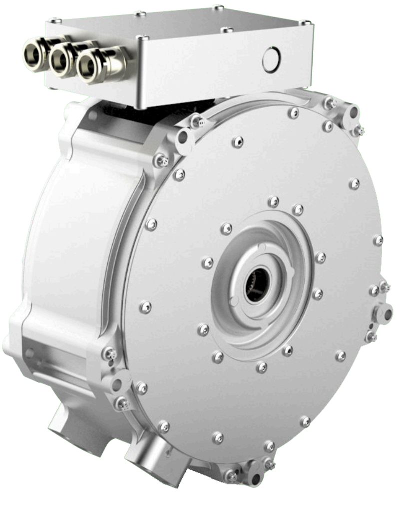

Figure 2.2: M21 AFPM motor

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[2] Taken from [6]

Most of the models have 5 pole pairs. Figure 2.2 shows the representative M21 with a peak torque of 206 Nm. In table 2.1 the specifications of the most common models can be found.

With increasing diameter, the machines produce higher torques but show lower top speeds.

Torque Cont:	46 Nm
Torque Peak:	131 Nm
Power Cont:	44 kW
Power Peak:	116 kW
Efficiency Peak:	>95 %
Speed Max:	15 000 rpm
Case Ω:	268 mm
Case L:	119 mm
Mass:	19.5 kg

(a) M19

Torque Cont:	85 Nm
Torque Peak:	206 Nm
Power Cont:	58 kW
Power Peak:	120 kW
Efficiency Peak:	>95 %
Speed Max:	12 000 rpm
Case Ω:	288 mm
Case L:	119 mm
Mass:	23 kg

(b) M21

Torque Cont:	162 Nm
Torque Peak:	368 Nm
Power Cont:	75 kW
Power Peak:	161 kW
Efficiency Peak:	>95 %
Speed Max:	9000 rpm
Case Ω:	323 mm
Case L:	129 mm
Mass:	32.5 kg

(c) M24

Torque Cont:	215 Nm
Torque Peak:	580 Nm
Power Cont:	77 kW
Power Peak:	174 kW
Efficiency Peak:	>95 %
Speed Max:	7350 rpm
Case Ω:	348 mm
Case L:	143 mm
Mass:	43.5 kg

(d) M27

Table 2.1: Key Specifications

2 Requirement Definition

The management's requirement for the assembly line, is to produce **5000 units/year**.

As discussed in [11, p. 398], the necessary production rate can easily be calculated as[3]:

$$R_p = \frac{D_a}{50\, S_w\, H_{sh}} \tag{2.1}$$

Where

R_p is the resulting production rate per hour

D_a the yearly demand, i.e. 5000 units

S_w the number of shifts per week

H_{sh} the hours per shift

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[3] considering 1 year = 50 weeks

Assuming to perform 1 shift per day and operate only on workdays, $S_w = 5$. With regular 8 h/shift we get:

$$R_p = \frac{5000}{50 \cdot 5 \cdot 8} = 2.5\ \text{units/h} \tag{2.2}$$

To achieve, this required production rate of 2.5 units/h, line efficiency needs to be taken into account, as suggested also in [13, p. 49] and [11, p. 399]. The cycle time in minutes can therefore be defined as:

$$T_c = \frac{60\,E}{R_p} \tag{2.3}$$

Considering a line efficiency E of 85 %, which will ensure that operators maintain a high-quality and can avoid defects, the resulting cycle time is:

$$T_c = \frac{60 \cdot 0.85}{2.5} = 20.4\ \text{min} \tag{2.4}$$

In conclusion, a target cycle time of **20 min** should be considered. In this way, the production goal of 5000 units/year can be achieved.

Furthermore, there is a product variety to cope, ranging from M19 to M27.

2.1 Model Variety

The models which needs produced flawlessly in the assembly line are M19, M21, M24 and M27. The expected sales distribution is illustrated in fig. 2.3.

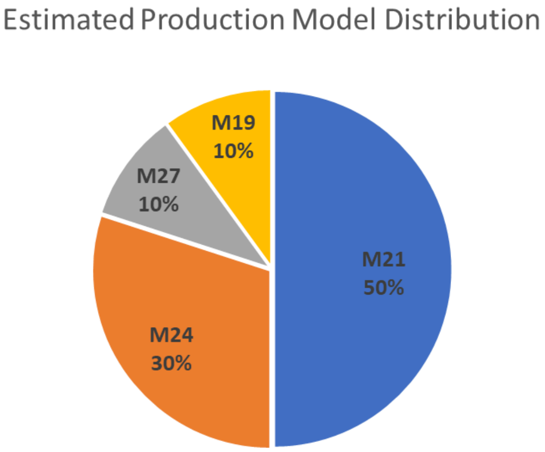

Figure 2.3: Expected model variety

2.2 Plant Facilities

Regarding the production plant facility, the current location includes the prototype shop and a hall where the cooling plates are machined. In this facility there is a free space of about 40 mx10 m. However, the whole production is planned to be moved to a new location, dedicated to AFPM manufacturing. Given the upcoming changes, the assembly line layout has to be kept location independent and planned in a logical manner.

3 Prototype Manufacturing Process

Table 2.2 lists all the manufacturing steps needed for producing one prototype. This is the original list with a logical division in sub units. It is important to note, that the presented timings are provided by previously performed tests and estimates, without any statistical elaboration.

ID	Unit	Step	Description	Time [min]	Unit Time [min]	Personnel
M-OP010	**Front Cooling Plate Assembly**	1	Assemble the pin into the front cooling plate	0.25	7.33	1
		2	Smear thermal grease	3.00		1
		3	Assemble the stator and cooling plate (just merge two components)	0.25		1
		4	Assemble the heat shrink tube on PT100	0.50		1
		5	Tighten the bolts (includes brush glue)	3.33		1
M-OP020	**Front Cooling Cover Assembly**	6	Assemble the metal gasket	0.17	8.67	1
		7	Assemble the cooling cover	0.17		1
		8	Tighten the bolts (25 x bolts, glued by supplier)	8.33		1
M-OP030	**Rear Cooling Plate Assembly**	9	Assemble the pin into the rear cooling plate	0.25	13.33	1
		10	Smear thermal grease	3.00		1
		11	Assemble the resolver (3 mins for weaving the wires)	6.00		1
		12	Assemble the stator and cooling plate (just merge two components)	0.25		1
		13	Assemble the heat shrink tube on PT100	0.50		1
		14	Tighten the bolt (include the brush glue)	3.33		1
M-OP040	**Rear Cooling Cover Assembly**	15	Assemble the metal gasket	0.17	8.67	1
		16	Assemble the cooling cover	0.17		1
		17	Tighten the bolts (25 x bolts, glued by supplier)	8.33		1
M-OP050	**Leakage Test**	18	Leakage test rear stator	4.00	8.00	1
		19	Leakage test front stator	4.00		1
M-OP060	**Rotor Assembly**	20	Assemble rotor with shaft	3.00	18.00	1
		21	Balance rotor	15.00		2
M-OP070	**Shimming Calculation**	22	Measure the stators, the rotor and the middle ring	30.00	30.00	1
M-OP080	**Magnetizing**	23	Magnetizing	2.00	17.00	2
		24	Detect magnetic flux	15.00		2
M-OP090	**Final Assembly**	25	Assemble rotor sub unit with front stator sub unit	2.00	17.50	2
		26	Fix front stator sub unit and rear stator sub unit on assembly bench	3.00		2
		27	Assemble the O-ring on the middle ring	1.00		2
		28	Assemble the middle ring	0.50		2
		29	Assemble rear stator sub unit	8.00		2
		30	Tighten the bolts (includes take out from assembly bench)	3.00		2
M-OP100	**Connection Box Assembly**	31	Assemble the connection box	30.00	30.00	1
M-OP110	**Insulation Test**	32	Winding resistance measurements	5.00	5.00	1
		33	Insulation measurements			1
		34	HIPOT DC			1
		35	Surge Test			1
M-OP120	**Functional Test**	36	Install motor on functional test bench	30.00	115.00	2
		37	Motor BEMF Measurement	10.00		2
		38	High Speed Test	15.00		2
		39	Continue Torque PAT 500rpm & 600 rpm	60.00		2
M-OP130	**Final LeakageTest**	40	Close connection box cover	2.00	6.00	1
		41	Final Leakage Test	4.00		
M-OP140	**Inspection**	42	Inspect Motor	-	-	-
M-OP150	**Warehouse**	43	Storage	-	-	-
M-OP160	**Package**	44	Package	-	-	-

Table 2.2: Prototype Manufacturing Process

In the next sections, every process step will be explained in detail.

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2. **Pre-high-voltage test:** For safety reasons, 1 kV of potential difference is applied between one common phase and the motor chassis to ensure the insulation is working, as shown in fig. 2.20.

Figure 2.20: Pre-high-voltage test (M-OP110)

After the successful safety check, the high-voltage tests can be performed with the special equipment shown in fig. 2.21:

3. **High voltage test:**
   (a) 3.5 kV voltage is applied between each of the common phases one by one and the motor chassis.
   (b) Resistance values are taken after 30 s and 60 s from test start.
   (c) The test is considered passed if phase-to-chassis resistances are all higher than 10 GΩ.

Figure 2.21: High-voltage test (M-OP110)

3.12 Functional test EOL M-OP120

The functional prototype test is performed on a special test bench with a drive motor, shown in fig. 2.22. This is the most essential test for ensuring the motor's functionality in the EOL tests.

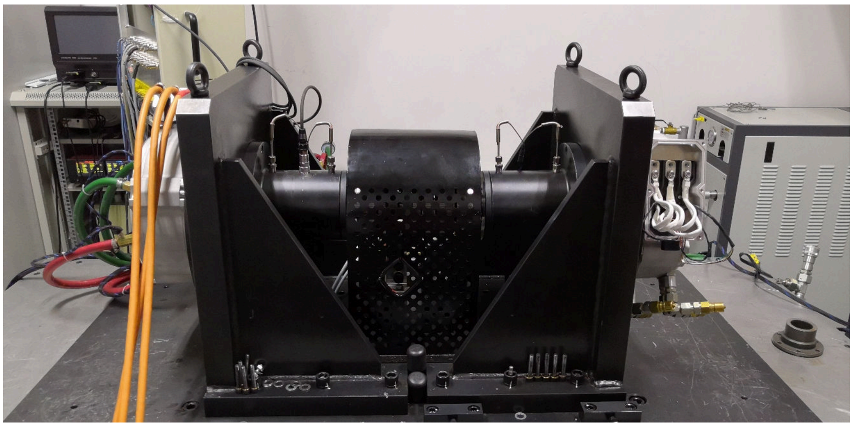


Figure 2.22: Test Bench (M-OP120)

1. **Motor loading:**
   (a) The motor is loaded on the functional test bench by coupling the shaft to the drive motor.
   (b) The motor frame is then locked on the test bench with 5 screws.
   (c) The cooling liquid connectors are tightened on the motor's cooling inlets, see fig. 2.23

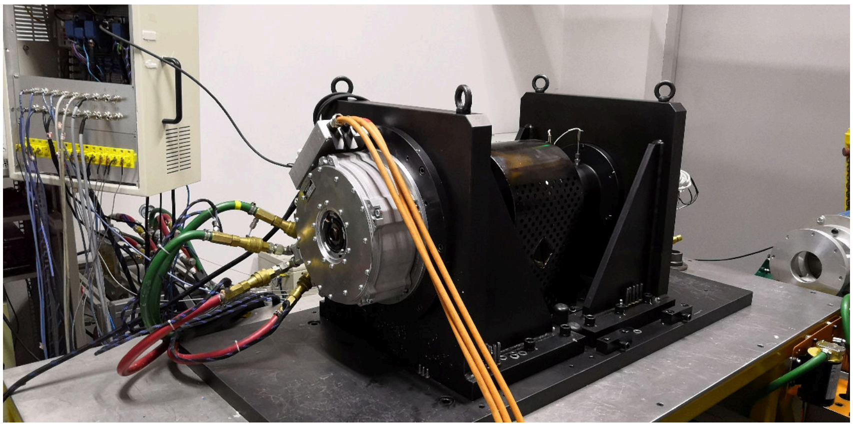


Figure 2.23: Motor Connections (M-OP120)

2. **Test initialization:**
   (a) The low voltage connector is plugged into the test control system.
   (b) The resistance values of temperature sensors RTD1, RTD2 and of the three resolver pole pairs are measured under room temperature conditions.
   (c) Current probes are installed on the three phase cables of the rotor inside the connection box.

   (d) The drive motor's cooling system is started.

3. **Recirculating current test:**
   (a) The drive motors runs in velocity control at 1000 rpm
   (b) Recirculating current on open circuit, temperature and mechanical torque are measured.
   (c) The test is repeated with the drive motor running at 2000 rpm, 3000 rpm and 4000 rpm.
   (d) The mechanical torque is also measured under open circuit at 50 rpm, 100 rpm, 250 rpm, 750 rpm, 5000 rpm, 6000 rpm, 500 rpm and 2000 rpm.

4. **Back-EMF phasing test:**
   (a) Two oscilloscope voltage probes are connected to two of the high voltage terminals of each stator
   (b) The drive motor is started at 1000 rpm
   (c) The two BEMF oscilloscope curves are compared and the amplitudes and the time delay between them is measured

5. **BEMF measurement test:**
   (a) The three phase cables are connected to the open circuit terminals of the power analyzer panel.
   (b) The drive motor is started to 1000 RPM.
   (c) Star and delta RMS values of the BEMF are measured from the power analyzer.
   (d) The test is repeated with drive motor spinning at 2000 rpm, 3000 rpm and 4000 rpm.

6. **Short circuit test**
   (a) Test motor supply cables are moved to short circuit terminals of the power analyzer.
   (b) Drive motor starts to 100 rpm.
   (c) The RMS short circuit currents and temperature are measured.
   (d) The test is repeated for drive motor spinning at 200 rpm, 300 rpm, 400 rpm, 500 rpm, 750 rpm, 1000 rpm, 2000 rpm, 3000 rpm and 4000 rpm

7. **Torque vs current test:**
   (a) The computed values of K_i, K_p and resolver calibration are set.
   (b) The drive motor is controlled in speed at a given set point.
   (c) In torque control, the test unit records the current at various torque settings.
   (d) The test is repeated several times with different speeds and different torque set points, in order to define a K_t for the motor and to detect the phase current's saturation point.

8. **Winding heating test:**
   (a) The drive motor starts to 500 rpm.

   (b) The test motor is controlled in current on some initial value.
   (c) The current setpoint is then tuned in order to make the stator coils reach a stable temperature just under their limit of 150°.

9. **Continuous torque curve**
   (a) The drive motor starts to 500 rpm.
   (b) The test motor is set in torque control on an initial set point.
   (c) The torque set point is tuned in order to make the stators coil reach a stable temperature just under their limit of 150°
   (d) The test is repeated at 10 000 rpm.

10. **High speed test**
    (a) The drive motor is set to spin at 12 000 rpm
    (b) The temperature RTD1 and RTD2 are recorded for the whole test period of 5 min

11. **Motor unloading**

3.13 Final leakage test M-OP130

This test is currently not performed for the prototype production. However, the connection box cover is closed after each successful functional test, since the terminals are free afterwards. Furthermore, the cooling inlets and the phase connectors are closed with some packaging material.

4 Bottleneck Analysis

In this section, the bottleneck and main risks for failures are identified. Not only timing must thereby be considered, but also the eligibility of the process steps for mass production. This means that quality critical steps must be improved

The main issues, considering timing and process sensitivity in table 2.2 on page 13, are:

- Shimming Measurement
- Magnetization, especially flux detection
- Functional test (EOL)

4.1 Shimming Measurement Machine

Considering the process explained in section 3.7, the shimming measurements not only take long time but are also crucial for product quality. For this reason, automating this step is *compulsory* even for a low capacity production line.

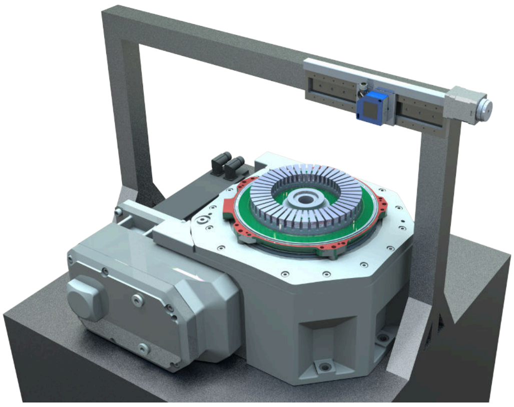


Figure 2.24: Shimming measurements machine

The design concept shown in fig. 2.24, plans a laser based measuring machine. Basically it consists of two parts: the *rotary table* and a *linear guide* place on top of it handling the *laser distance sensor*. The workpiece is meant to be placed on the rotary table so that, combining the linear motion of the sensor with the rotation of the table, all the points of the piece surface can be measured. All the details are provided in [4].

4.2 Magnetization Machine

For the magnetization step the same reasoning applies. In the current process the magnets are aligned manually, which may compromise performance.

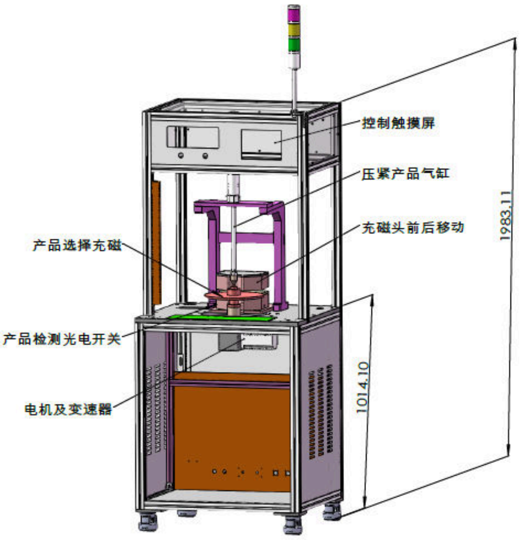


Figure 2.25: Magnetization Machine

The current solution can be upgraded to an automatic machine which performance the magnetization by rotating the shaft with an actuator, pictured in fig. 2.25. The measuring equipment (see section 3.8) can be upgraded in a similar way with a simple tool which automatically rotates and *measures the flux*. No special equipment is therefore needed.

