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SPECIFIC QUALITY DEVIATIONS IN IEC LV MOTORS 71-250 FRAME SIZE SQUIRREL-CAGE ROTORS

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TIIVISTELMÄ

ABB:n IEC LV Motors -yksikössä on havaittu laatupoikkeamia häkkikäämiroottoreissa. Tämän seurauksena ABB:n laatutiimi päätti teetättää aiheeseen liittyvän selvityksen, jonka tuotoksena syntyi tämä diplomityö. Ongelmien tutkimiseksi läpikäytiin kaikkien vuonna 2021 valmistuneiden pienjännitemoottoreiden rutiinitestitulokset ja tutkittiin tarkemmin erityisesti niitä yksilöitä, jotka eivät ole läpäisseet rutiinitestejä oikosulkutestien takia tai joiden rutiinitestin läpäisy on vaatinut häkkikäämiroottorin vaihtamista. Tämän pohjalta johdettiin seuraavat tutkimuskysymykset:

- Missä roottoripaketeissa laatupoikkeamia esiintyy?
- Mitkä voisivat olla poikkeamien juurisyyt?
- Kuinka laatupoikkeamia voitaisiin havaita mahdollisimman varhaisessa vaiheessa toimitusketjua?

Näiden kysymysten pohjalta määritettiin roottorit, joille tehtiin lisätutkimusta ja selvitettiin laatupoikkeamat, joita häkkikäämiroottoreissa on esiintynyt. Samalla etsittiin myös muita keinoja, joilla häkkikäämiroottoreiden laatupoikkeamia pystyttäisiin havaitsemaan ja ennaltaehkäisemään toimitusketjun mahdollisimman varhaisessa vaiheessa. Ajatuksena oli, että jatkossa alihankkijat voisivat tehdä laaduntarkkailua jo ennen komponenttien toimittamista moottoreiden kokoonpanolinjalle.

Tässä diplomityössä päädyttiin tutkimaan 71–250 runkokoon pienjänniteoikosulkumoottoreiden häkkikäämiroottoreiden laatuvikoja. Tavoitteena oli parantaa jokaisen kokoonpanolinjan rutiinitestauksen FPY -arvoa. FPY on lyhenne englanninkielisistä sanoista *first pass yield*. Sillä tarkoitetaan kokoonpanolinjan moottoreiden lukumäärää tai prosenttilukua niistä moottoreista, jotka ovat läpäisseet rutiinitestauksen ensimmäisellä kerralla.

Työn tuloksena löydettiin testaustapa, jolla pystytään havaitsemaan häkkikäämiroottoreihin liittyvät valupoikkeamat jo roottoreiden kasausvaiheen jälkeen. Tämän lisäksi työssä analysoitiin juurisyitä laatupoikkeamien ilmaantumiselle. Analyysin avulla pystytään keskittymään roottorin valmistusprosessissa oikeisiin parametreihin laadun parantamiseksi.

AVAINSANAT: pienjänniteoikosulkumoottori, häkkikäämiroottori, laatu, tuotanto, rutiinitesti

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ABSTRACT

Quality deviations in squirrel cage rotors have been detected in ABB IEC LV Motors manufacturing unit. Due to this ABB´s quality team decided to investigate the defects and this thesis is a report of that. To inspect these deviations, the routine testing results from 2021 were examined to research the deviations for squirrel-cage rotors. The focus of the studies were the motors which did not pass the routine tests because of deviations related to short circuit tests. These motors were required to change rotor before passing the routine test. Based on these the following research questions were formed:

- What are the most common rotor cores where quality deviations occur?
- What might be the cause for those deviations?
- What would help to detect quality deviations at the earlier stages of the supply chain?

The most problematic squirrel-cage rotors were determined based on these questions which became the focus for extra studies specifying the main quality deviations involved. At the same time other ways to detect and prevent rotor related quality deviations in the earlier stages of the supply chain were researched so that subcontractors would be able to do quality control for those rotors before delivering them to the motor manufacturing line.

This study focused on squirrel-cage rotor components used in 71–250 frame size IEC LV motors. The purpose was to increase FPY values of each manufacturing line. FPY is an abbreviation from English words first pass yield. It means the amount or percentage of motors from a specific manufacturing line which have passed the routine testing in first try.

As a result of the thesis one potential testing method was discovered to help detect casting related quality deviations right after rotor manufacturing. Besides this an analysis of the causes and effects of rotor related quality deviations were performed. Based on the results rotor manufacturing parameters can be enhanced to improve the overall quality of the product.