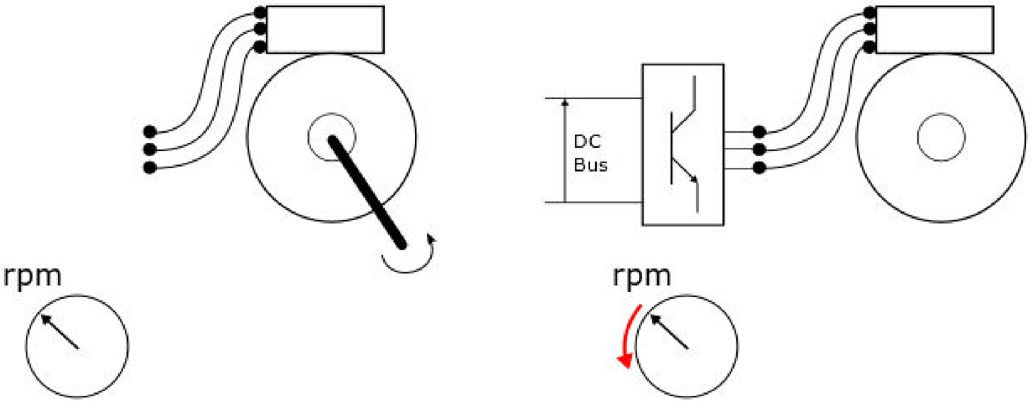
4.3 EOL

The current functional prototype test lasts more than 2 h, as summarized in table 2.2. However, for the EOL tests in a mass production environment, only few characteristics need to be measured in order to ensure that the unit is working correctly. The *characterizing* prototype test needs therefore to be changed into a *quality control* logic. Details on this approach are described in [5].

The following tests are planned (in addition to the insulation tests):

1. temperature sensor check
2. back-emf test
3. no-load-losses test, also called *drag torque* test
4. resolver calibration check
5. final leakage test

In this section, the ones requiring a *spinning* Device Under Test (DUT), i.e. Back-emf, drag torque and resolver calibration are tried to realize *without* prime mover. The DUT itself can be used to reach a certain speed without any mechanical load attached, after which the control is disabled and the motor spins down. The operating modes are compared in fig. 2.26.



(a) Prime mover operating mode

(b) Spin down operating mode

Figure 2.26: Dynamic Test Operating Modes

To verify the feasibility of this new procedure, in the following sections, the speed *transient* impact on the phase is analyzed and estimated.

To investigate if the drag torque test can be redesigned for the final end of line, this draft suggests two kind of tests to characterize the drag torque and test the spin down.

4.3.1 Drag Torque

The drag torque generally summarizes all the no-load losses as a torque component and is the reason why the motor spins down in the first place.

For now, the drag torque is tested in different points with a manual data acquisition procedure:

1. Set the velocity command for the prime mover (see fig. 2.26a)
2. Ensure to reach steady state conditions
3. Read the torque value on the screen
4. Save it in the excel file

As a first approximation, the drag torque can be characterized as a linear component with respect to speed.

$$\tau_{\text{drag}}\left(\omega_m\right) = \tau_{\text{dry,friction}} + b\,\omega_m \tag{2.5}$$

From previous functional test data we can estimate the linear parameters to be around $b = 0.003\,\text{Nm/rpm} = 0.0029\,\text{Nm/rad/s}$ and $tau_{dry,friction} = 0.6\,\text{Nm}$. Figure 2.27 shows the graph.

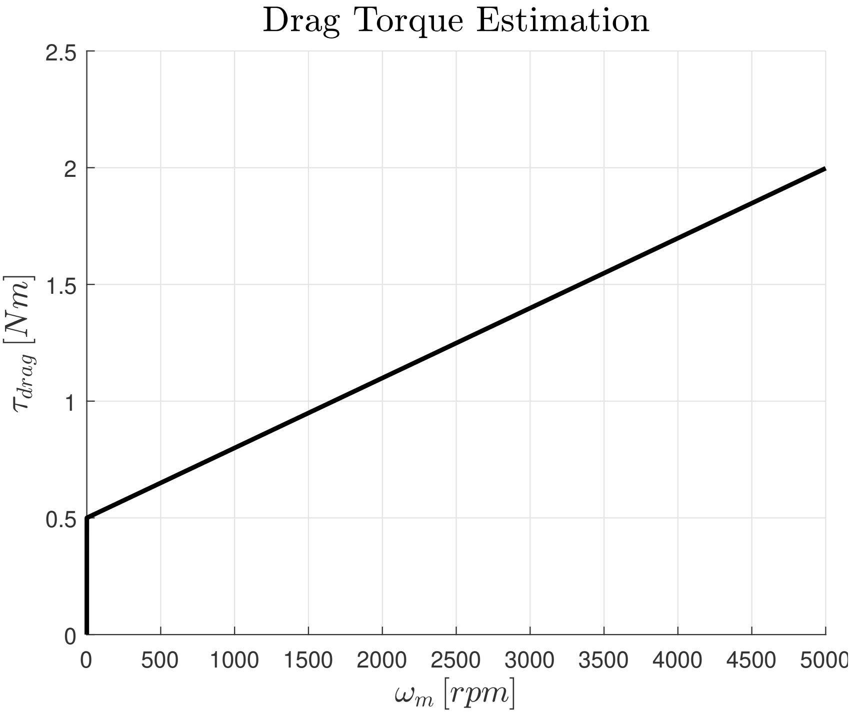


Figure 2.27: Drag torque estimation

In order to perform the drag torque in the new spin-down configuration, the spin down *time* can be measured instead. Afterwards, a quality criteria can be easily be defined by requiring a *minimum* time in seconds. In this way, no prime mover and *no torque sensor* is needed.

To have a rough estimate how long it will take for the motor to spin down, let's consider the following equation:

$$\tau = J\,\frac{\partial}{\partial t}\,\omega\left(t\right) \tag{2.6}$$

Where τ is the sum of all torques applied to the system and J the its inertia.

Substituting τ from eq. (2.5) as the only applied torque to the system yields:

$$-\tau_{\text{dry,friction}} - b\,\omega\left(t\right) = J\,\frac{\partial}{\partial t}\,\omega\left(t\right) \tag{2.7}$$

Letting the motor now start the spin down from e.g. 2000 rpm results in the condition which completes the Cauchy problem of the first order Ordinary Differential Equation (ODE):

$$\omega\left(0\right)=\frac{200\,\pi}{3} \tag{2.8}$$

The analytical solution is as follows:

$$\omega_m\left(t\right)=-\frac{\tau_{\text{dry,friction}}-\mathrm{e}^{-\frac{b\,t}{J}}\,\left(\tau_{\text{dry,friction}}+b\,\omega_{\text{start}}\right)}{b} \tag{2.9}$$

For an M21 the values are approximately:

$\tau_{\textbf{dry,friction}}$ = 0.0029 Nm/rad/s

b = 0.6 Nm

J = 0.011 kgm^2

By substitution the following graph is obtained:

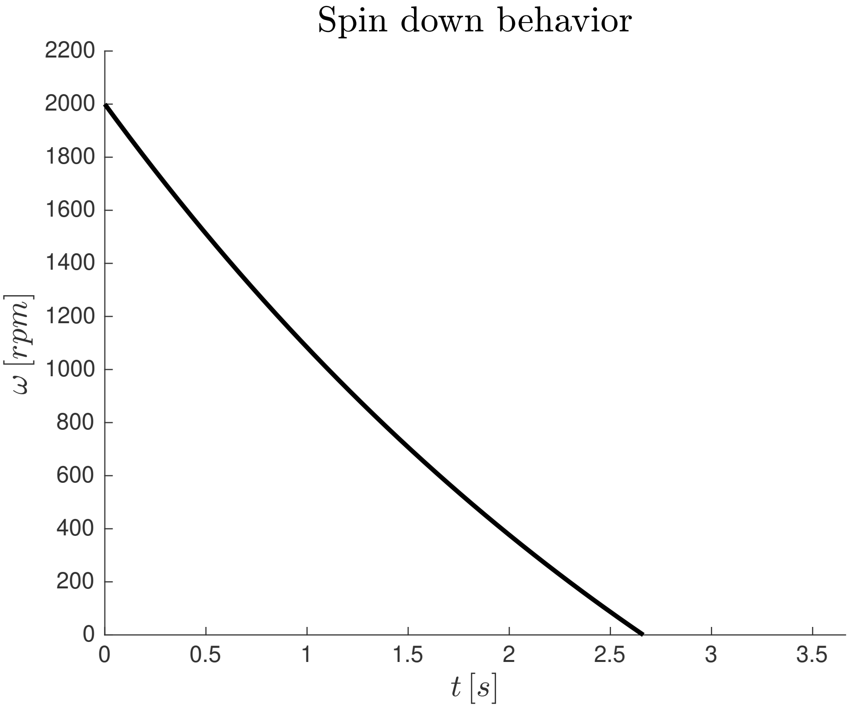


Figure 2.28: Predicted spin-down behavior

The stop time can be shown to be:

$$t_{stop}=-\frac{J\,\ln\left(\frac{\tau_{\text{dry,friction}}}{\tau_{\text{dry,friction}}+b\,\omega_{\text{start}}}\right)}{b} \tag{2.10}$$

Which for the values of M21 yields approximately 2.663 s.

4.3.2 Back-EMF estimation

Given the speed evolution in time, i.e. $\omega(t)$, also the flux change and the back-emf can be estimated. The results are presented in figs. 2.29 and 2.30

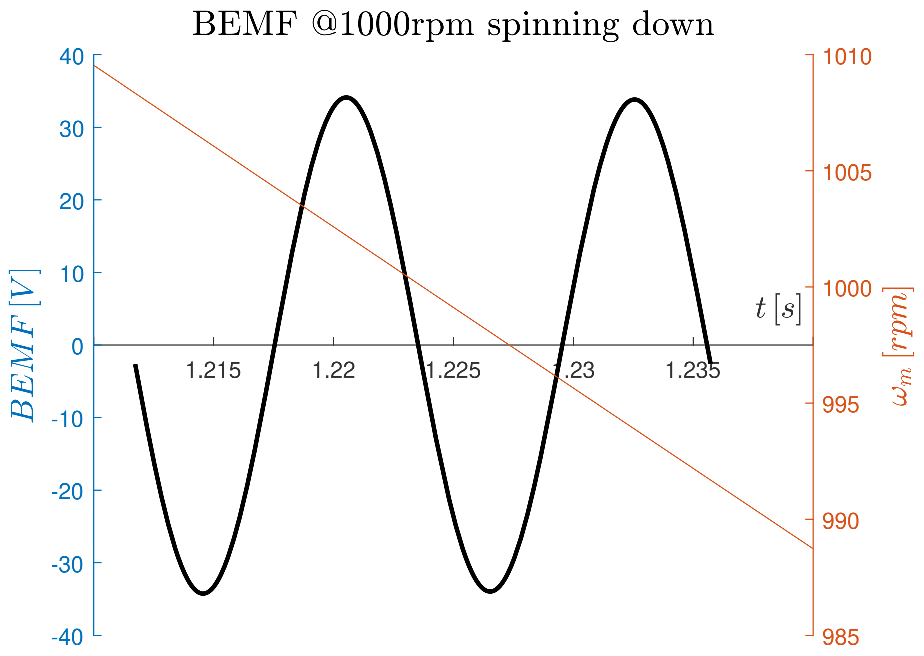


Figure 2.29: Transient Back-EMF prediction

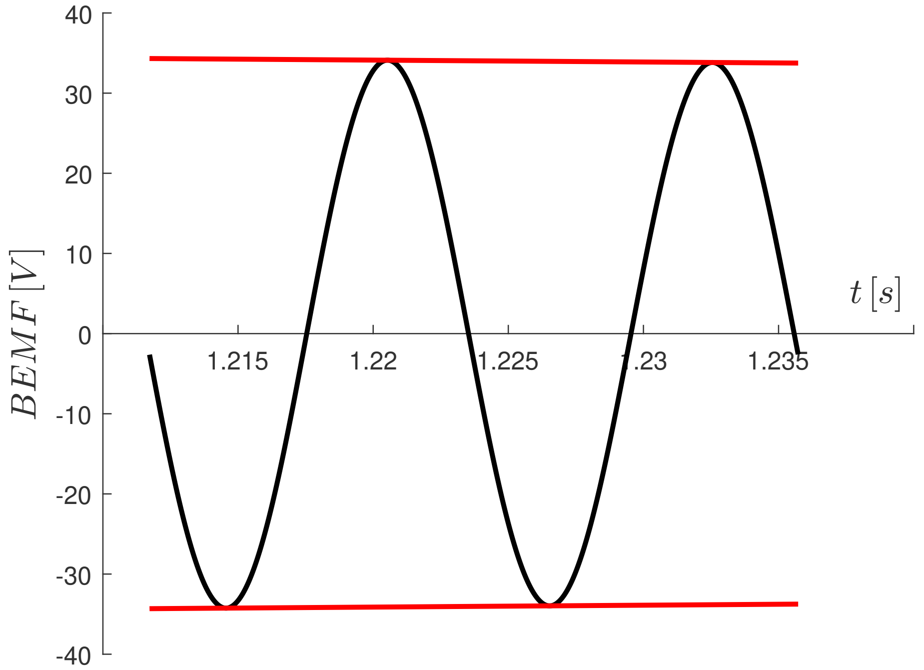


Figure 2.30: Transient Back-EMF with amplitude boundaries

According to the predictions over one period (considering 5 pole pairs as used in M21) the amplitude decreases by 1.8 %.

Chapter III

Mechanical Resolver Calibration

In this chapter, the resolver calibration is discussed.

The main purpose of the mechanical resolver calibration is to ensure that all produced motor units become *interchangeable*. Up to now, the resolver rotor and the resolver stator are assembled *without* fixed angular position in the motor, making it necessary to always *calibrate the inverter with the specific motor unit*. So besides of being a practical advantage for the client, a fixed mechanical alignment would also *eliminate the calibration process with the drive motor* in the functional test bench.

1 Requirements

The inverter supplier requires a precision of **±1.5° electrical degrees**.

With the current electronic calibration this can easily be satisfied, but mechanically this requirement becomes hard to meet, e.g. with 5 pole pairs, 0.3° mechanical degrees of overall alignment precision are needed.

2 Theoretical background

For injecting the currents with the right frequency and phase shift, the inverter needs to get an estimate of the angular position of the rotor's PM rotating magnetic field. Therefore, the rotor's *electrical* degrees are needed.

Mechanical degrees are electrical degrees divided by the number of pole pairs p:

$$\theta_{me} = \frac{\theta_{el}}{p} \tag{3.1}$$

It is important to note, that measuring electrical degrees does not allow to determine the mechanical angular position in an absolute way[1]. This means that a resolver rotor with more than one pole pair ($p > 1$) yields just its own *electrical* position. To get the motor's PM rotor position, generally, a conversion is needed. For this reason it is common practice to use the *same number of poles on PM- and resolver rotor*. In this way the electrical degrees share the same scale on both rotors and the conversion is not of interest anymore.

---

[1] unless a homing procedure is performed

2.1 Resolver's working principle

The angular position sensor in use is a variable reluctance resolver. Just like regular resolvers, there is one primary excitation winding and two secondary sensing windings, generating two signals (basically sine and cosine, as shown in fig. 3.1) which after data processing yield the rotor's angular position and velocity.

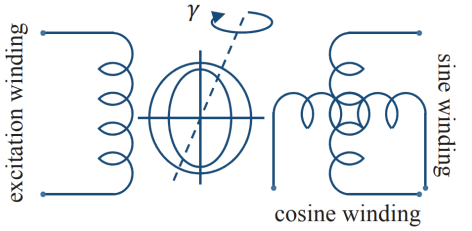


Figure 3.1: Resolver's working principle

A more detailed introduction to variable reluctance resolvers can be found in [18] or [19, pp. 245-248].

3 Alignment Procedure

To better understand what needs to be aligned, firstly the calibration process shall be discussed in greater detail, i.e. what is actually measured.

3.1 Resolver Calibration Process

By letting the motor spin through a drive motor, the sinusoidal back-EMF is measured, and simultaneously the angle perceived by the resolver. At the maximum back EMF value of phase 1, the angle is evaluated. This shall be the offset angle, called gamma adjust in the inverter documentation.

Two factors influence the offset:

1. Relative position of the resolver's rotor with respect to the motor's PM rotor
2. Relative position of the resolver's stator with respect to the motor's stator

3.2 Approach

Instead of trying to get a 0° offset, it is enough to get the same offsets for all units. To test this assumption, a few sample models can simply be assembled in the exact same way and the calibration be performed. If the calibration yields always the same value the test can be considered successful.

3.2.1 Advantage

This approach of allowing a random offset angle, as long as it remains consistent among all units, significantly simplifies the problem. The alternative would indeed imply not only to align the low reluctance path with the exact south/north pole, but also to align the resolver's stator coils with the motor's stator coils. Since the resolver stator hides the internal coils with its housing and provides just a mark where the zero-degree angle is measured, it would be rather complex to accomplish a precise alignment on the stators. This complexity is eliminated with the chosen approach.

3.3 Chosen alignment

The following alignments have been chosen.

For the rotor, as shown in fig. 3.2, the low reluctance path (i.e. the hump) is aligned with the left edge of the permanent magnet number 1.

For the stator, as shown in fig. 3.3 the marked position is aligned with one of the pole's slot on the inner side of the rear plate in such a way that also the cables fit well.

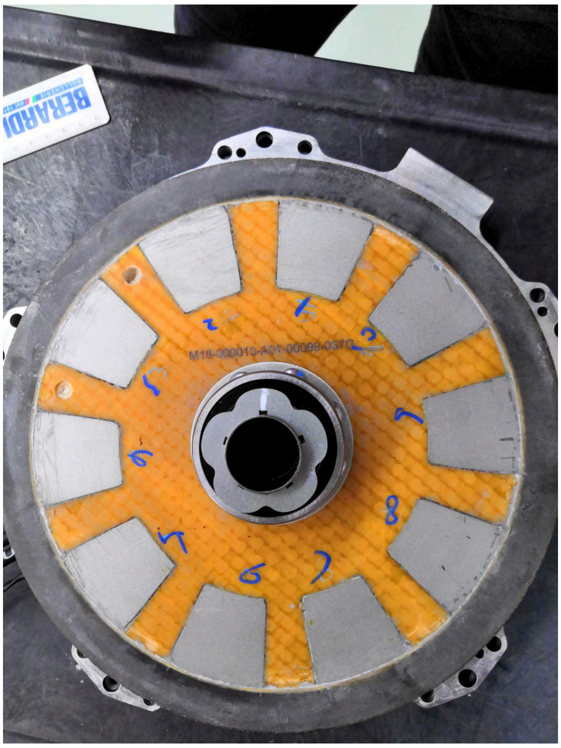


Figure 3.2: Rotor alignment

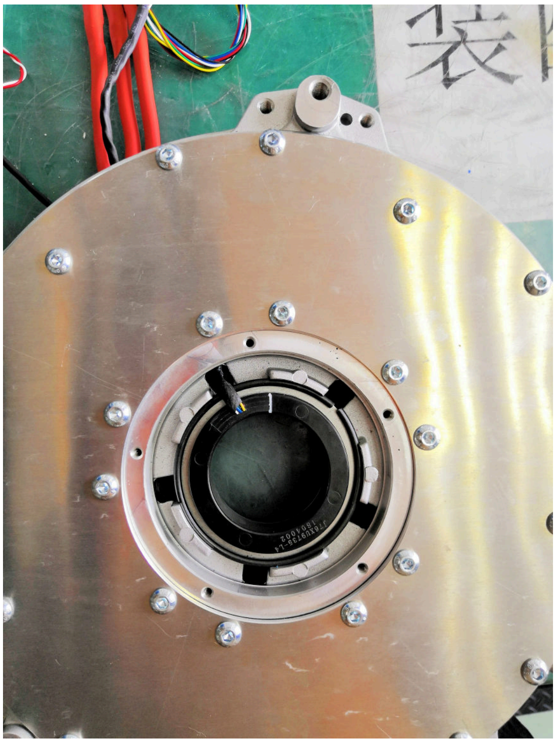


Figure 3.3: Stator alignment

4 Results

Two series of tests have been performed: The first on an order of 4 motor units, model M21P5, the second on an order of 5 motor units, model M21P4. Unfortunately, in the first series the alignment procedure was not controlled properly, and after two units even changed, by flipping the rotor up-side down. The two series are not comparable and the first series has alignment issues. For completeness, however, all results are shown.

4.1 First Test Series

The results from the first test series are as follows.

Serial Number (M21P5)	Offset in electrical degrees	Mechanical degrees
A01-001-190409	27.4°	5.48°
A01-002-190410	34.6°	6.92°
A01-003-190415	-153.2°	-30.64°
A01-004-190415	-188.8°	-37.76°

Table 3.1: First test results

As the table shows, only the first two units and the last two units show similar offsets. This is due the alignment procedure issues as mentioned before.

The mechanical offset between the first two assemblies, considering the 5 poles, are about 1.44° mechanical degrees, and between the last two 7.12°.

4.2 Second Test Series

The results from the second test series artoprulee shown in Table

Serial Number (M21P4)	Offset in electrical degrees	Mechanical degrees
A01-001-190507	73.7°	14.74°
A01-002-190507	90.6°	18.12°
A01-003-190508	70.1°	14.02°
A01-004-190509	85.9°	17.18°
A01-005-190510	68.6°	13.72°
A01-006-190513	91.3°	18.26°

Table 3.2: Second test results

Among all of the 6 test samples, the offsets in mechanical degrees are *within a 5° range* from 13.5° to 18.5°. In fig. 3.4 the values are illustrated in a small plot.

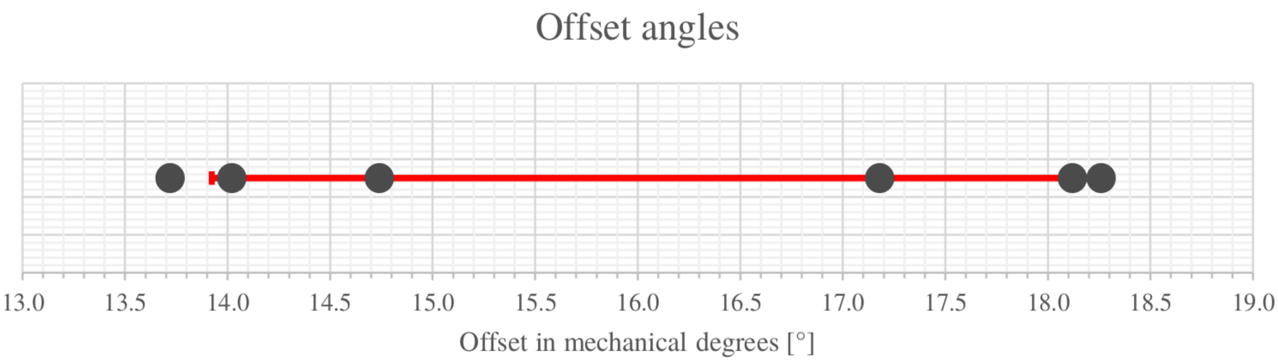


Figure 3.4: Resolver offset analysis

The standard deviation (even if statistically not meaningful for the small number of samples) is 1.9 mechanical degrees. The range of the 1-σ region is illustrated in red in fig. 3.4.

Overall, a precision of ± *2.5°* was obtained.

5 Result evaluation

After properly controlling and fixing the mechanical alignment process in test series 1, the results improved significantly. Test series 2 clearly shows a stable alignment with a fairly good precision, especially considering that each result depends on two distinct manual steps.

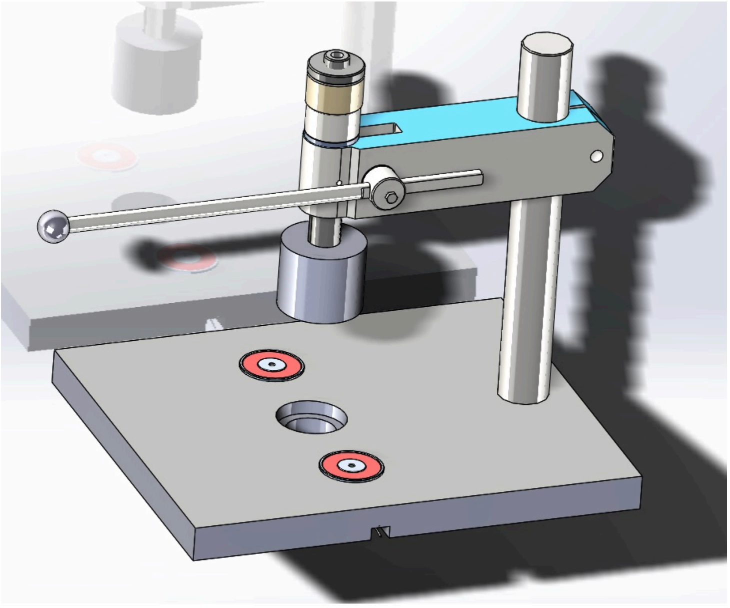
The possibility of carrying out consistently aligned motor units is hereby demonstrated. However, the precision obtained by manual alignment is – as expected – not sufficient. Furthermore, the manual procedure is error-prone and therefore unacceptable in production environment.

6 Robust alignment procedure

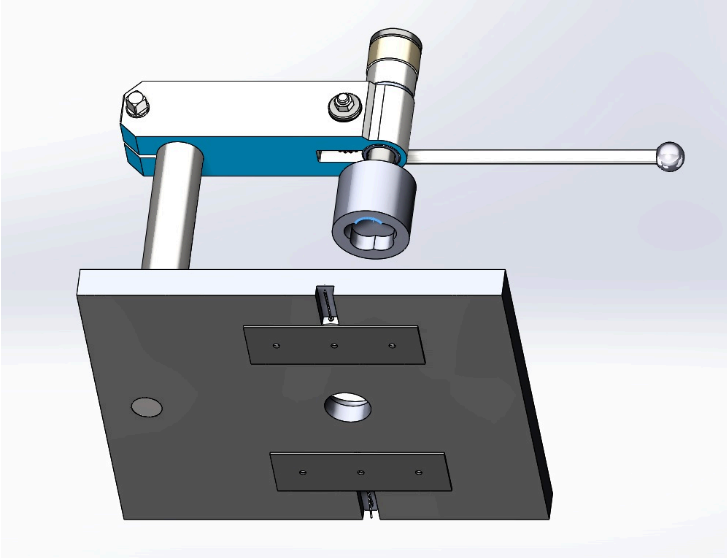
As the data shows, for the final assembly line, a more *robust* alignment procedure must be designed.

6.1 Rotor alignment

Regarding the alignment of the two rotors a special fixture for the manual press can be used to insert the resolver's rotor always in the same angular position. The fixture contains two coils aligning the motor's before pushing the resolver motor down. In this way the position is aligned to the actual magnetic field. Figure 3.5 shows the concept.



(a) Coils integrated in fixture



(b) Resolver rotor adapter

Figure 3.5: Resolver rotor alignment fixture

6.2 Stator alignment fine-tuning

The stator is firstly put in randomly during the rear cooling plate assembly *without* snap ring, compare with section 3.3 on page 16. When the motor unit is fully assembled, this alignment can be fine tuned, see fig. 3.6.

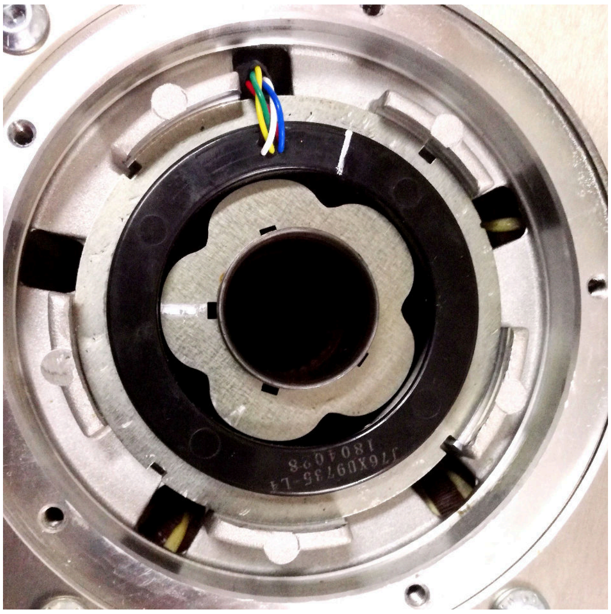


Figure 3.6: Resolver stator fine tuning position

The fine tuning is performed by firstly energizing the stator windings with DC current to the rotor position. Then an angular position indicator, as shown in fig. 3.7 is used to read the resolver's angle and bring it to the desired value.

Figure 3.7: Angular Position Indicator

This fine-tuning process is also the most common way in the industry to achieve the tight inverter requirements.

Chapter IV

Assembly Line Design

In this chapter, the design of the assembly line based on the major automization arrangements and the recently introduced resolver calibration procedure is carried out. Integral part thereby is the design of the standard workbench, satisfying ergonomic and technological needs.

1 Production Process Design

Beyond the gross modifications in the bottleneck workstations, explained in section 4 on page 33, several improvements and clarifications are applied to the process step list:

- The rotor sub assembly being independent from the other steps is performed *before* the final assembly line and can in this way be seen as a material preparation step. This is especially useful, given that the balancing includes removing material from the rotor spider by drilling holes, which means to have waste materials.
- Updates step numbers to contain work unit and step, e.g.: Step 4001 represents first step of Unit M-OP040
- The radial bearing is mounted on the shaft before Shimming / Magnetizing and part of the rotor assembly (not part of the assembly line) for the following reasons:
  - It is possible and has already be done when we documented the process
  - The more steps we can perform on the rotor sub assembly before the assembly line, the better in terms of timings
- Added the missing bearing mounting step in the front cooling plate assembly
- Added missing bearing pretensioning step

1.1 Line Balancing

The proposed solution plans 6 balanced workstations from MOP-010 to MOP-060 in the assembly line. The rotor balancing step, being an independent sub assembly can be performed outside of the final assembly line, as mentioned before. Table 4.1 lists the new solution.

ID	Sub Unit	Step	Description	Step Time [min]	Unit Time [min]
M-OP010	**Front Unit Sub Assembly**	1001	Push the bearing inside the cooling plate (eventually using rubber hammer)	0.25	18.25
		1002	Fix the bearing with the locking ring and tighten the screws	2.00	
		1003	Assemble the pin into the front cooling plate	0.25	
		1004	Smear thermal grease	3.00	
		1005	Assemble the stator and cooling plate (just merge two components)	0.25	
		1006	Assemble the heat shrink tube on PT100	0.50	
		1007	Tighten the cooling plate bolts (includes brush glue)	3.33	
		1008	Assemble the metal gasket	0.17	
		1009	Assemble the cooling cover	0.17	
		1010	Tighten the cooling cover bolts (25 x bolts, glued by supplier)	8.33	
M-OP020	**Rear Unit Sub Assembly**	2001	Assemble the pin into the rear cooling plate	0.25	19.00
		2002	Smear thermal grease	3.00	
		2003	Assemble the resolver	3.00	
		2004	Assemble the stator and cooling plate (just merge two components)	0.25	
		2005	Assemble the heat shrink tube on PT100	0.50	
		2006	Tighten the cooling plate bolts (include the brush glue)	3.33	
		2007	Assemble the metal gasket	0.17	
		2008	Assemble the cooling cover	0.17	
		2009	Tighten the cooling cover bolts	8.33	
M-OP030	**Leakage, Shimming, Magnetizing**	3001	Leakage test front stator	4.00	21.08
		3002	Leakage test rear stator	4.00	
		3003	Shimming measurements	8.00	
		3004	Calculate the shim dimension	0.08	
		3005	Magnetize	2.00	
		3006	Detect magnetic flux	3.00	
M-OP040	**Final Assembly**	4001	Assemble rotor sub unit with front stator sub unit on manual press	2.00	20.00
		4002	Add the resolver rotor on the shaft (using press)	0.50	
		4003	Preload bearing using locking ring	1.00	
		4004	Fix front stator sub unit and rear stator sub unit on assembly bench	3.00	
		4005	Assemble the O-rings on the middle ring	1.00	
		4006	Assemble the middle ring	0.50	
		4007	Put spring washer into rear unit and close motor partially	6.00	
		4008	Stator alignment through back EMF	2.00	
		4009	Bolts tightening	2.00	
		4010	Take out from assembly bench	2.00	
M-OP050	**Connection Box, Insulation Test**	5001	Assemble the low voltage pins	5.00	19.67
		5002	Assemble the connection box	10.00	
		5003	Winding resistance measurements	2.00	
		5004	Insulation measurements	2.00	
		5005	HIPOT DC	0.25	
		5006	Surge Test	0.42	
M-OP060	**Functional EOL, Final Leakage**	6001	Load to workbench: setup accelerometer + wire connections	3.00	19.80
		6002	Temperature sensors check (RTD)	1.00	
		6003	Resolver calibration check + No Load Torque test + BEMF test	1.30	
		6004	Mechanical Vibrations test	2.50	
		6005	Close connection box cover	2.00	
		6006	Mount resolver cover	1.00	
		6007	Motor sealing for leakage test	2.00	
		6008	Final Leakage Test	4.00	
		6009	Breather assembly and take out from bench	2.00	
		6010	Glue serial number plate	1.00	

Table 4.1: Balanced Production Process Steps

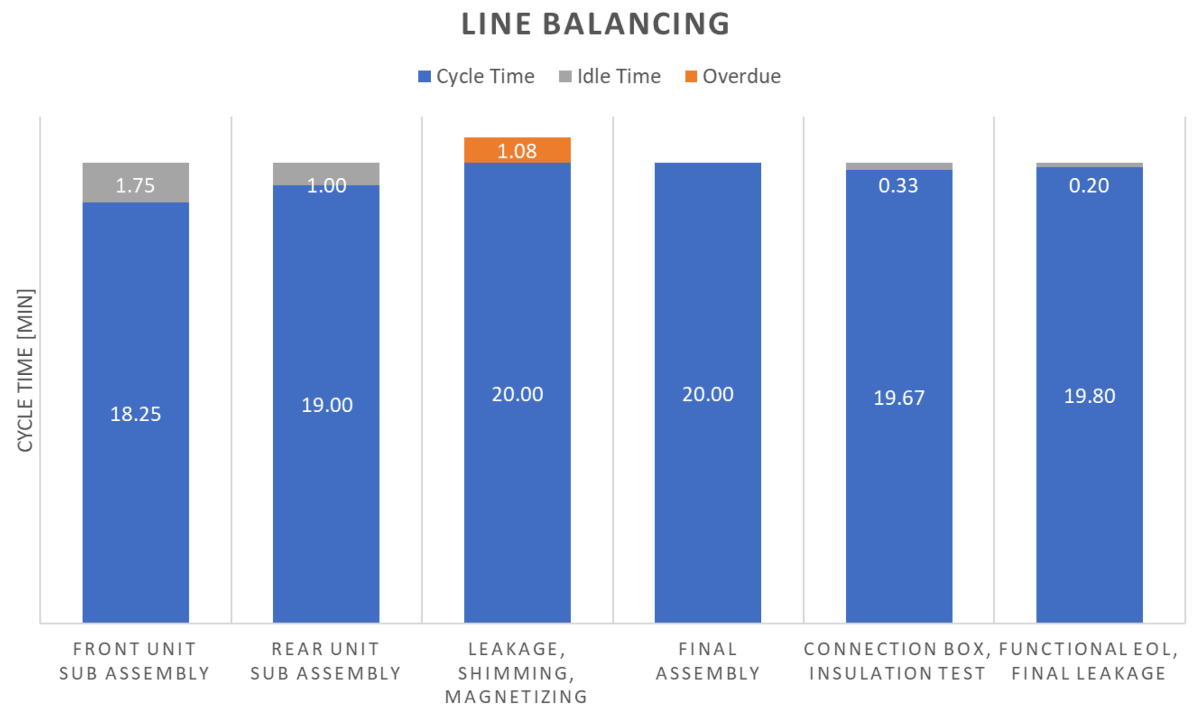


Figure 4.1: Line balancing illustration

As fig. 4.1 shows, there is still an open issue in the Leakage, Shimming, Magnetizing step with an overdue of 0.52 min. All numbers are rough estimates, which is why it needs to be evaluated in the future if the balancing must be changed. However, solve the overdue in M-OP030, the line balancing efficience E_b can be calculated as follows:

$$E_b = \frac{T_{wc}}{w\,T_S} \tag{4.1}$$

Where

E_b is the line efficiency

T_{wc} is the work content time, i.e. the total work time needed to complete 1 unit

w number of workers

T_s the maximum available service time on the line

With respect to the definitions found in [11], the repositioning losses shall hereby be neglected, and just included in the requirement buffer of 15 %. So T_s can be considered = 20 min.