KEYWORDS: Squirrel cage motor, squirrel cage rotor, quality, production manufacturing, routine test

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Symbols and abbreviations

ABB	Asea Brown Boveri
FPY	First pass yield
IEC	International Electrotechnical Commission
AL3A	Manufacturing line for frame sizes 71 - 132
AL3B	Manufacturing line for frame sizes 160 – 250

$2N_{1t}$	Effective wire factor for phase
P_p	Friction losses
P_{Fe}	Iron losses in the stator
I_{q0}	Magnetizing current
m_0	Magnetomotive force
I_0	No load current
P_0	No load power
φ_0	No load power factor
U_0	No load voltage
U_N	Nominal voltage
m_1	Phase number
U_{V1}	Phase voltage
p	Pole pair number
I_{p0}	Reactive part of the no load current
I_{km}	Reduced value for short circuit current

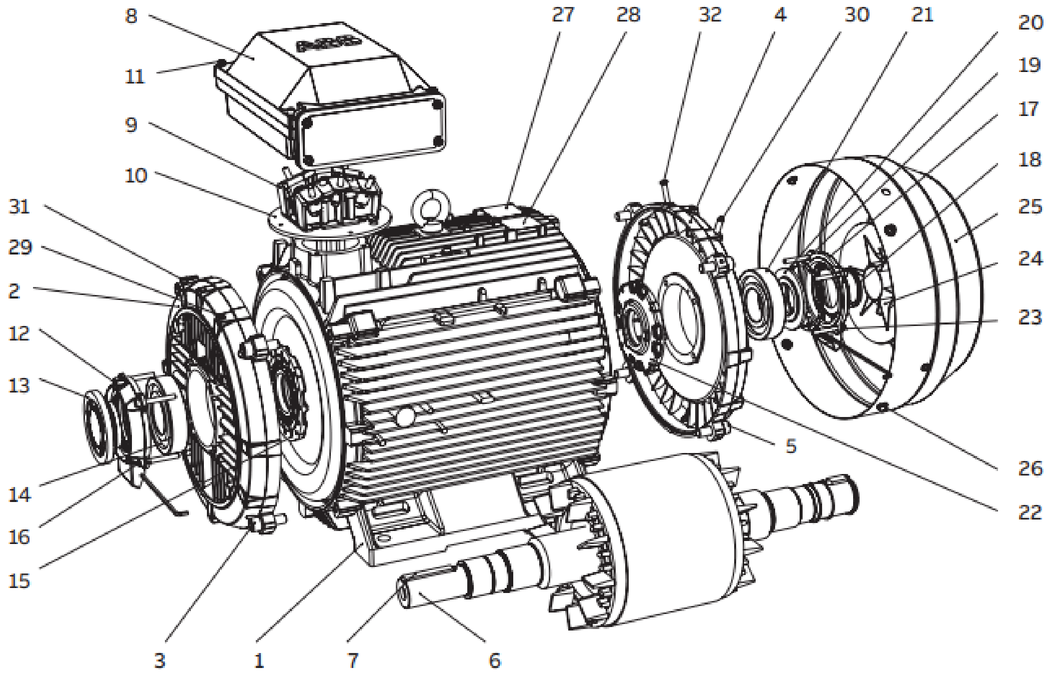
U_{km}	Reduced value for short circuit voltage
P_K	Short circuit power
φ_k	Short circuit power factor
ξ_1	Winding factor of the stator

1 Introduction

According to Aura and Tonteri (1994, pp. 304-305) electrical motors are widely used within the industry and they are the most common single component for consuming energy. That is one of the reasons why they see that electrical motor manufacturers are investing and monitoring the quality of the products. Aura and Tonteri (1994, pp. 304-305) also describe that big portion of the motors used in industrial applications are squirrel cage motors. They describe that the main purpose of squirrel cage motor is to convert electrical energy into mechanical energy. To produce this mechanical energy or torque Aura and Tonteri (1994, pp. 304–305) describe the main components in motors to be the stator frame, stator, rotor, bearings, end shields and terminal box. According to them the relatively low number of different components in motor makes it a reliable prime mover.

The placement of different components in squirrel cage motors is seen in the Figure 1. It consists of freely rotating rotor resting on top of bearings which is then inserted inside the stator coil. The rotor is placed inside the stator frame and inside the stator coil which leaves room for the air gap between the stator and the rotor. This makes it possible for the rotor to rotate freely depending on the bearings inserted in the end shield. The motor is manufactured in a way so that the stator coil is pressed inside the stator frame. Bearings are compressed in the rotor which are then inserted in the end shields screwed at both ends of the stator frame. The rotor is inserted inside the stator coil which is inserted in the stator frame. The rotor of a squirrel cage motor has squirrel cage structure, and the stator coil has been wounded for 3-phase. At the non-drive end of a rotor there is usually a fan inserted in the rotor which cools down the motor when the rotor is rotating. In some cases, the cooling of a squirrel cage motor is handled with a separate cooling motor usually located also at the non-drive end of the motor or on top of the motor which allows bigger loadability of the motor in cases where the actual rotor of the motor is needed to rotate on slower rounds per minute (ABB, 2022, p. 111). Terminal box is usually located at the top of the motor or attached on the motor frame on either side. Supply cables are connected inside the terminal box.

Exploded view, frame size 315



1 Stator frame
2 End shield, D-end
3 Screws for end shield, D-end
4 End shield, N-end
5 Screws for end shield, N-end
6 Rotor with shaft
7 Key, D-end
8 Terminal box
9 Terminal board
10 Intermediate flange
11 Screws for terminal box cover
12 Outer bearing cover, D-end
13 Valve disc with labyrinth seal, D-end; standard in 2-pole motors, V-ring in 4-8 pole motors
14 Bearing, D-end
15 Inner bearing cover, D-end
16 Screws for bearing cover
17 Outer bearing cover, N-end
18 Seal, N-end
19 Wave spring
20 Valve disc, N-end
21 Bearing, N-end
22 Inner bearing cover, N-end
23 Screws for bearing cover
24 Fan
25 Fan cover
26 Screws for fan cover
27 Rating plate
28 Lubrication plate
29 Grease nipple, D-end
30 Grease nipple, N-end
31 SPM nipple, D-end
32 SPM nipple, N-end

Figure 1. IEC LV motor components. (ABB, 2022, p.111).

The construction shown in Figure 1 is the most common one but there are also different variations of that. Motors made in ABB Oy, IEC LV Motors, Vaasa factory are mainly made of the components seen in the picture but usually some of the components are modified based on the customer´s needs or the motor is manufactured with additional components such as tachometers or separate cooling motors. These customer specific modifications to the original motor are called variant codes in ABB Oy, IEC LV motors.

1.1 Background of the research

The main purpose of this thesis is to investigate and solve quality deviations present in squirrel-cage rotors used in frame size 71 – 250 motors (numbers meaning height of axis in millimeters) which are manufactured in AL3A and AL3B manufacturing lines. The request to conduct this kind of investigation came from my current employer, which is ABB Oy, IEC LV Motors corporation. The goal is to investigate what are the most common rotors where some sort of quality deviations appear and try to determine ways to observe the possible quality issues before assembling the whole motor and testing it in routine testing process. So basically, trying to determine quality control points which would stop the faulty components at the earlier stages of the supply chain and thus saving a lot of resources both in manufacturing and routine testing.

The data of this thesis will most likely be used furthermore in the quality control check-ups, since the data includes the information about which rotors have the most quality issues and what are the main components used in that specific rotor. The thesis also includes more thorough research about few of the faultiest rotors which provides a good outlook on which sort of problems might occur in the process of making a rotor. The subject of this thesis was kind of familiar for me because I used to work on the AL3A manufacturing line (frame sizes 71-132) before. Now I´m working in R&D department as a technical product manager in IEC LV Motors, Vaasa.

1.2 Research methods and questions

This thesis focuses on the manufacturing process of a squirrel cage rotor and different quality issues that the component might have. Research was made in co-operation with ABB Oy, IEC LV Motors quality team. Data used in this study is defined as internal and not-to-be published. The aim of this thesis is to answer these three research questions:

- What are the most common rotor cores where quality deviations occur?

- What might be the cause for those deviations?
- What would help to detect quality deviations at the earlier stages of the supply chain?

The research started by investigating routine test results of motors manufactured in KK -factory (frame sizes 71-250) in 2021 (see Figure 2). The gathered raw data consisted of over 50 columns and over 2200 records. The purpose of the research was to identify reasons why the motors have not passed the routine test process in a first try and further to investigate those motors, where the solution to pass the routine test was to change the rotor of the motor. The scale of investigated motors was determined to be 71-250 frame size motors because a lot of those rotors are manufactured by a subcontractor. ABB Oy, IEC LV Motors Vaasa factory mainly manufacturers rotors in their own process for motors with frame sizes 280 and up.

The purpose of the thesis was to include a wide range of different motor types. It was decided that most common motor types (BP/AA/GP/KP/JP) would be sufficient for the research. The types included cast iron safe area motors (BP), aluminum framed safe area motors (AA), spark safe Ex-motors (GP) and firesafe Ex-motors (JP & KP). All the other frame sizes and motor types were excluded from the research mainly because their rotor design differs from these motor types (for example synchronous reluctance motors and permanent magnet motors) and because in these frame sizes and types of motor own production of rotors is more common.

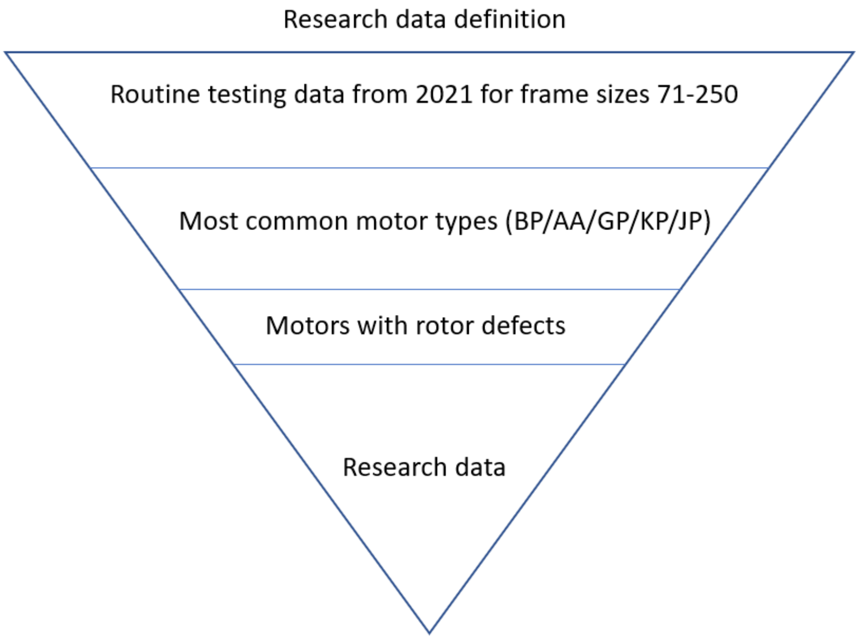


Figure 2. Research data definition.