With a total labour of 6 workers, the line balancing efficiency is:

$$E_b = \frac{116\,\text{min}}{120\,\text{min}} = 97\,\% \tag{4.2}$$

1.2 Process Flow Chart

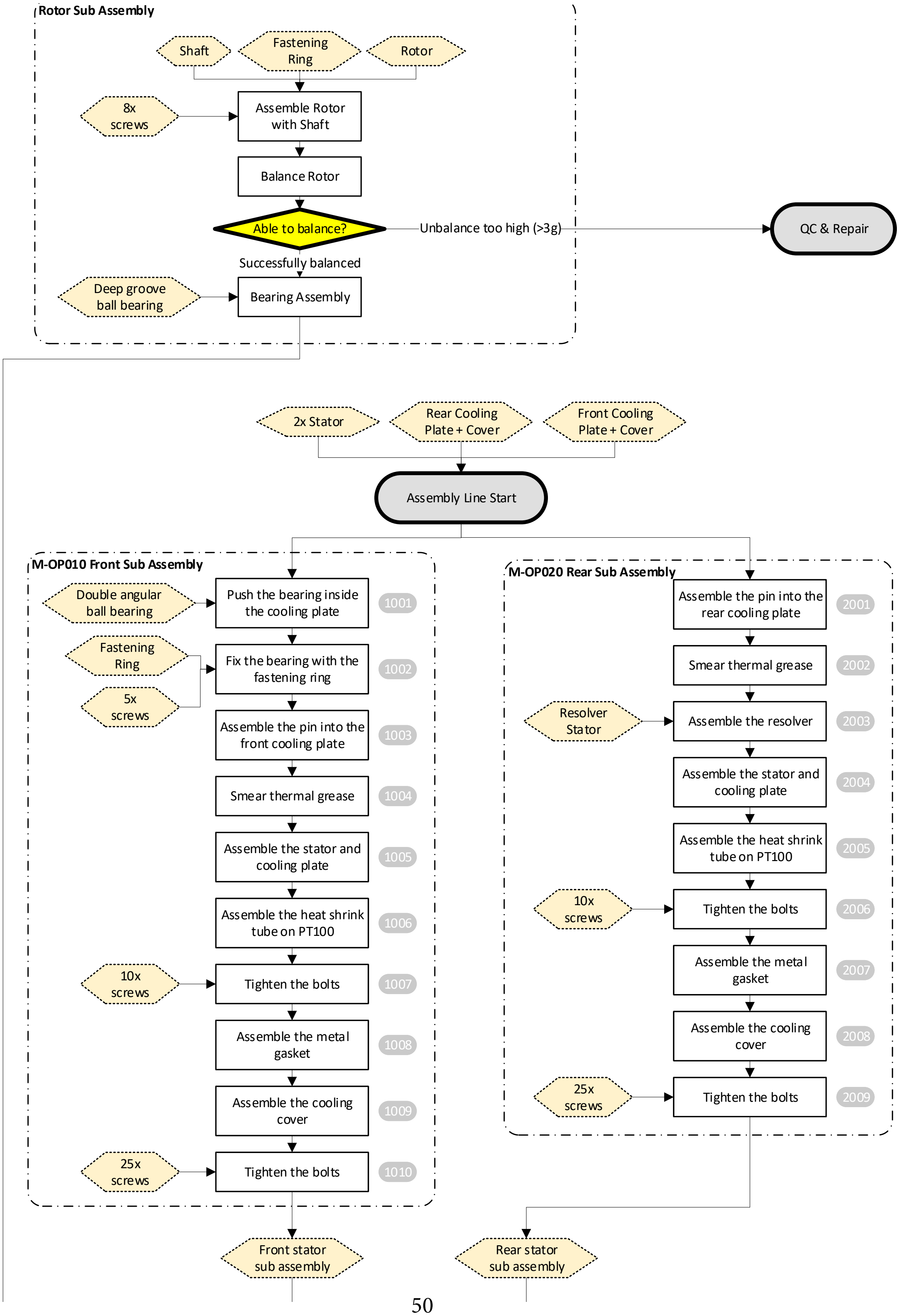


Figure 4.2: Production Process Flowchart

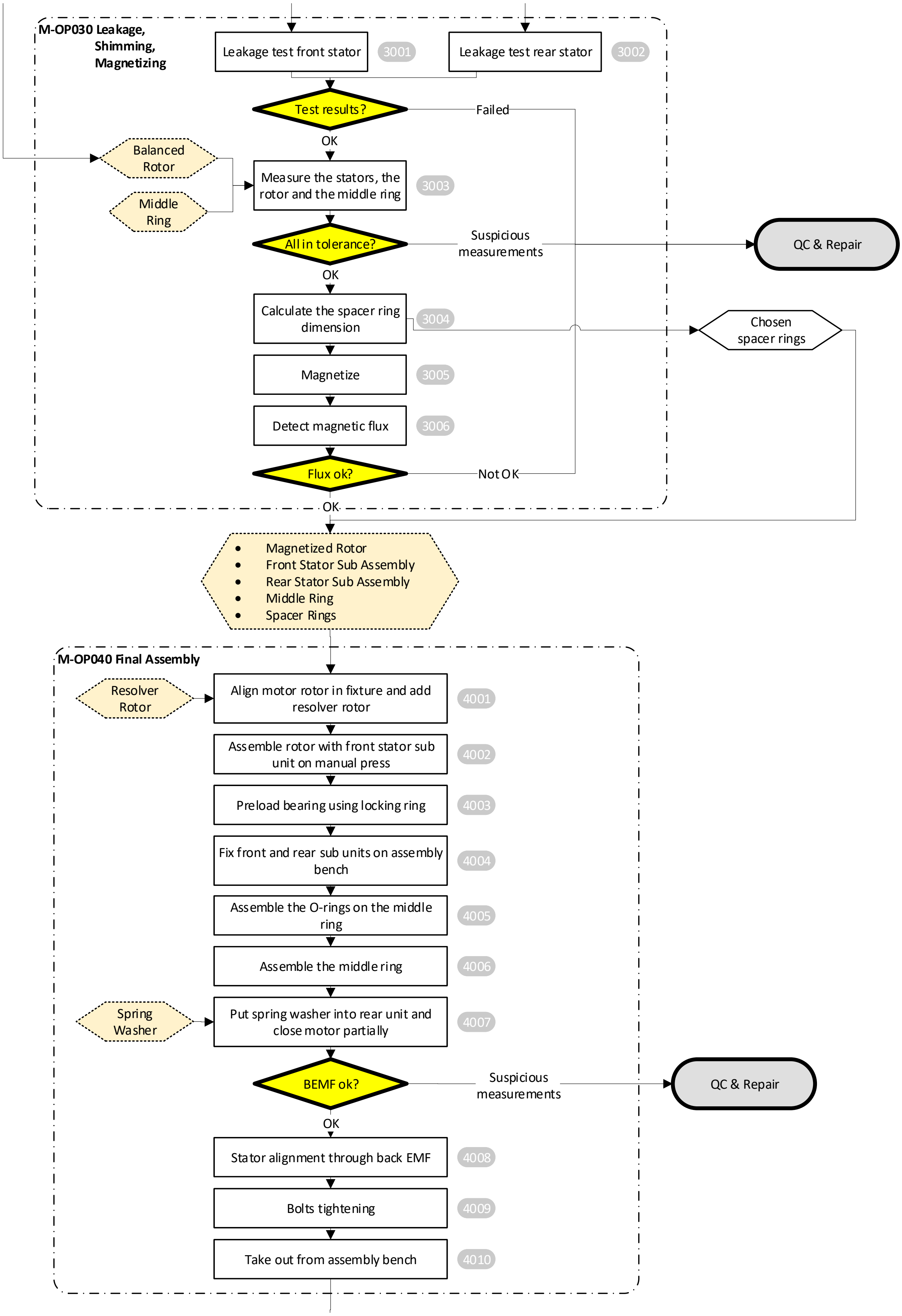


Figure 4.2: Production Process Flowchart (Continued)

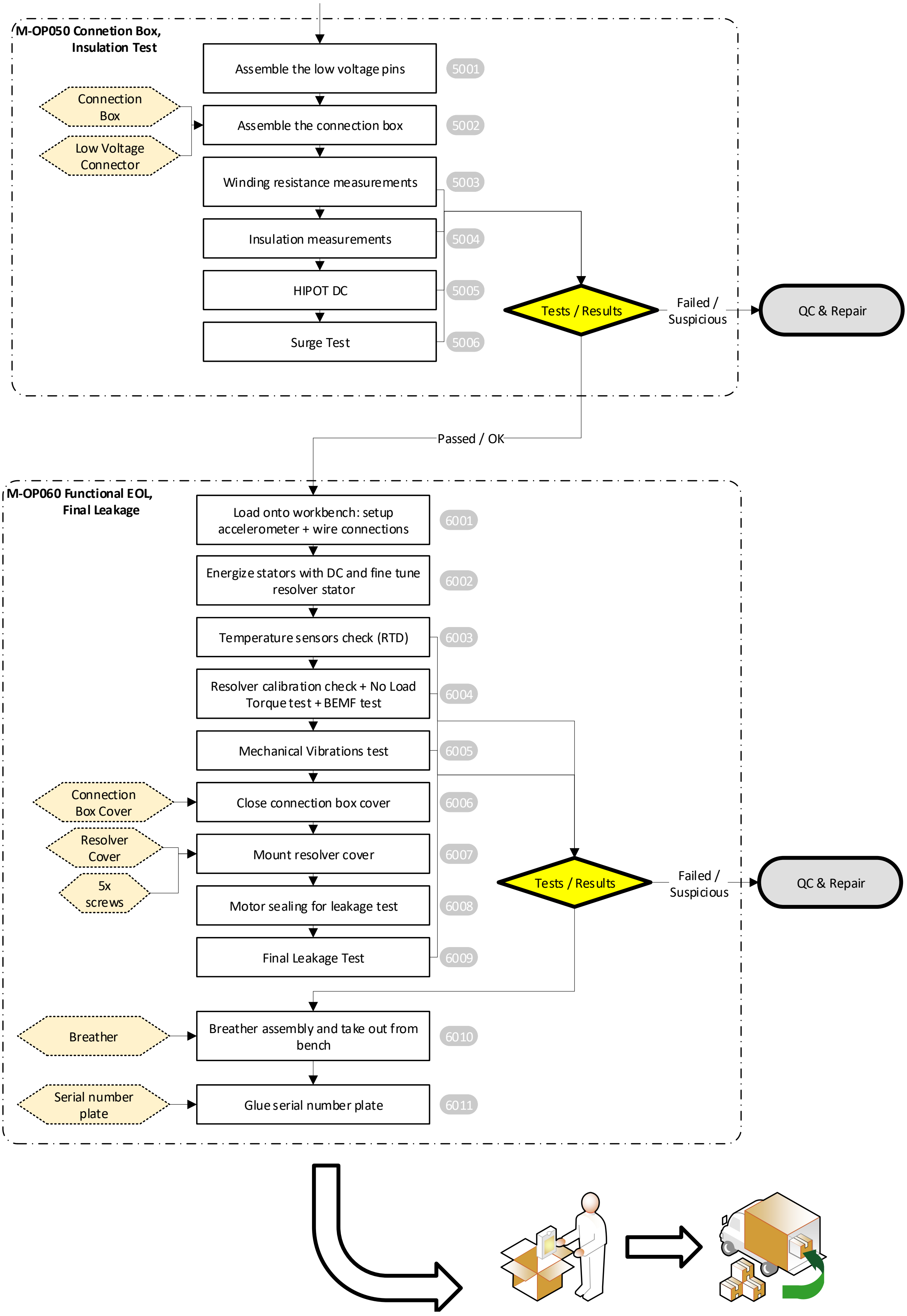


Figure 4.2: Production Process Flowchart (Continued)

2 Workbench Design

For all workunits, a *standard* workbench design is needed. It should provide a *common infrastructure* to the whole production system. In this way the manual assembly line can be constructed in the same fashion for different tasks.

2.1 Requirement Analysis

The following desirable characteristics have been collected:

1. **Dynamic Width**: the workbench must be flexible for different stations but should standardize the basic workstation layout.
2. **Ergonomically work in golden zone**: large movements should be minimized, meaning that all the necessary tools and materials should be in front of the operator. This implies:
    (a) **Light from the top**
    (b) **Tools in the backside or from the top**
    (c) **Material flow from back or sidewards**
3. **Scrap box**: the operator must have a convenient possibility to remove defect parts.
4. **Easy maintenance**: the workbench should be accessible from the back to be able to fix any issue without interrupting ongoing work.
5. **Bus bar connection from top**: the workbench should be connected to pressurized air and electricity from the top, in order to keep the floor clean.
6. **Dust protection cover:** To protect the workpieces a cover over the whole station is needed.
7. **Visual Information**: every station should have a monitor with instructions and/or information on the workpiece.
8. **Working position**: except for high-precision tasks, which in the final assembly are not needed, all operators should stand

With this list as a starting point a flexible design and a common equipment list such as LED-lights, power sockets, ...

2.2 Design

To ease the supplier sourcing process, industry standard aluminum profiles have been used throughout the bench. Figure 4.3 presents the design.

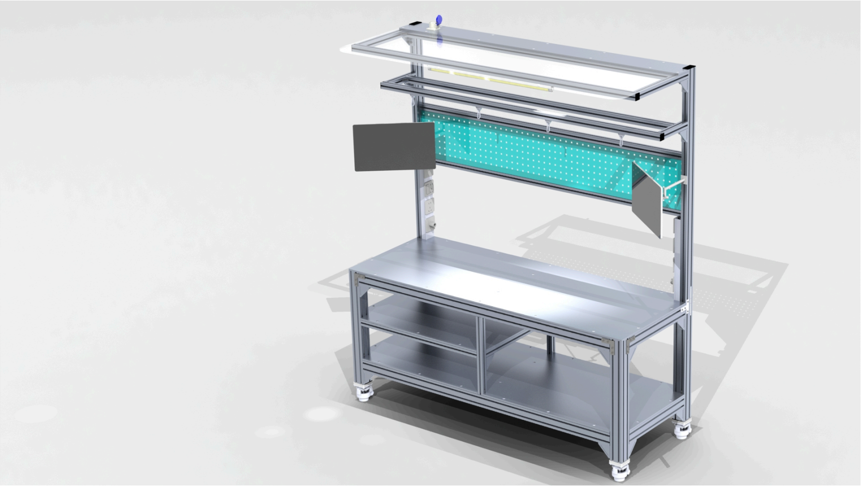


Figure 4.3: Standard Workbench

Figure 4.4: Standard Workbench Connections on top side

As defined the industrial power and air socket connectors have been placed on the top, as shown in fig. 4.4.

3 Line Layout

As a final design the logical assembly line layout is presented in the next pages, fig. 4.5.

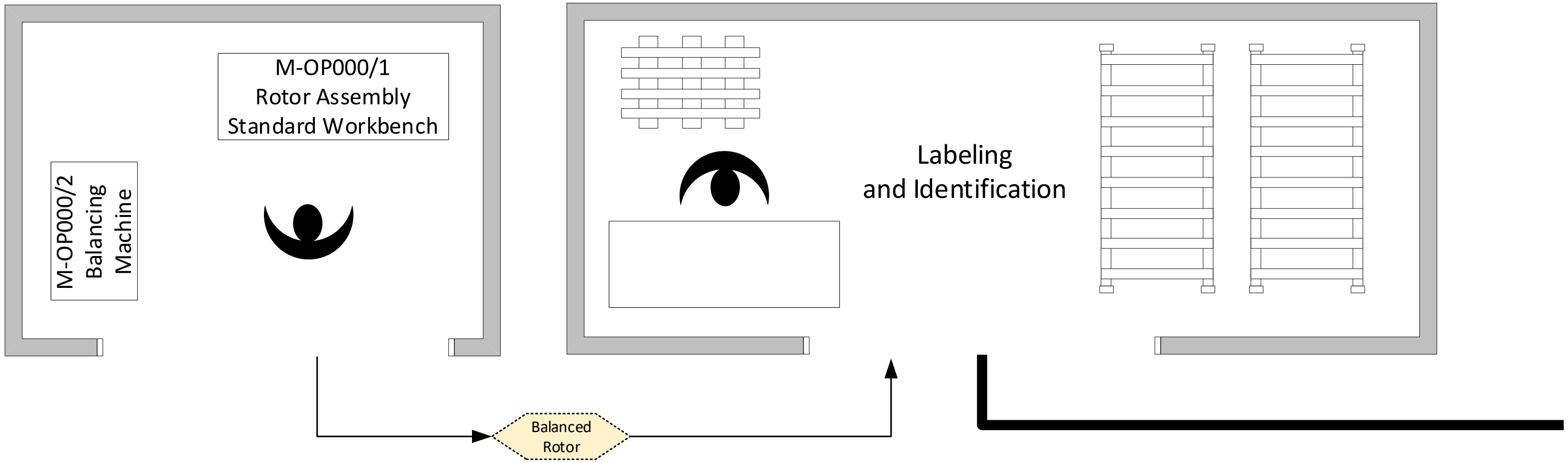


Figure 4.5: Logical Plant Layout with Material Flow

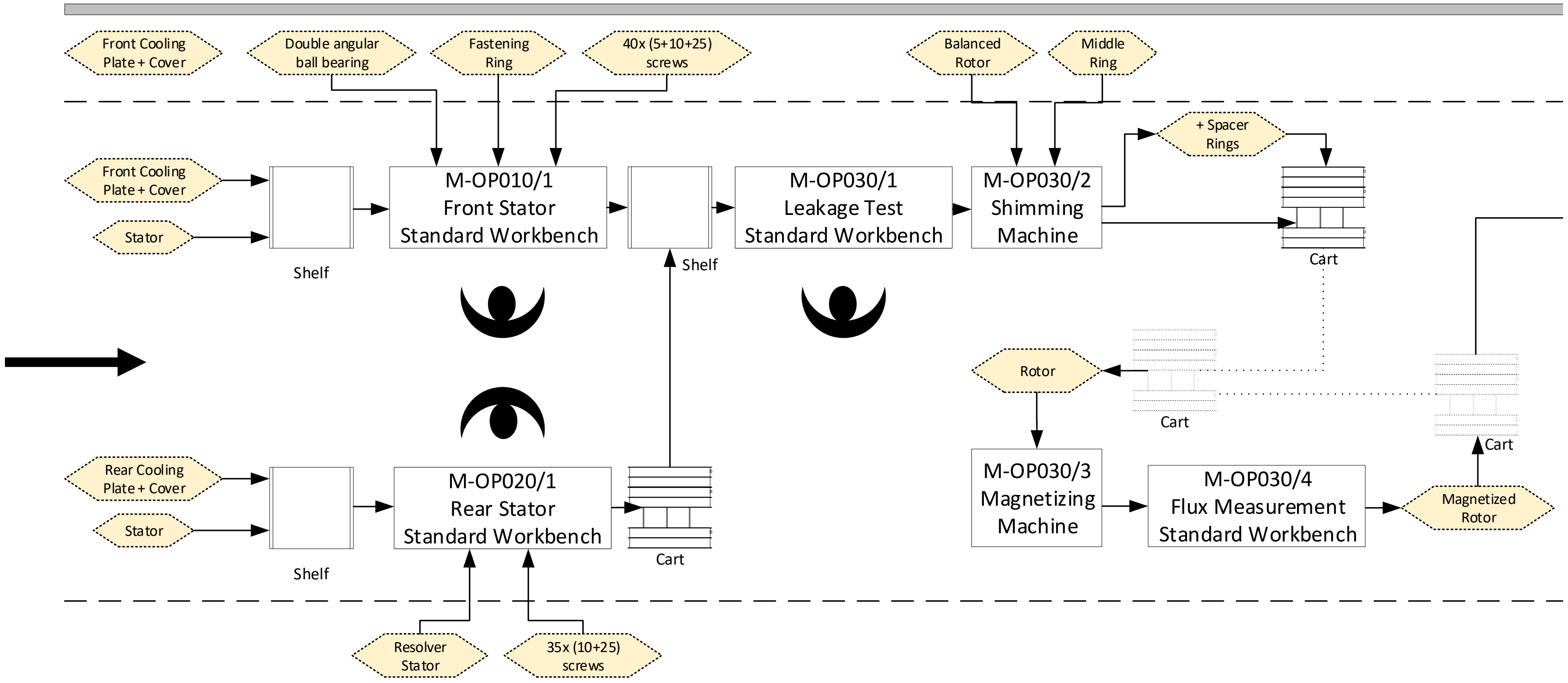


Figure 4.5: Logical Plant Layout with Material Flow (Continued)

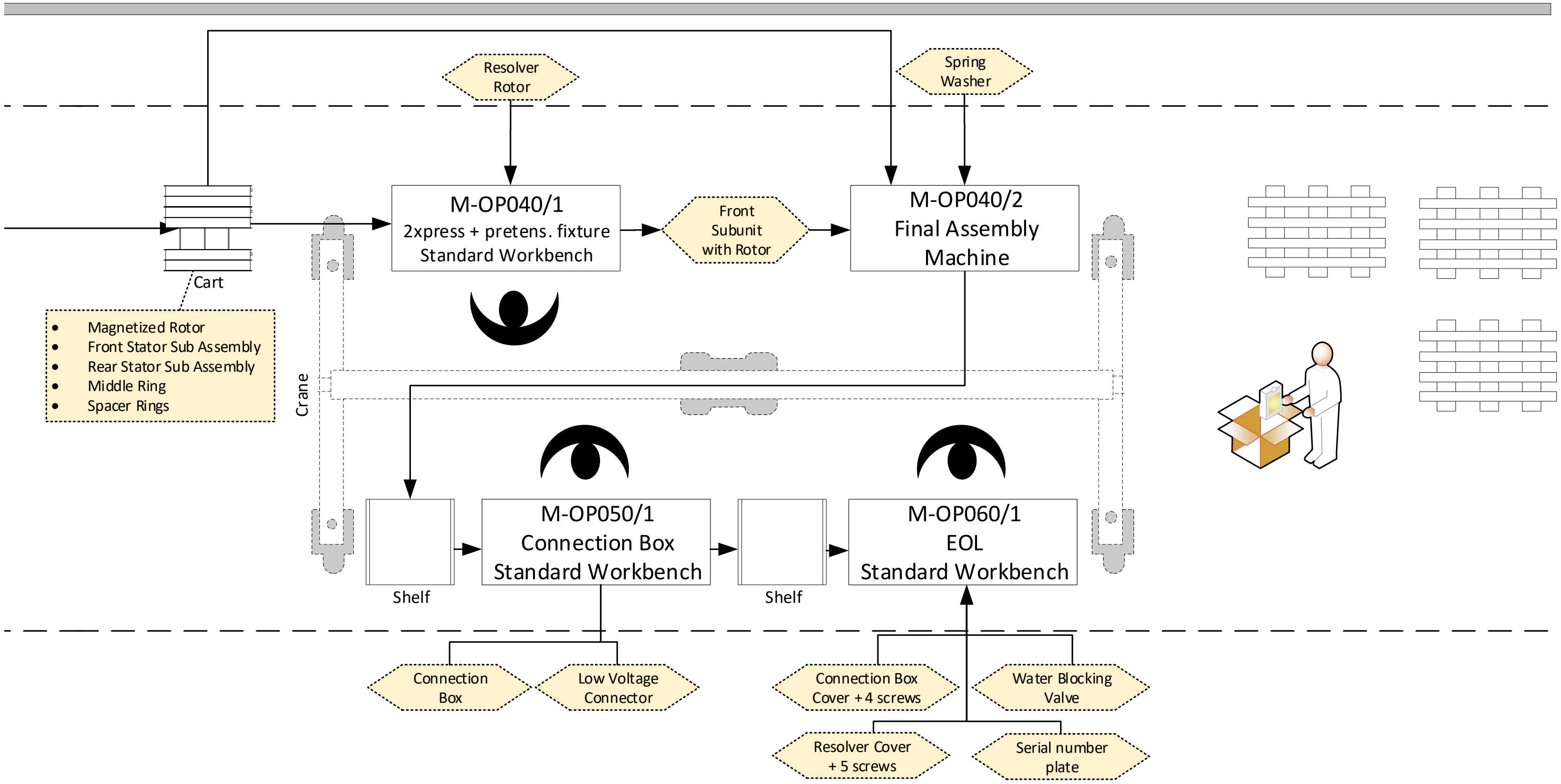


Figure 4.5: Logical Plant Layout with Material Flow (Continued)

Chapter V

Automatic Identification and Data Capture

In this chapter the manufacturing system design is completed by integrating a possible software system for AIDC. All the soft- and hardware requirements for the **manufacturing execution system** are collected. The MES needs to track and document the transformation of raw materials to finished goods. The basic goal is to substitute the hand-written *Assembly Report for Prototype Motor*, which for the medium capacity production line will reach its practical feasibility limits.

1 System Overview

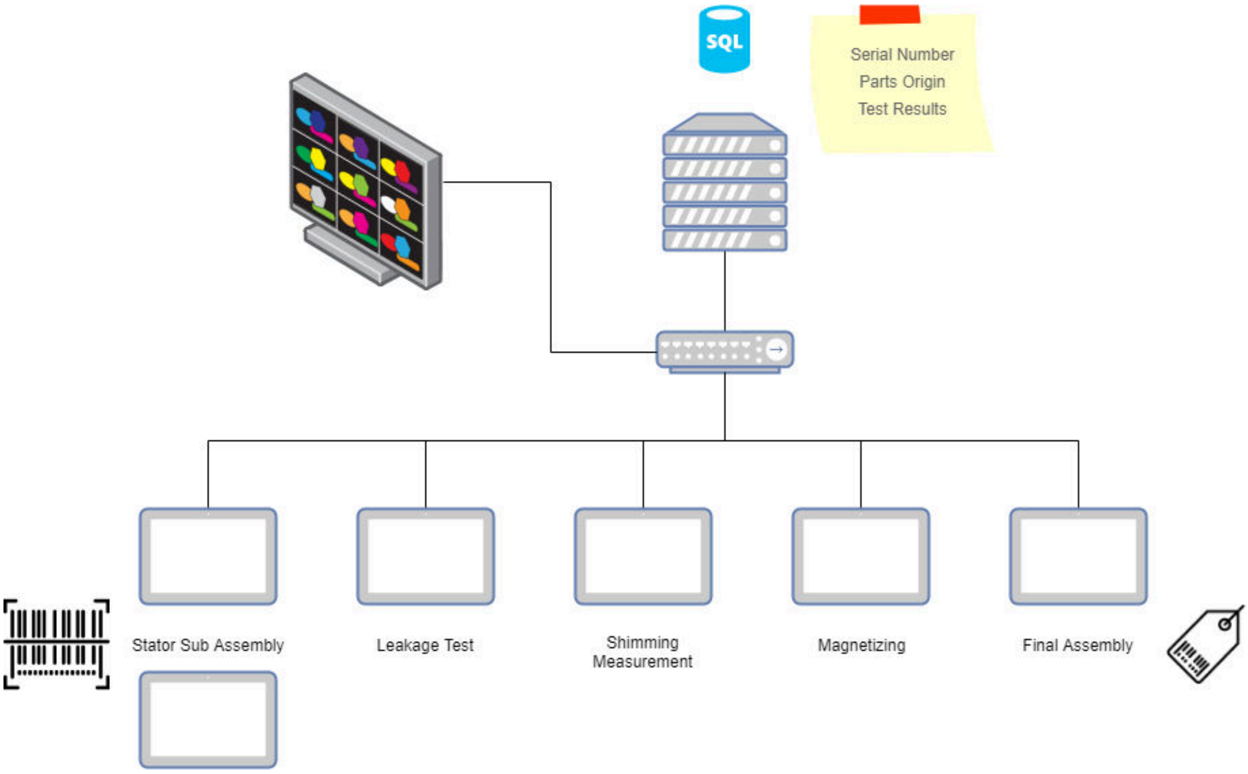


Figure 5.1: MES System Overview

The system topology with the main stations in the final assembly line is shown in fig. 5.1.

All the workstations shown are equipped with an HMI, which allows simple touch interaction and data visualization. Generally, the HMI runs on an IPC integrated in the workbench and is therefore flexible from a software point of view, i.e. will run a **Windows based system**. Some of them may have additional devices such as barcode scanners attached or even run on PLCs, providing production related data to be saved in the database.

Along the product routing path, parts and sub-assemblies should be scanned whenever necessary to guarantee satisfying monitoring coverage and traceability. This requires an automatic part identification solution, such as barcode scanner. A technical overview of possible technologies can be found in [11, pp. 337-352].

1.1 Actors

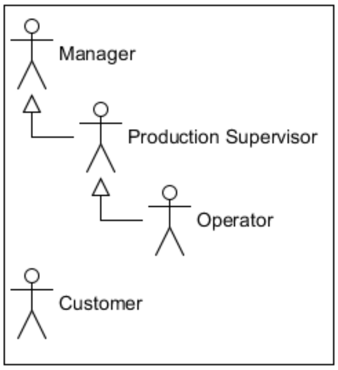


Figure 5.2: Actors

The main users interacting with the system, as illustrated in fig. 5.2, are:

1. Operator
2. Supervisor
3. Manager
4. Customer

Operators are placed in each workstation and responsible for performing the production tasks. The supervisor is responsible for managing the production activity in every shift, picking the orders to be manufactured and ensuring production flow by monitoring raw material stocks, the workstations and solving any issue.

The manager represents any business layer role, which needs to interact with the manufacturing system. Examples may be:

1. Production planner
2. Purchasing
3. Customer support (e.g. returning parts from clients)
4. …

The customer uses the final product and may need to interact with some of the manager roles.

2 Data to be recorded

The following data is currently collected on the assembly report:

1. General information
    (a) Model
    (b) Product
    (c) **Product Code**
    (d) Assembly DWG. No.
    (e) Weight
    (f) Operator
    (g) Comments
2. Rotor Sub-Assembly
    (a) Rotor
        i. **Part Retrospect Number**
        ii. Weight
        iii. Spider color
        iv. Magnet color
        v. Magnet segments (4 or 8)
    (b) Shaft
        i. **Part Retrospect Number**
        ii. Weight
    (c) Resolver
        i. **Part Retrospect Number**
        ii. Weight
    (d) Assembly
        i. Bolts torque
        ii. Thread locker (Loctite 243 or 263)
    (e) Balancing
        i. Residual unbalance
        ii. Balancing holes diameter and depth
    (f) Magnetization
        i. Magnetic flux density in all sections e.g. 10x4 for M18
    (g) Sub-Assembly general information
        i. **Part Number**
        ii. Weight
3. Stator Sub-Assemblies (same for Front and Rear)

   (a) Front Stator
      i. **Part Retrospect Number**
      ii. Weight
      iii. Coil diameter (inside, outside)
      iv. Core thickness
      v. Ground cooling surface (yes, no)
   (b) Front Plate
      i. **Part Retrospect Number**
      ii. Weight
      iii. Machining technology (machine, casting)
      iv. Anodizing (yes, no)
   (c) Stator Assembly
      i. Thermal conductive material (XF-X50) and weight (20g)
      ii. Bolts type and torque (5Nm)
      iii. Thread locker (Loctite 243, 263)
   (d) Sealing Assembly
      i. Sealing method (Gasket, O-ring, sealing washer, …)
      ii. Bolts type and torque (10Nm)
      iii. Thread locker (Loctite 243, 263)
   (e) Leakage Test
      i. Pressure [bar]
      ii. Flow rate [cm^3/min]
   (f) Sub-Assembly general information
      i. **Part Number**
      ii. Weight (before and after potting)

4. Final Assembly
   (a) Middle Ring
      i. **Part Retrospect Number**
      ii. Weight
      iii. Machining technology (machine, casting)
      iv. Anodizing (yes, no)
   (b) Shimming
      i. All raw data dimension measurements (2 stators, middle ring, rotor)
      ii. Front and rear theoretical and actual gap size
   (c) Motor Assembly
      i. Bolts torque and thread locker (Loctite 243, 263) for 8 sections

5. Test results

- (a) Functional test (pass / suspect) with comments and signature
- (b) Insulation High Port test (pass / suspect) with comments and signature
- (c) Product inspection (pass / suspect) with comments and signature

The provided list gives an almost complete summary of the relevant information on the assembly report. However, for the assembly line some points may be omitted or changed if necessary.

3 Requirements Definition

This section defines the use cases which need to be performed with the MES. The use cases are prioritized, starting from the most important basic requirements, up to the optional features. Therefore, they are categorized from Level 1 to Level 3. First, the overall requirements are listed and then workstation specific details are reported.

3.1 Implementation levels

Level 1 implementation includes:

1. **Product traceability**: every motor gets a serial number to which all the essential information from section 3 is associated in the database system

Level 2 adds:

1. **Manufacturing management**: the supervisor can actively control the production tasks by showing on the specific HMIs information on the model to be manufactured, together with specific instructions on what to do next (e.g. scan parts, show drawings, etc.)