Possible deviations were researched both in routine test values and notifications, which were made by the testing personnel in manufacturing line after the motor haven´t passed the routine test process. The routine test is made for every motor in the manufacturing line. In case the tested motor doesn´t pass the routine test, a notification is opened by the testing personnel to the SAP -information system to further investigate the reasons why the motor did not pass the test. In the notification there is usually a brief description of which routine test values were out of tolerance compared to the control values. In this thesis further investigation was made to those motors tested in 2021 which required a rotor to be changed to the motor to pass the routine test process.

The process of analyzing these notifications was important, because one of the main research questions for this thesis was to determine which of the rotor cores in frame sizes 71-250 had possible quality deviations and what could be the reasons for them. The results of the analyze phase also provided a good overview of the quality situation. It thus also provides answers for the first and second research question.

Based on the monthly data received from motors that were routine tested in 2021 in KK-factory an Excel- file was made which included all the routine test results from no-load- and short circuit tests, order numbers, notification numbers and solutions of what was made to the motors to get them pass the routine test. In gathered routine testing data there is also further research made on the cases where the solution was to change the rotor of the motor to pass the routine test successfully. In the data the focus was on short circuit test results and especially the data concerning the short circuit current values.

1.3 Structure of the thesis

This thesis will proceed as follows. First, I´ll focus on rotor manufacturing process and testing related to it to explain how rotors are made and tested to clarify possible defects that may occur when manufacturing the rotor. Secondly, I look at routine testing theory and standards. This is then followed by describing the routine testing practices in a more detailed manner concerning the whole structure of the motor, stator and rotor. Chapter 4 consists of routine testing processes in IEC LV motors and describes all the phases of a routine test made in ABB. Finally, I´ll conduct analysis on the defects of rotors in IEC LV Motors KK-factory and draw conclusions on how to quality processes could be developed in the future.

2 Rotor manufacturing

According to Jeong et al. (2017, p. 233) rotors are one of the key components in motors since they are the part which converts electrical energy into mechanical energy. It determines the motor torque and is a big part of operating efficiency.

The detection of defective rotors in the manufacturing process has become one of the main tasks to quality teams. Asad et al. (2018) states that defects in an induction motor are divided to components by percentages of bearing 41%, stator 37%, rotor 10%, and others 12%. Although the defect rate of rotors is not very high, good rotor quality is essential because defective rotors can decay the performance of the whole motor.

2.1 Rotor manufacturing process & testing

The construction of squirrel-cage rotor includes rotor lamination sheets, rotor bars or slots which are casted with either aluminum or copper, short circuit rings, shaft, bearings and possibly a fan usually installed at the non-drive end of the rotor. Bar is a critical part of a rotor when concerning quality, because casting the bar is one of the most uncontrollable phases of manufacturing a rotor and thus different kind of defects can form in the process. As an example of a defect, as stated by Lee et al. (2020, p. 1), blowholes in rotor bars can be formed in the die casting process when the casting parameters are not set properly.

The manufacturing process and adequate tolerances are critical factors for rotor manufacturing. They define the mechanical rigidity of the rotor alongside with rotor dimensioning and material selection. Barta et al. (2019) presented and tested several manufacturing approaches and two of the manufacturing options demonstrated promising results. One was brazing by silver brazing alloy and the second was shrink fit assembly. Out of the two shrink fit assembly worked better for high-speed rotor designs.

Jeong et al. (2017, p. 234) describe that research and development have been lately focusing on detection of different kinds of defects when the motor is in-service in the field. According to them there are nowadays numerous ways to evaluate rotor cage asymmetry to ensure the reliability of a motor. One of the ways to evaluate the porosity of rotor is to use motor current signature analysis or single-phase rotation test or rotor influence check. Jeong et al. (2017, p. 234) however see that the downside for these testing methods is the lack of sensitivity because they can´t detect minor porosity or porosity which does not produce asymmetry. These tests can´t also be used for rotor alone.

For a standalone rotor testing methods Jeong et al. (2017, p. 234) suggest growler or rated rotor flux tests. They can be used to detect localized rotor faults by observing the rotor cage conditions from the rotor surface. The downside for these tests is that they don´t provide a quantitative measure of porosity on a sufficient level and they are also dangerous due to high voltage being present during the tests (Jeong et al., 2017, p. 234).

Jeong et al. (2017, p. 239) suggests a new way of testing to detect rotor cage porosity based on electromagnetic flux injection. Based on their test results this testing method can be used to obtain a quantitative measure of rotor bar conditions, and it can detect distributed porosity not observable with previous methods. It can also be used for both aluminum and copper rotors.