2. **Production monitoring**: every production step includes triggering actions (start / stop e.g. by scanning the parts) which allow to monitor the production flow in better detail

Level 3 adds:

1. **ERP integration (Macola)**: information such as suppliers, customers and orders are directly linked to the company's management IT system

2. **Operator authentication**: on all workstations the operator in charge is identified and associated with the manufactured motor unit

3.2 Factory Layout Requirements

The traceability requirement implies to have a standard labeling procedure, as explained in use case UC104. The process is illustrated in fig. 5.3.

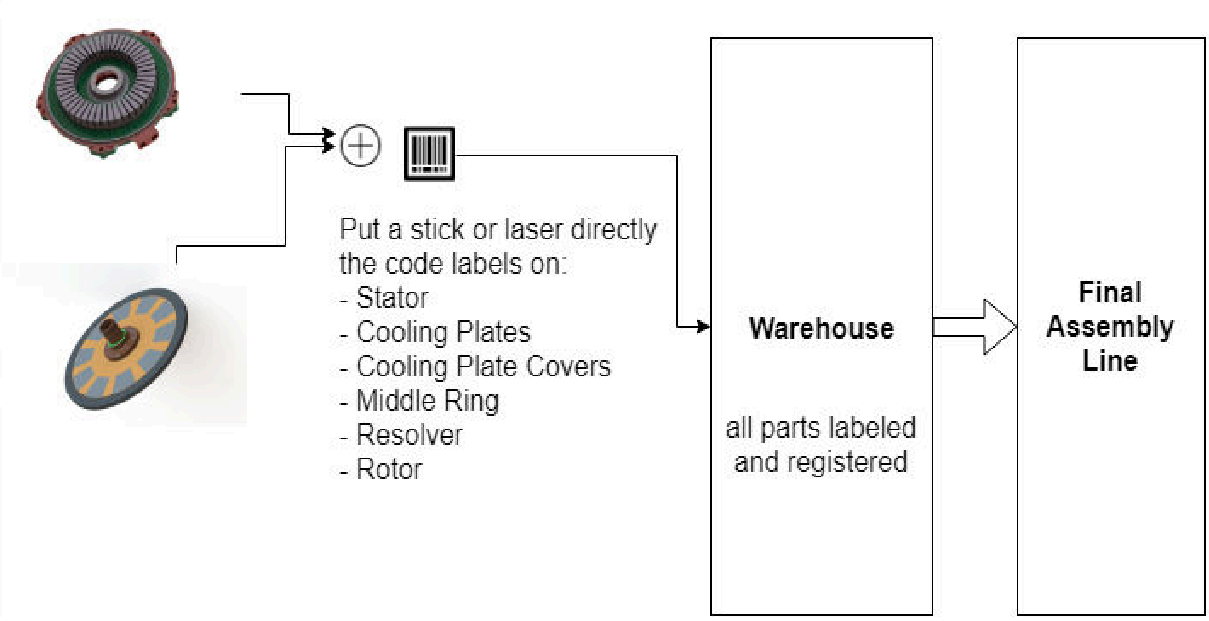


Figure 5.3: Labeling Procedure

This process can either be minimized for Level 1, to do the minimum required in the final assembly bench or implemented up to Level 3, with integration in the ERP system.

3.3 Level 1

The following use cases must be covered in the basic level 1 solution.

3.3.1 UC101 Motor Unit Identification

This use case represents the need for the finished motor unit to be identifiable in a simple way.

Use Case ID	**UC101**
Use Case Name	Motor Unit Identification
Actor	Customer / Operator
Description	The operator or customer encounters a problem with an assembled motor unit. This specific unit is determined by reading or scanning the serial number.
Preconditions	The assembled unit contains some identification tag The identification tag is visible, meaning that the motor unit is accessible
Postconditions	The unit's unique number is known
Frequency of Use	1/week at customer's side, 5/h in factory (for regular EOL tests)
Activities	The user inspects the assembled motor unit The user gets the serial number
Alternative Flow	*N/A*
Includes	*none*
Notes and Issues	The identification technology is still to be defined (bar code, QR code, ...). Consider however that a readable serial number as fallback may have advantages in customer support.

Table 5.1: UC101

3.3.2 UC102 Post Production Investigation

This use case represents the basic support case: the customer identifies the motor and the company's support team (represented by manager role) investigates the eventual issues by analyzing the saved production data of the specific unit.

Use Case ID	**UC102**
Use Case Name	Post Production Investigation
Actor	Manager
Description	A motor unit with problems, such as performance issues, is analyzed by checking all the data recorded in the production phase.
Preconditions	During production, the data was recorded and linked correctly to the identified serial number
Postconditions	All reports, suppliers, order numbers, … are available
Frequency of Use	1/week
Activities	Motor unit is identified (UC101) The manager looks up the serial number in the system Production data shows up
Alternative Flow	*N/A*
Includes	UC101
Notes and Issues	Details on how the data is retrieved may be defined when section 3 is finalized. For sure it all needs to be saved in the database.

Table 5.2: UC102

3.3.3 UC103 Final Assembly Parts Record

As given in section 3, the assembly report includes the part retrospect numbers. This requires (at least) in the final assembly step the identification of all sub-assemblies.

Use Case ID	**UC103**
Use Case Name	Final Assembly Parts Record
Actor	Operator
Description	When closing the motor unit, the main parts are identified and recorded
Preconditions	The records of the subassemblies are known to the system before entering the final assembly line, e.g. the rotor unit record with the specific PM supplier is saved already before
Postconditions	A new serial number is assigned to the motor and linked with all the subassemblies in the database
Frequency of Use	3/h
Activities	Identify rotor unit Identify front stator unit Identify rear stator unit Apply new serial number and link data in the system
Alternative Flow	*N/A*
Includes	*none*
Notes and Issues	Regarding the serial number generation, an alternative approach could be to use e.g. the front plate part ID as final motor serial number. For this, the part ID tag needs to be outside, i.e. visible on the motor. To avoid confusion, the rest of the IDs should be placed inside.

Table 5.3: UC103

3.3.4 UC104 Parts Origin Record

To better capture the origin of assembled parts, before entering the final assembly line, additional information can be added to the system.

Use Case ID	**UC104**
Use Case Name	Parts Origin Record
Actor	Operator
Description	Beyond their id, all identifiable parts, may include additional data, such as raw material suppliers, order numbers, and so on. This information needs to be linked to the subassembly ID before entering the production line.
Preconditions	*None*
Postconditions	The subassemblies record exists with raw material information and is ready to be used in the assembly line
Frequency of Use	1/shift if bulked when entering production before each shift
Activities	Gather additional information when producing or buying parts (e.g. rotor) Put a new part record into the system, with a unique identifier (bar code, QR code, …)
Alternative Flow	*N/A*
Includes	*none*
Notes and Issues	A correct integration in the company's IT system would ease this process, as foreseen in implementation level 3.

Table 5.4: UC104

3.4 Level 2

The following use cases must be covered in the basic level 1 solution.

3.4.1 UC201 Trigger Production

When the shift starts the supervisor may actively control the production by picking an order, i.e. choosing the model to be produced and pushing the information out on all HMIs.

Use Case ID	**UC201**
Use Case Name	Trigger Production
Actor	Supervisor
Description	In the master control the supervisor chooses the model to be produced, which automatically enables the respective instructions and drawings on each workbench.
Preconditions	Production is in idle or every workstation has finished the previous task All workstations are ready, i.e. input materials available, system running, etc.
Postconditions	The correct instructions are shown on each workstation
Frequency of Use	1/shift
Activities	Trigger production of specific model (e.g. M21) If all workstations are ready, production flow starts with workbench specific instructions
Alternative Flow	Trigger production Show warnings and errors for workbenches with issues such as uncompleted tasks
Includes	*none*
Notes and Issues	Error handling requires every workbench to have a specific state (idle, ongoing task, task completed)

Table 5.5: UC201

3.4.2 UC202 Workbench Specific Visualization

This use case is a generalization of the instruction visualization. Every workbench may include several production tasks, such as scan materials, assemble according to drawings and signal task completion. The common requirement for monitoring the production flow is to have material input and output signals.

Use Case ID	**UC202**
Use Case Name	Workbench Specific Visualization
Actor	Operator
Description	Once the production of a specific model has been triggered, every workbench shows specific instructions. The operator needs to follow those and let the system know that he starts or stops the production task
Preconditions	Production start has been triggered
Postconditions	Repeat instructions (unless production is stopped)
Frequency of Use	3/h
Activities	Scan input materials, or signalize start Follow workbench specific instructions with the help of additional information shown on the monitor such as drawings When finished, signalize by pushing button on monitor or scanning output material
Alternative Flow	Scan input materials, or signalize start Report any issues to the supervisor by aborting the current task (e.g. by pushing a yellow button on the monitor)
Includes	*None*
Notes and Issues	This use case is essential for level 2 implementation, since it allows monitoring the material flow

Table 5.6: UC202

3.4.3 UC203 Changeover

The supervisor manages the model changeover, while production is running.

Use Case ID	**UC203**
Use Case Name	Changeover
Actor	Supervisor
Description	When the model to be produced is changed, the MES helps the supervisor to queue the right instructions on the specific workbenches.
Preconditions	Running production
Postconditions	After one production cycle every workstation shows the new instructions
Frequency of Use	1/shift
Activities	Supervisor initiates changeover Once the first workbench is finished with its current task, the changeover instructions are shown which may include also some tasks (e.g. for shimming measurement) The operator completes eventual changeover tasks The new instructions are shown on the displays Step 2-4 is repeated for the next workstations in the pipelines All workstations have changed to the new model
Alternative Flow	*N/A*
Includes	*none*
Notes and Issues	*none*

Table 5.7: UC203

3.4.4 UC204 Production Monitoring

The supervisor must be able to monitor the production flow and fix upcoming issues.

Use Case ID	**UC204**
Use Case Name	Production Monitoring
Actor	Supervisor
Description	The supervisor's workstation includes
Preconditions	Running production
Postconditions	After one production cycle every workstation shows the new instructions
Frequency of Use	continuously
Activities	Check workstation overview Select workstation and see current tasks with the input materials that have been scanned
Alternative Flow	*N/A*
Includes	*none*
Notes and Issues	This use case should be split up in real use cases, such as tracking missing materials and react to reported errors from workstations

Table 5.8: UC204

3.5 Level 3

3.5.1 UC301 ERP Integration

The production system needs to be integrated in the company's IT system.

Use Case ID	**UC301**
Use Case Name	ERP Integration
Actor	Manager
Description	The manager wants to link the MES with the Macola ERP system to have access to customer, order and suppliers list in the production environment.
Preconditions	*N/A*
Postconditions	*N/A*
Frequency of Use	1/shift
Activities	Use integration
Alternative Flow	*N/A*
Includes	*none*
Notes and Issues	This is not a real use case and needs to be elaborated

Table 5.9: UC301

4 User Interface Proposal

To better clarify the requirements, a possible user interface draft is given in this section.

4.1 Workstation Client

The basic workflow defined in UC202 requires three main pages in the user interface:

1. A placeholder page for the case in which the production has not yet been started (i.e. the supervisor did not choose the model to be produced)

2. An interface for scanning the parts

3. An instruction viewing page

The following figures contain some mockups as a basic idea of how an implementation could look like.

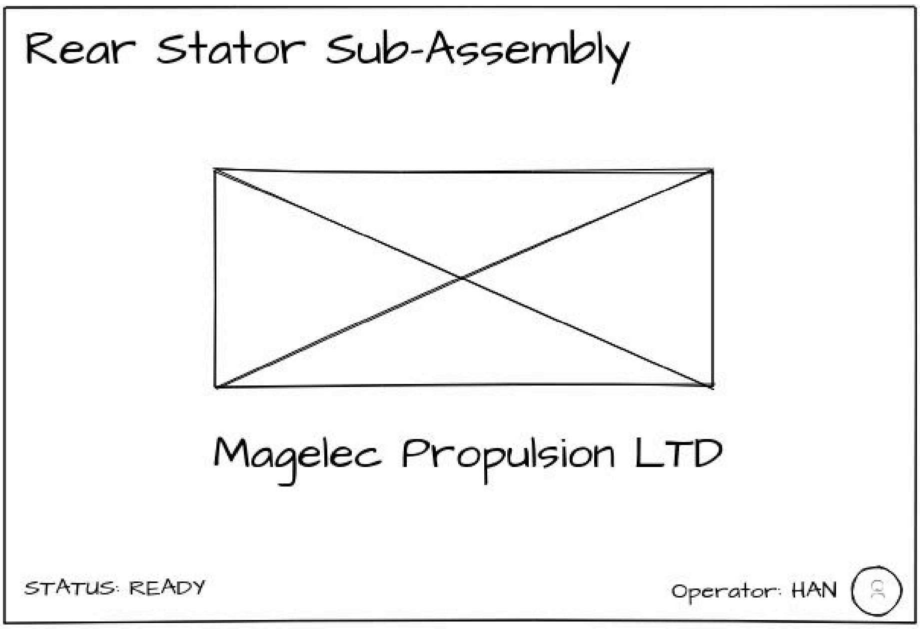
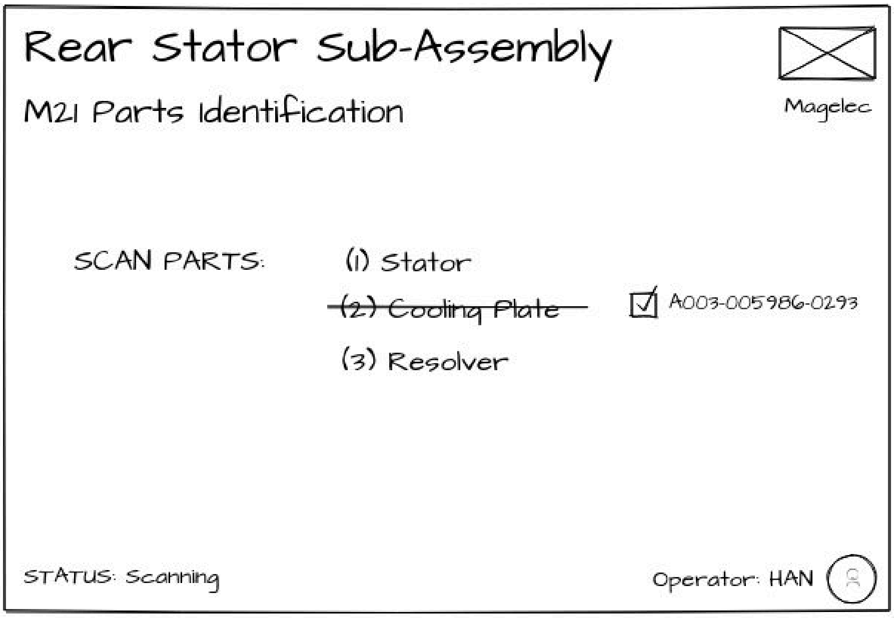


Figure 5.4: Placeholder Page

Figure 5.4 shows a simple dummy page. For greater flexibility, some buttons could be added to manually **pick a model and start the workflow on the workbench itself**.

In fig. 5.5 a possible input parts scanning interface is drafted. This page is shown as soon as the supervisor triggers the production of a specific model, M21 in this case.



Rear Stator Sub-Assembly

M21 Parts Identification

SCAN PARTS: (1) Stator

~~(2) Cooling Plate~~ ☑ A003-005986-0293

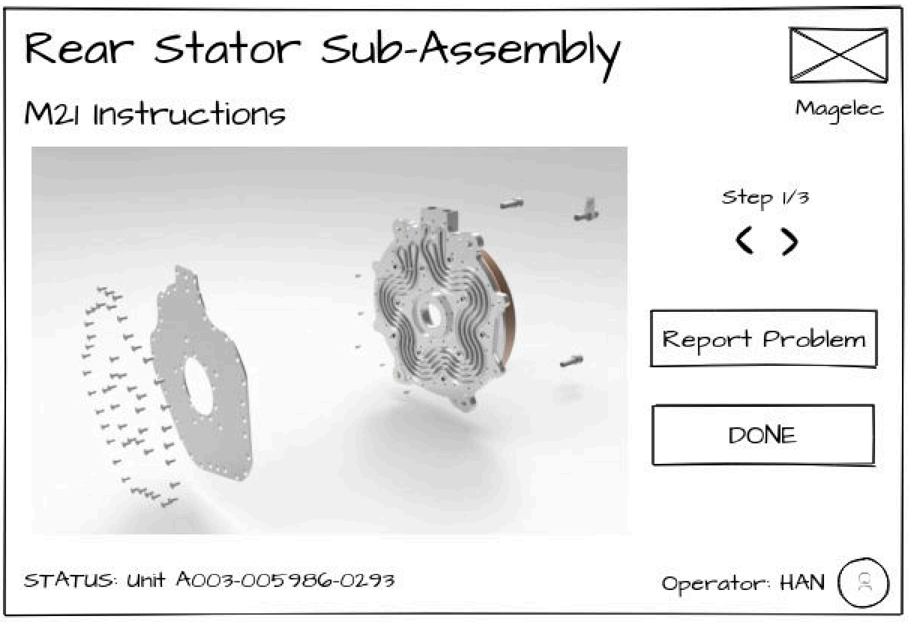
(3) Resolver

STATUS: Scanning

Operator: HAN

Figure 5.5: Scanning Parts Interface

Figure 5.6 shows a draft for the instruction visualization.