2.2 Squirrel-cage rotor manufacturing process in ABB

There are basically two different types of rotors manufactured and/or sourced by ABB Oy, IEC LV Motors. The types are configurable rotor or rotor with static code. Configurable rotors are used in orders where the customer has ordered some modifications to the rotor such as higher balancing grade, special shaft end or special rotor dimensions or a certain surface finish for the rotors against corrosion. Rotors with static product codes are usually used for basic motor orders without any ordered modifications to the rotor itself and they are usually stocked in the warehouse in some quantities. The actual manufacturing process of a rotor is sometimes divided to two different subcontractors so that the other one manufactures the rotor core, and the other one inserts the shaft to the core and does the balancing of the rotor. The construction of a typical squirrel-cage rotor can be seen in Figure 3.

Figure 3. Squirrel-cage rotor. (Zureks 2023).

The actual manufacturing process of squirrel-cage rotor consists mainly of nine different phases which can be seen in Figure 4. The first phase is manufacturing the rotor laminations and punching the sheets. The second phase is manufacturing the shaft. The third phase is the stacking of rotor sheets or in other words assembling the rotor core. The fourth phase is casting of the rotor. The following phases are inserting the shaft into the rotor, cooling down the rotor and straightening the shaft. Finally, the rotor must be balanced, and possible surface treatments added.

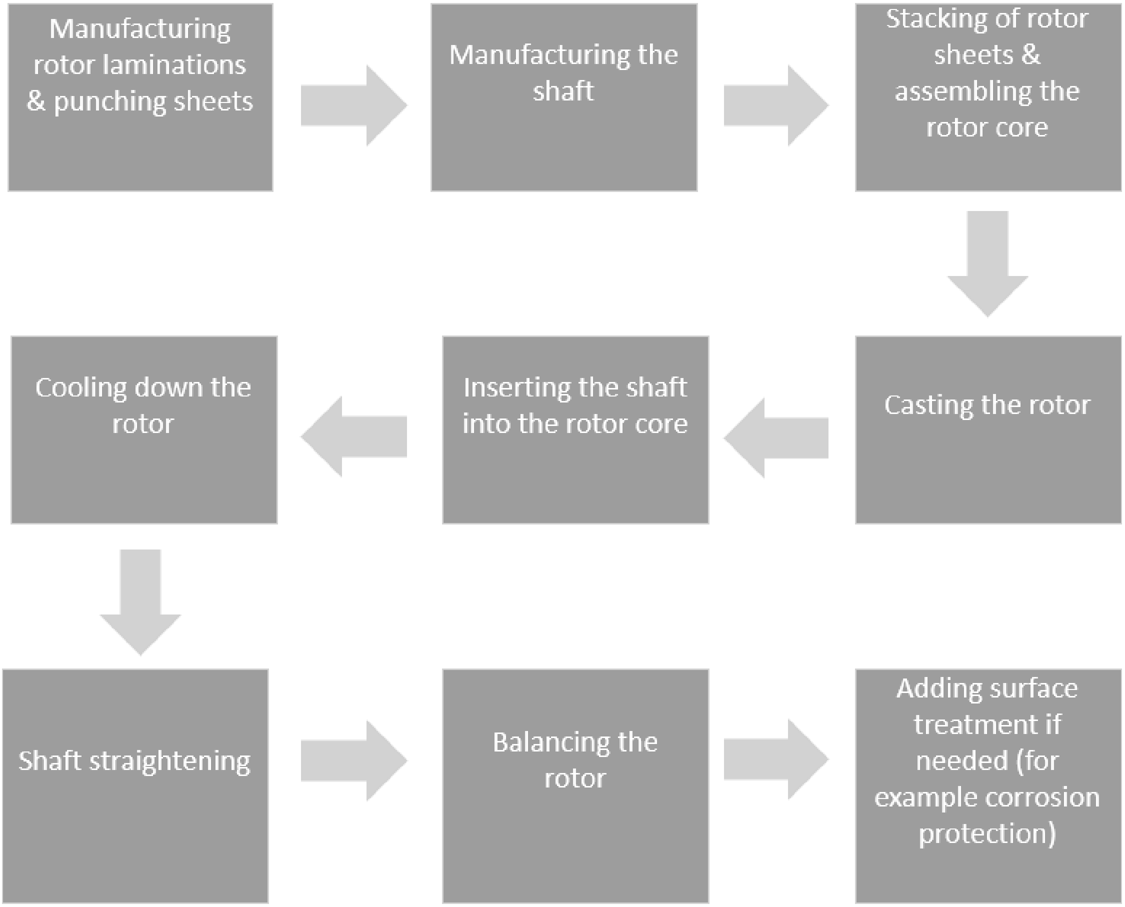


Figure 4. Rotor manufacturing process.

2.2.1 Manufacturing the rotor laminations & shaft

This paragraph explains the manufacturing and quality process of separating and punching different laminations plates. The purpose of good quality control in this process phase is to confirm the success and smoothness of the following work phases (Laatu, 2018, p. 1). The aim is to prevent proceeding with defective lamination plates to the next working phases. ABB uses many kinds of rotor laminations such as M270-50A, M350-50A etc. (Rantala, 2014, p. 41).