Rear Stator Sub-Assembly

M21 Instructions

Step 1/3

STATUS: Unit A003-005986-0293

Operator: HAN

Figure 5.6: Instruction View

By clicking on the “DONE” button the sub assembly is registered to be finished on this workbench. For better usability this action could also be triggered by rescanning one of the input parts.

4.2 Monitoring Interface

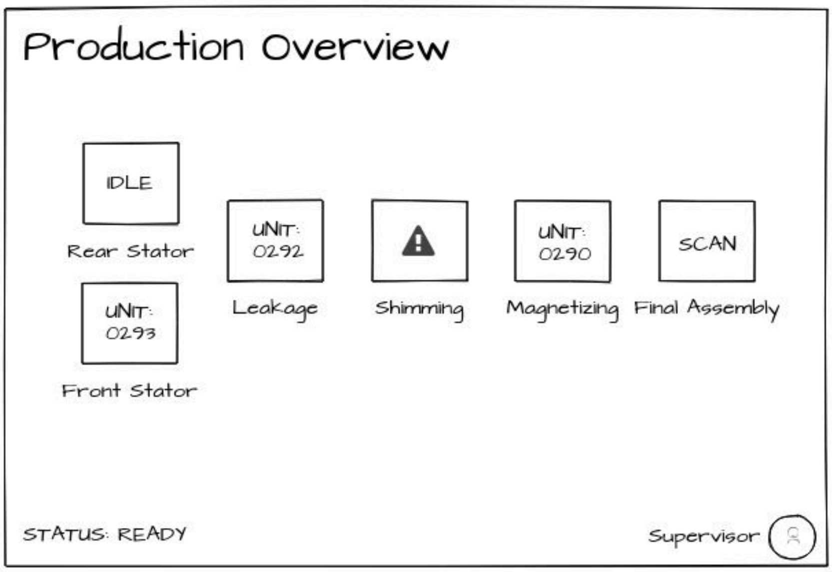
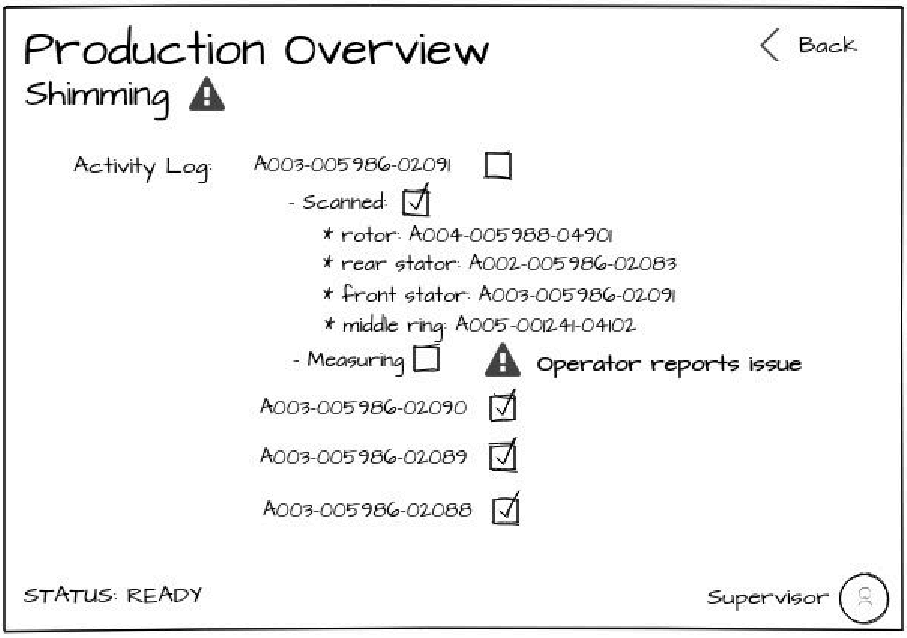


Figure 5.7: Monitoring Interface

The supervisor should have an interface to see all workstations, as drafted in fig. 5.1.

Reported errors from the operators should be shown immediately and at least the last digits of the main workpiece scanned on each workbench should be visible. A detailed workstation view, as shown in fig. 5.8.



Activity Log: A003-005986-02091 ☐
- Scanned: ☑
  * rotor: A004-005988-04901
  * rear stator: A002-005986-02083
  * front stator: A003-005986-02091
  * middle ring: A005-001241-04102
- Measuring ☐ Operator reports issue

A003-005986-02090 ☑

A003-005986-02089 ☑

A003-005986-02088 ☑

Figure 5.8: Monitoring Detail Workstation

Chapter VI

Experimental Results

This chapter presents some experimental results of tests that have been carried out in the design stage. Due to deadline constraints, the validation results of the assembly line balancing and layout e.g. timing validations are not vailable for this written work, since the line is under construction. However, several tests on the motor models have been performed to evaluate the feasilbility of the design concept. The results are shown in the following sections.

1 EOL design validation test

As explained in section 4.3 on page 35, the functional test procedure is planned to be minimized just several seconds.

Figure 6.1 shows the spin-down in velocity, as expected in 2.6 s.

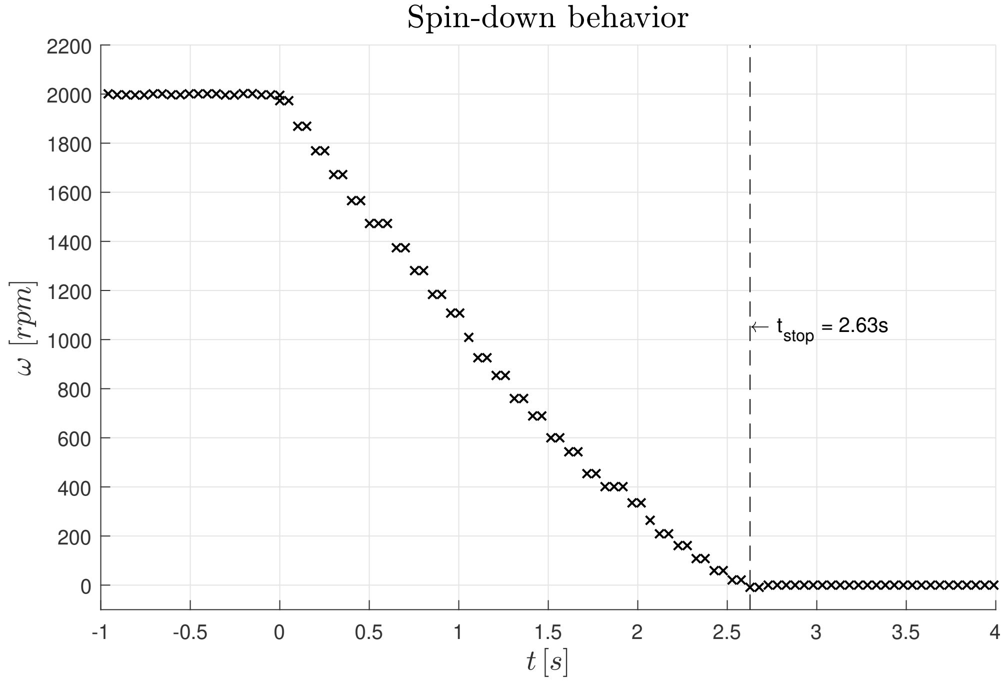


Figure 6.1: Spin down behavior

Figure 6.2 shows the same test starting from −2000 rpm.

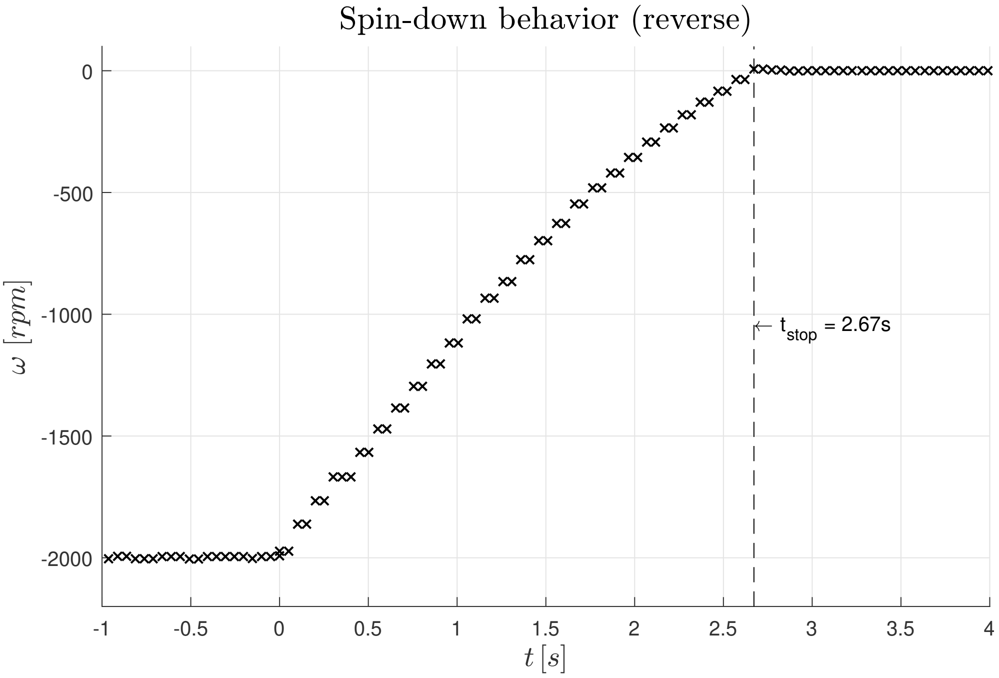


Figure 6.2: Spin down behavior (reverse)

More interestingly, the back-emf waveform was recorded during the motor spin down. As expected, the waveform decreases with speed and takes around 2.6 s to stop starting from 2000 rpm. Even the unfiltered signal is quite clear and looks as follows – closeup from 1.0 s to 3.0 s in fig. 6.3:

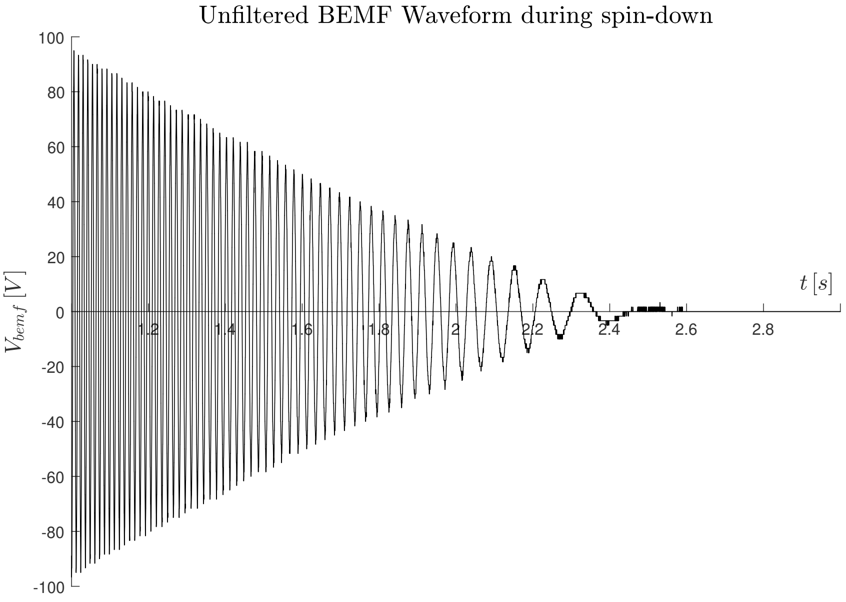


Figure 6.3: Unfiltered Back-emf waveform in speed transient

After filtering high-frequency signals, it is possible to estimate the frequency by using the zero-crossing points. In this way the motor speed is obtained and can be interpolated to get a continues function, as given in fig. 6.4.

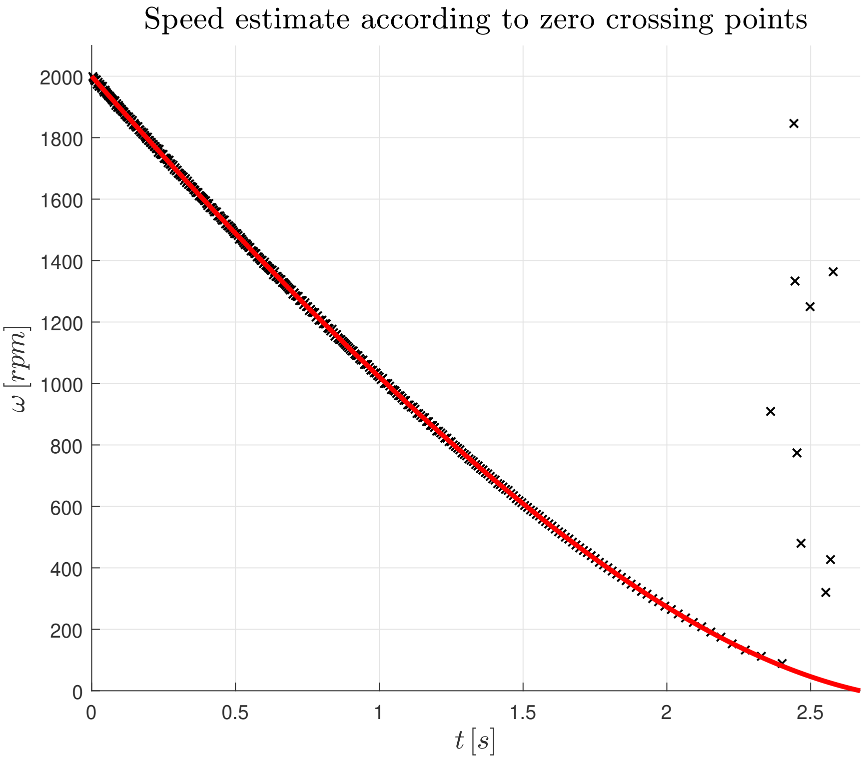


Figure 6.4: Speed estimate based on zero-crossing points

The same procedure can be performed using the Root Mean Square (RMS) values of the back-emf in between the zero-crossing points. See fig. 6.5.

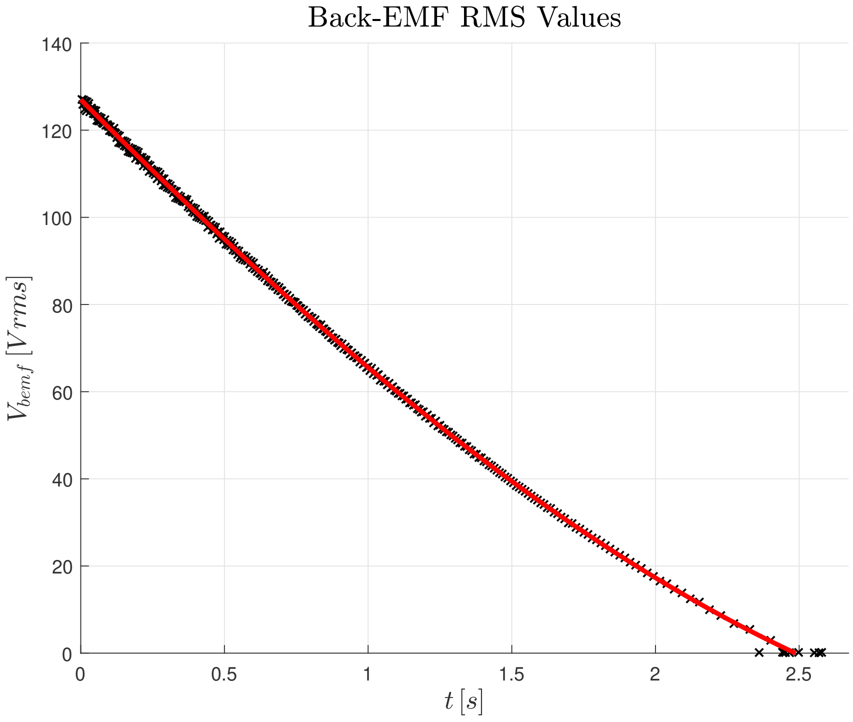


Figure 6.5: Back-EMF RMS interpolation

Those two fitted functions combined, lead to the useful Back-emf RMS vs speed curve in fig. 6.6

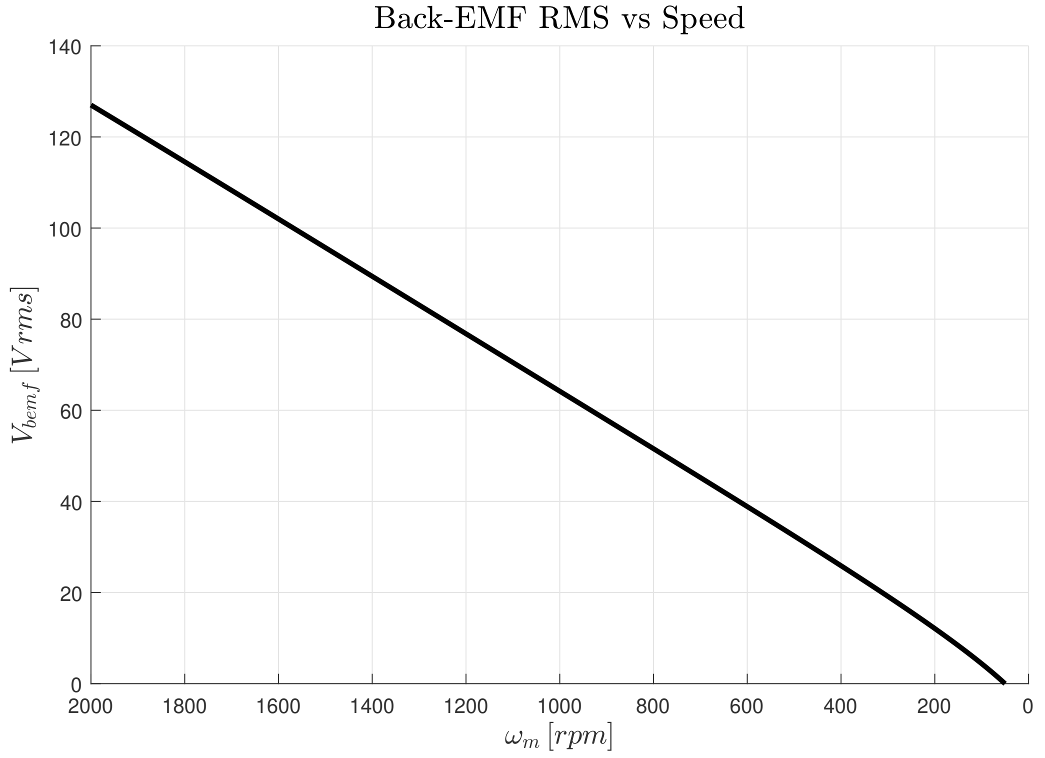


Figure 6.6: Estimated Back-EMF RMS vs speed

This curve yields the characteristic value needed: $V_{rms,@1000rpm}$ = 64.6 Vrms.