According to the instruction of Laatu (2018, p. 4) the process of manufacturing and controlling the punched rotor plates starts by counting the number of slots at the start of the run. After that you need to control the height of the burr and then control the straightness of the slots by turning two slotted plates with their backs against each other, so that the burred sides face opposite directions. The plates are positioned like this so that the slots must be parallel. After that Laatu (2018, p. 4) asks to check the punching measure of the rotor plate from the work card. The punching measure from the rotor plate can be measured with a digital sliding gauge. The punching measure may vary from the nominal measure to a certain tolerance. Air slot and slot must be cut on pitch and tolerance at place for key slot. According to Laatu (2018, p. 4) this is done to ensure that these rotor sheets are alike even though sheets are not made in same production lot. At the end one is instructed to check that the sheets fulfill requirements according to quality control and inspection card and mark results into inspection card which will be put on pallet with the sheets.

Laatu (2018, p. 2) instructions state that the production quality is checked frequently. The dimensions of the billets and sheets are controlled at the start of the run with a test sheet to make the necessary corrections if needed. Quality check for the last plate at pallet is necessary for the sheets made with compound die and another quality check is necessary for the sheets which are made at separate punching control which must be performed on the last plate of every third pile. Inspection card must be filled up about every controlled billet and plate. The card is set between the plates or on the hole inside the plate pines.

Most shafts used in IEC LV motor manufacturing comes from subcontractors. They are usually turned from a big block of steel using the needed shaft materials according to order or according to requirements given by the marine certification societies. They are manufactured according to the mechanical design and drawing usually made by ABB.

2.2.2 Stacking of rotor sheets & assembling the rotor core

According to Haarala (2018, pp. 2-4) the assembly of rotor core consists of six different phases. It starts by putting a suitable mandrel on the assembly pressing table. Then the rotor sheets are lifted to the work bench and arranged in a way so that the slots of the sheets are against each other. After that the arranged sheets are assembled on the mandrel in appropriate bundles. All the bundles are turned compared to the previous bundle while considering the tooth pitch of the sheet. The bundles are usually turned about 90 degrees to compensate the effect of the rolling direction and the fluctuation of thickness of the sheets. The turning also helps to eliminate the imbalance caused by the arrangement. The stacking process can be seen in Figure 5. During the whole assembly phase, it´s important to ensure that the slots of the sheet bundles are open.

Figure 5. Stacked rotor core when the bundles are turned 90 degrees (Haarala, 2018, p. 3).

Haarala (2018, pp. 2–4) describes the assembly process and how to control the length of the ready-assembled sheet bundles during the pressing. Sheets need to be added or removed until the length of the package is correct. Some tolerance is accepted for the length. It is also important to control the slot skew of the package during the assembly process. Help keys can be used to ensure the correct tooth pitching and straightness of the slots. The slot skewness (U measurement) is set with the help of an assembly pin. It can also be controlled with the help of measuring plate and caliber gauge. The control phase of the slow skewness can be seen in Figure 6.

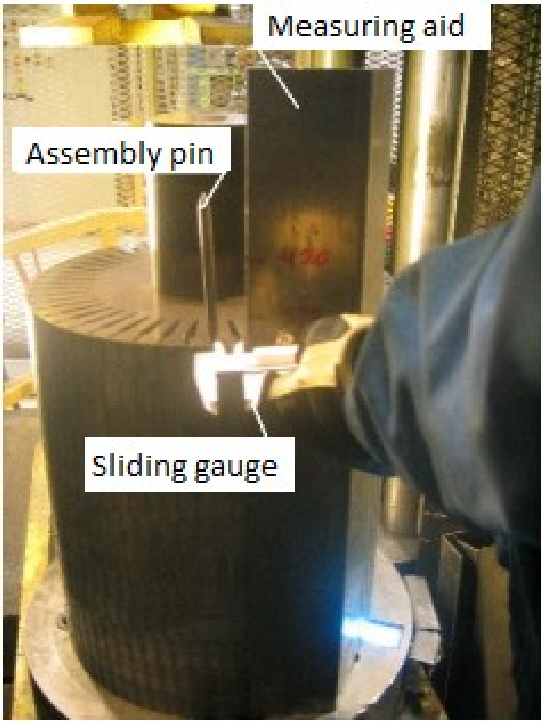


Figure 6. Control of slot skewness (Haarala, 2018, p.4).

The last phase of the assembly is fastening the lifting hook and removing the assembly pin (Haarala, 2018, pp. 2–4). The assembled sheet package is moved straight into the casting machine. For some of the assemblies the sheet package must be pre-heated before the casting. It is also instructed in internal instruction FIMOT0906 to inform and report any possible errors noticed on the rotor laminations or in the shafts by making a notification in SAP -information system.

2.2.3 Casting the rotor

The casting of the rotor core is usually an automated process and thus controlling the casting process completely is not possible without breaking the rotor. Since the quality of the process can´t be affected during or afterwards, the conditions for the casting should be as optimal as possible from the start of the process. In the following paragraphs some of the key actions are described to help ensure good product quality.

According to Haarala (2018, p. 4) the aluminum to be used in the rotor casting process should be clean and fluent so that the slots of the rotor core can be filled completely during the casting. It is important to ensure that no shortages, gaps or waste is left on the casting. The melting process is a crucial part of the process as well as the service and use of the casting oven. Sufficiently high temperatures of the aluminum ensure that the fluid stays liquid during the whole casting process. Haarala (2018, p. 4) also states that there should be optimal temperature difference between the casting cylinder and the casting piston to get the correct margin and good quality. If the temperature is too high on the cast, it may cause gas bubbles or other errors on the casting. The temperature in dosage chamber for the oven should be around 750 degrees C before casting small rotors with the TCS-1 casting machine (Haarala, 2018, p. 4). For bigger size rotors the temperature of the fluid should be higher with casting machines TCS-2 and THT. The set temperature should be about 100-200 degrees C for the spraying cylinder and the set values of the temperatures should be less than that for the cylinder and piston. The temperature difference between the top cast and the bottom cast is usually about 20 - 80 degrees C before casting (Haarala, 2018, p. 4).

Haarala (2018, pp. 4-5) describe that it is also crucial to ensure good service of the casting patterns, -cylinder and -piston. They should be regularly greased and maintained to protect them from corrosion and to ensure the good production quality throughout the process.

Haarala (2018, p. 5) raises up the importance of pre-heating the rotor cores before the casting. The pre-heating is described being done to slow down the cooling of the liquid aluminum during the process. This is especially needed for longer (>800 mm) and small-slotted (>100 slots) cores to get the fluid flowing through the package and to fill the core and short circuit rings completely. Good quality can be ensured by using and adjusting the correct casting parameters to fit the specific rotor (Haarala, 2018, p. 5).

It is important to adjust the shutoff pressure as low as possible, so that the gas can leave between the sheet package and the cast, and to prevent that the corner of the cast does not cut the sheet package (Haarala, 2018, p. 6). The spraying pressure is normally adjusted along with the shutoff pressure. In general, the spraying pressure is increased when the length of the package increases, and the shutoff pressure is increased when the diameter of the package increases. It is also important to ensure that there is enough air outlets in the process to let the excess air out during the pressuring phase (Haarala, 2018, p. 6). It is also important to adjust the time between the spraying and the congealment of the fluid, and the cooling time when the slug touches the end of the spraying piston. According to Haarala (2018, p. 6) the cooling time is generally adjusted between 50-70 seconds. The times should be increased when the size of the core is increased or if the casting slug starts to touch the bottom of the cast. The position of the spraying piston or the starting point for the spraying should be adjusted so that the air layer between the fluid and the cylinder is as small as possible after the dosage of the fluid. The spraying speed of the piston should be as fast as possible. Too low speed may create non-consistent wings or cause a deficiency in the short circuit ring. The wing patterns or gas bubbles may also be caused by too high temperature of the cast or if the gas has not had enough time to get out of the cast (Haarala, 2018, p. 6).

Haarala (2018, p. 7) also states that it is good to check that the side supports of the rotor core do not squeeze the intermediate short circuit ring when casting these types of cores. The rotor core should be put on the bottom cast in the casting machine. The casting itself is an automatic process, where the rotor core and the bottom cast are moved into the machine. The casts then close and the sheet cover comes down. After that the fluid is dosed into the cylinder (Haarala, 2018, p. 7). The spraying cylinder moves under the bottom cast and the spraying phase starts. At the end of the casting squirrel-cage winding, short circuit rings, wings and balancing pins form on the rotor. After the process the top cast and the sheet cover come up and the slug congeals on the end of the piston. After the cooling phase is finished the bottom cast comes up and the fluid feeding channels are severed so that the slug remains on the end of the piston (Haarala, 2018, p. 7. The casting slug removes from the end of the piston, the bottom cast moves out and the release piston pushes the rotor core free from the bottom cast. After the process the caster stamps the identification product code of the rotor core and his personal signature on the short circuit ring on the D-end. (Haarala, 2018, p. 7).

Directly after every casting of a rotor core, the short circuit rings, the fan wings and the balancing pins are controlled visually (Haarala, 2018, p. 7). The rotors must have no casting errors. It must be checked that the gas has been released through the gas outlet slots between the cast and the sheet package, and that the cast edge has not cut the sheet package. If the gas has been let out freely, aluminum spikes should be visible on the end of the sheet package on the outer edge at the gas outlet slots, and patterns should have formed on the gas outlets of the short-circuiting ring. After the process is it possible to weight the core before and after the casting to ensure that the correct amount of aluminum has been used in the production (Haarala, 2018, p. 7). Rotor cores to be weighed are weighed before and after the casting. The filling of the rotor or the amount of aluminum cast into the core, is controlled by the weighing. Possible casting defects should be checked if many balancing plates are needed to be installed on the rotor to get it balanced (Haarala, 2018, p. 7). That might indicate that some of the slots have not been fulfilled correctly during casting.

2.2.4 Inserting shaft into the rotor core

Haarala (2018, p. 8) describes that before inserting the shaft into the rotor, the casted rotor core is visually checked. If the quality of the cast rotor core is acceptable, the shaft is inserted shortly after the casting process, because it makes it easier to remove the casting mandrel and to press the shaft to the core. The casting mandrel is removed by knocking it with a hammer or with the help of a press. Lubrication is added to the shaft hole before pressing. The shaft is pressed as straight as possible into the correct A-measurement against the installation bushing or with the help of protective bushing without stopping (Haarala, 2018, p. 8). After the insertion the A-measure is checked with a depth sliding gauge from the outer track of the D-end on the sheet package to the bearing collar of the D-end of the shaft unless it is automatically measured by the insertion machine (Haarala, 2018, p. 8).