This procedure is performed for every DUT with a reasonable amount of computational power. The resulting value is then compared to the acceptable range for the specific model.

To investigate the repeatability several tests have been carried out on the same unit. As long as the sample rate is kept in a similar order of magnitude, the results are very similar, see table 6.1

Test Number	Sampling Frequency [kHz]	Estimated Stop Time [s]	Estimated time @1000rpm [s]	Estimated RMS @1000rpm [Vrms]
03	20	2.7051	1.0246	63.9462
01	20	2.7052	1.0247	63.9462
06	100	2.6452	1.0012	64.5656
02	200	2.6114	1.0021	64.5546
04	200	2.6114	1.0021	64.5546
05	200	2.5955	1.0027	64.6822
07	200	2.6107	0.9988	64.6452
08	200	2.5787	0.9981	64.6004

Table 6.1: Spin down test series results[1]

Figure 6.7 shows test results obtained with the higher sample rates, 100 kHz and above.

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[1] as the data shows, the stop time indicating the no-load losses, cannot be interpolated accurately by just using the oscilloscope's data. The resolver speed should be considered instead, see fig. 6.1

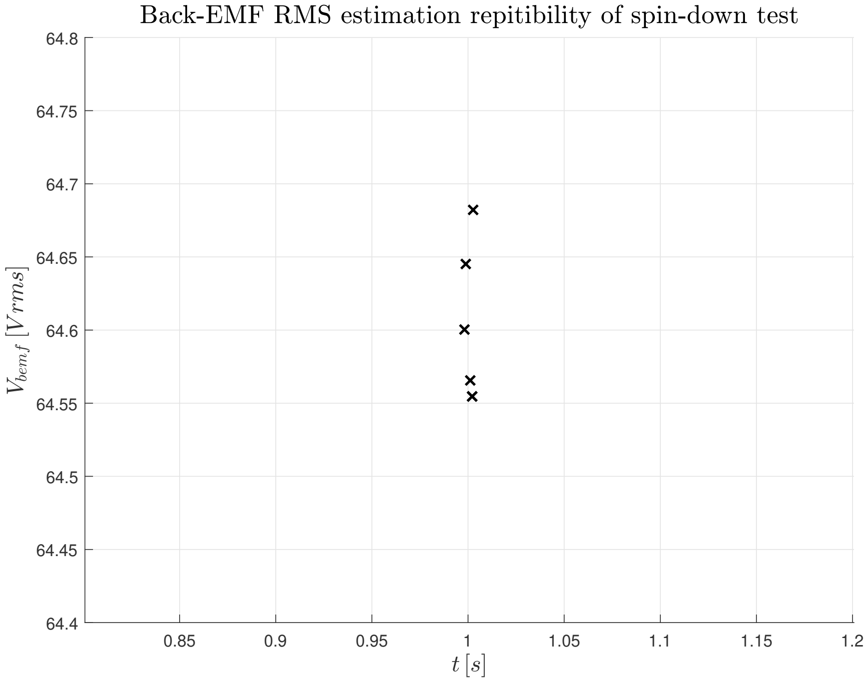

Figure 6.7: Back-EMF RMS estimation repeatability[2]

Considering these higher sampling frequencies a mean value of 64.6 Vrms ±0.13% (maximum deviation) is obtained. Motor units are usually required to stay in the range of a few percent from the nominal value. With 0.13 % of measurement error, this can easily be handled.

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[2] two measurement points are overlapping

Chapter VII

Conclusion and Future Work

This work provided a design case study of an assembly line for axial flux drives. With respect to the previous prototype production, the manufacturing time for one motor unit could greatly be reduced from more than 4 h to a cycle time of 20 min in 7 workstations.

1 Project Review

As the thesis tried to show, many subproblems had to be addressed with diversified fields of application, from mechanical workbench and fixture design, to electronic data acquisition during motor spin down tests. Such an environment with frequently changing requirements and high demand on interdisciplinary knowledge justifies the need for the *automation engineer* as a professional figure. The project was therefore an ideal way to recap and enhance the learning achievements obtained during the degree program.

From an industrial point of view, with this project the requirements and specifications have all been finalized and the assembly line is ready to be built. The first workstations will be ready soon and production will start in the next few months.

1.1 Academical Outcomes

From an academic point of view, the project successfully shows the attempt and possibility of scaling axial flux drives up to mass production in an economically sustainable way. State of the art technology and trends such as collaborative robotics, turned out to be unfeasible from a cost and entropenoureal risk point of view. However, the main point of finding a feasible trade-off between quality and cost, allowing to actually start a mass production of axial flux drives has been realized.

This case study shows once more that even theoretically outperforming approaches and designs such as the AFPM motor, must face the markets in order to compete on the industries. Thereby, cost is the major driver which drastically limits the theoretical options.

1.2 Lessons learned

The most important outcome from a personal point of view is the experience of how the design phase is handled in an industrial context. Soft skills like communication across language barriers, explaining concepts using the white-board with some drawings or preparing 3D CAD models turned out to be crucial for successful idea discussion and propagation. The engineering capability of quickly estimating and dimensioning at least the order of magnitude was particularly useful in this belongings. From a certain point of view, the main ability obtained in University is therefore the *way of reasoning* rather than industry specific knowledge. In many cases, a clear explanation and structured reasonings solves already most of the problems.

2 Future Work

The indispensable next step, is to perform the timing validations. The first workstations will be ready in a few weeks and tests can be performed. Eventual re-balancing may be necessary.

Other approaches could be investigated and developed, such as:

- Additive Manufacturing techniques for easier stator fabrication, as suggested in [3]
- Asynchronous transportation systems, such as rails with carts for easier product handling
- Implementation of the production planning system along with the MES described in chapter V

Appendix A

References

[1] M. Yoshimura, *System Design Optimization for Product Manufacturing*, en. London: Springer London, 2010, ISBN: 9781849960076. DOI: `10.1007/978-1-84996-008-3`. [Online]. Available: `http://link.springer.com/10.1007/978-1-84996-008-3` (visited on 2019-03-23).

[2] *World Bank Open Data*. [Online]. Available: `https://data.worldbank.org/` (visited on 2019-03-23).

[3] A. Kampker, P. Treichel, K. Kreisköther, R. Pandey, M. K. Büning, and T. Backes, "Alternative Fabrication Strategies for the Production of Axial Flux Permanent Magnet Synchronous Motors for Enhanced Performance Characteristics," in *2018 8th International Electric Drives Production Conference (EDPC)*, 2018-12, pp. 1–7. DOI: `10.1109/EDPC.2018.8658341`.

[4] M. Rimondi, "Design of a semi-automatic Shimming Measurement Machine for Axial Flux Electric Motors," Bachelor's Thesis, Tongji University, Shanghai, 2019-06.

[5] L. Bezzi, "Design of an automatic End Of Line process for mass production of Axial Flux Electric Motors," Bachelor's Thesis, Tongji University, Shanghai, 2019-06.

[6] J. F. Gieras, R.-J. Wang, and M. J. Kamper, *Axial flux permanent magnet brushless machines*. Dordrecht ; Boston: Kluwer, 2004, OCLC: ocm56755522, ISBN: 9781402026614 9781402027208.

[7] J. MacDonald, "Electric vehicles to be 35% of global new car sales by 2040," *Bloomberg New Energy Finance*, vol. 25, 2016.

[8] B. Nykvist and M. Nilsson, "Rapidly falling costs of battery packs for electric vehicles," en, *Nature Climate Change*, vol. 5, no. 4, pp. 329–332, 2015-04, ISSN: 1758-6798. DOI: `10.1038/nclimate2564`. [Online]. Available: `https://www.nature.com/articles/nclimate2564` (visited on 2019-05-25).

[9] M. Philippot, G. Alvarez, E. Ayerbe, J. Van Mierlo, and M. Messagie, "Eco-Efficiency of a Lithium-Ion Battery for Electric Vehicles: Influence of Manufacturing Country and Commodity Prices on GHG Emissions and Costs," en, *Batteries*, vol. 5, no. 1, p. 23, 2019-03. DOI: `10.3390/batteries5010023`. [Online]. Available: `https://www.mdpi.com/2313-0105/5/1/23` (visited on 2019-05-25).

[10] M. Khan and R. Pope-Ford, “Improving and modifying the design of workstations within a manufacturing environment,” *Procedia Manufacturing*, vol. 3, pp. 4927–4934, 2015, 6th International Conference on Applied Human Factors and Ergonomics (AHFE 2015) and the Affiliated Conferences, AHFE 2015, ISSN: 2351-9789. DOI: `https://doi.org/10.1016/j.promfg.2015.07.631`. [Online]. Available: `http://www.sciencedirect.com/science/article/pii/S2351978915006320`.

[11] M. P. Groover, *Automation, Production Systems, and Computer-Integrated Manufacturing*, English, 4th edition. New York: Pearson, 2014-08, ISBN: 9780133499612.

[12] M. Faber, J. Bützler, and C. M. Schlick, “Human-robot cooperation in future production systems: Analysis of requirements for designing an ergonomic work system,” *Procedia Manufacturing*, vol. 3, pp. 510–517, 2015, 6th International Conference on Applied Human Factors and Ergonomics (AHFE 2015) and the Affiliated Conferences, AHFE 2015, ISSN: 2351-9789. DOI: `https://doi.org/10.1016/j.promfg.2015.07.215`. [Online]. Available: `http://www.sciencedirect.com/science/article/pii/S2351978915002164`.

[13] C. A. Ortiz, *Kaizen assembly: designing, constructing, and managing a lean assembly line*, eng. Boca Raton, Fla.: CRC/Taylor & Francis, 2006, OCLC: 730304433, ISBN: 9780849371875.

[14] L. Li, “China’s manufacturing locus in 2025: With a comparison of “Made-in-China 2025” and “Industry 4.0”,” *Technological Forecasting and Social Change*, vol. 135, pp. 66–74, 2018-10, ISSN: 0040-1625. DOI: `10.1016/j.techfore.2017.05.028`. [Online]. Available: `http://www.sciencedirect.com/science/article/pii/S0040162517307254` (visited on 2019-05-29).

[15] D. Moreels, *Axial Flux Machine Technology - Whitepaper*, en-us. [Online]. Available: `https://www.magnax.com/magnax-blog/axial-flux-machine-technology-whitepaper` (visited on 2019-05-25).

[16] S. Amin, S. Khan, and S. S. Hussain Bukhari, “A Comprehensive Review on Axial Flux Machines and Its Applications,” in *2019 2nd International Conference on Computing, Mathematics and Engineering Technologies (iCoMET)*, Sukkur, Pakistan: IEEE, 2019-01, pp. 1–7, ISBN: 9781538695098. DOI: `10.1109/ICOMET.2019.8673422`. [Online]. Available: `https://ieeexplore.ieee.org/document/8673422/` (visited on 2019-05-25).

[17] M. Alibeik, O. Nezamuddin, M. Rubin, N. Wheeler, S. Silvestri, and E. d. Santos, “Airgapless electric motor: A solution for high-torque low-speed applications,” in *2017 IEEE International Electric Machines and Drives Conference (IEMDC)*, 2017-05, pp. 1–8. DOI: `10.1109/IEMDC.2017.8002357`.

[18] N. Neidig, A. Wanke, Q. Werner, and M. Doppelbauer, “Influence of a variable reluctance resolver on an e-motor-system,” in *2016 18th European Conference on Power Electronics and Applications (EPE’16 ECCE Europe)*, 2016-09, pp. 1–10. DOI: `10.1109/EPE.2016.7695435`.

[19] C. D. Johnson, *Process control instrumentation.* English. Pearson, 2014, OCLC: 858656257, ISBN: 9781292026015.

Appendix B

论文主要内容介绍

自19世纪以来，成品在量产中的需求不断增加。制造工厂的技术改进在降低成本和提高更多人的生活水平方面发挥着至关重要的作用。的确，当今最先进的消费品都与高标准的生活息息相关，例如交通工具、通信电子设备、商务和休闲，以及消遣和娱乐产品。值得注意的是，几乎所有这些设备都包含不同功率范围内的电驱，从微小振动的直流电机到列车中的大功率异步电机。不用说，为了满足这一需求，生产系统需要平稳运行。

近十年来，全球制造业增值稳步增长，2017年累计达到13万亿美元。特别是对于小公司和创新的初创企业来说，给定的市场规模是一个真正的挑战。因此，对于初创企业来说，首先选择利基市场是一种常见的方法，避免了高需求。然而，当创新获得市场认可时，生产系统需要相应地进行调整。

这种从样件到大规模生产的扩展需要关键的设计决策，通常伴随着很高的创业风险。在保持客户定制产品设计的同时，生产过程需要标准化和简化。在保持低成本的同时，产量必须最大化。

本文以轴向永磁同步电动机为研究对象，针对上述问题进行了具体的研究。AFPM驱动，也被称为盘式机器，相对于径向永磁电机，具有紧凑的薄饼形状，轴向尺寸减小。与广泛采用的径向永磁（RFPM）电机相比，它们具有更高的功率密度，适用于各种不同的应用，其中包括电动汽车、机床、机器人、泵和风扇。然而，零件制造和最终组装中的几个问题使得生产和开发成本过高，无法与传统的射频电机竞争。为了提供真正的替代方案，需要大幅增加产量，以降低单位成本。

该项目通过分析现有的样件生产，并设计一条半自动化、低容量的装配线来解决制造问题。重点主要在于生产过程修改，而不影响现有的电机设计。

AF电机装配中的一个主要问题是均匀的气隙。与径向永磁电机不同，AF设计意味着将气隙平行于轴方向。所产生的双定子和单转子之间的两个气隙需要尽可能小，以避免性能损失。这就要求它们具有光滑和均匀的表面，即较小的制造公差。此外，还必须保证在任何操作条件下，在整个产品生命周期内，都能均匀地保持较小的距离。所实施的解决方案用激光扫描机对电机四个关键部件进行高精度测量。这样，可以通过选择适当的垫片厚度来修正公差。这就保证了转子在每个特定单元中的对称放置。

通过这些工艺优化，可以大大简化和标准化生产过程。相对于样件生产而言，一台电机机组的制造时间可在7个工作站中从4小时以上大大缩短为20分钟的循环时间。并设计了一个标准工作台，作为各工位的主要工作台。符合人体工程学的需求已经得到满足，并实现了电子功能，如触摸屏显示器和激光扫描仪等。定义并描述了制造执行系统。

该项目成功地展示了以经济可持续的方式扩大到量产轴向永磁电机的尝试和可能性。

Appendix C

Supplementary Information

1 List of Figures

2 List of Tables

Appendix D

Glossary

Airgap is the space between the stator and the rotor, through which the electromagnetic energy passes. 3, 21

Axial Flux is a type of flux direction used in electric drives, also called pancake design; in comparison to conventional RF machines the air gap surface is parallel to the shaft and for balancing reason doubled, i.e. Double Stator Single Rotor or Single Stator Double Rotor. vii

Electromotive Force is the action produced by converting other forms of energy into electrical energy, as observed e.g. on a closed loop conductor exposed to a time-varying magnetic flux. vii, 9

Induction Motor is an AC electrical drive where the rotor's magnetic field is generated by its winding currents being a response to the *induced* voltage from the asynchronously changing stator flux. 1

Insulated-Gate Bipolar Transistor is a semiconductor device primarily used as an electronic switch in high-power applications, due to its high efficiency and fast switching capability. vii

Magelec Propulsion LTD is a manufacturer of complete electric powertrains with AF drives, for which the underlying internship project has been carried out. 3, 9, 10

Magnetic Flux is the surface integral of the magnetic field which passes through the defined surface. 93

Magnetic Reluctance represents the opposition to magnetic flux, similar to the concept of resistance in electrical circuits, it is defined as Magnetomotive Force (mmf) over magnetic flux. 3, 93

Magnetomotive Force is a property that gives rise to magnetic fields and is measured in ampere-turns, appearing in Hopkinson's law as the closed line integral of the vector field $\vec{\boldsymbol{H}}$ approximated in magnetic circuits to magnetic flux times reluctance. vii, 93

Metal-Oxide-Semiconductor Field-Effect Transistor is a type of field-effect transistor whose primary advantage is that no current is needed to control the load. vii

Permanent Magnet are ferromagnetic materials, which after magnetization maintain their own persistent magnetic field, most commonly alloys used nowadays are neodymium (NdFeB) and samarium–cobalt (SmCo). vii

Powertrain compromises the main power-generating components in a motorized vehicle, that generate and deliver power. 4

Radial Flux is a type of flux direction used in conventional electric drives, with the air gap radially placed between stator and rotor. viii