According to Haarala (2018, p. 8) pressure is monitored during the pressing process and if the pressure rises higher than normal the diameter of the shaft end needs to be verified. After the rotor is fully assembled, a visual check is performed to ensure the quality of the work and to check that the rotor has not been damaged during the process (Haarala, 2018, p.8).

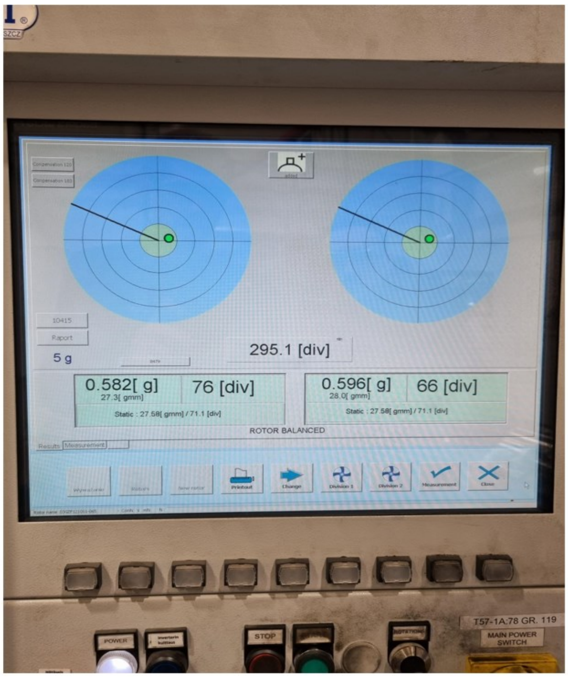
2.2.5 Balancing the rotor

Rautiainen (2021, p. 1) describes the importance of balancing the rotors. It is done to minimize all the mechanical vibrations of electrical motors. The balancing is done after turning according to the standard SFS-ISO 1940-1 and -2 (Rautiainen, 2021, p. 1). Balancing process of a squirrel cage rotor can be seen in Figure 7.

Figure 7. Rotor balancing process.

According to Rautiainen (2021, p. 1) the balancing at the D-end of the rotor is done with full key (F), half a key (H) or no key (N). The balancing key which should be used for a specific rotor is defined in the production work card. Rotors made with a fan is always balanced with a full key unless otherwise stated in the instructions. IEC Motors with frame size 80-250 fans will be balanced with full key and bigger motors with frame sizes 280-450 will be balanced without key. The fans themselves are balanced according to the FIMOT0961 instructions (Rantamarkkula, 2019, pp. 1–3). The balancing is done to class G 6.3 ISO 1940-1 at least. Residual unbalance is calculated according to 1000 rpm speed.

The balancing precision class of a rotor will be G 2.5 or to the more precise class G 1 according to the order. Residual imbalance corresponding to class G 2.5 means that the mechanical imbalance of the rotor reaches vibration class A. Vibration class B requires balancing according to precision class G 1. Balancing is usually done by adding balancing rings to the short circuit ring (Rautiainen, 2021, p. 2). Balancing status of a specific rotor can be seen in Figure 8.


5 g

295.1 [div]

0.582[g] 76 [div]
27.3[gmm]
Static : 27.58[gmm] / 71.1 [div]

0.596[g] 66 [div]
28.0[gmm]
Static : 27.58[gmm] / 71.1 [div]

ROTOR BALANCED

Figure 8. Rotor balancing report.

3 Routine testing

This chapter is focusing on routine testing and standards related to it. There are several different IEC standards which should be taken into consideration when testing a three-phase squirrel cage motor. In the next chapters I will go through the main points of the standards which contain instructions related to routine testing process of an electrical motor.

3.1 Routine testing practices

Motor testing can be a controversial subject (Soukup, 1989, p. 873). There are different practices among motor manufacturers to produce testing related documentation and different requirements for the end-users as well. Other end-users require more specific information and verifications about how the tests are made and others might be satisfied with less. According to Soukup (1989, p. 873) testing can verify the performance and capabilities of the motor, but the information is valid only at the time of the test and does not provide information for longtime use. Long lasting performance is always related to the past and present maintenance and therefore requires ongoing testing program and monitoring (Soukup, 1989, p. 873).

Naik et al. (2017) suggests that following tests should be carried out for three phase induction motors to verify essential performance, which is likely to vary during production:

1) No load test
2) Blocked rotor test
3) Phase sequence test
4) Measurement of winding resistance
5) Insulation resistance test
6) Vibration test
7)Temperature test

These tests are important to verify that the motor is working according to the respective standards (Naik et al., 2017, p. 1745). Routine testing is intended to prove the design and general qualities of the motor.

The no load test is performed to a motor to determine some of its equivalent circuit parameters and to measure the rotational losses (Naik et al., 2017, p. 1746). The test can be performed as seen in Figure 9.

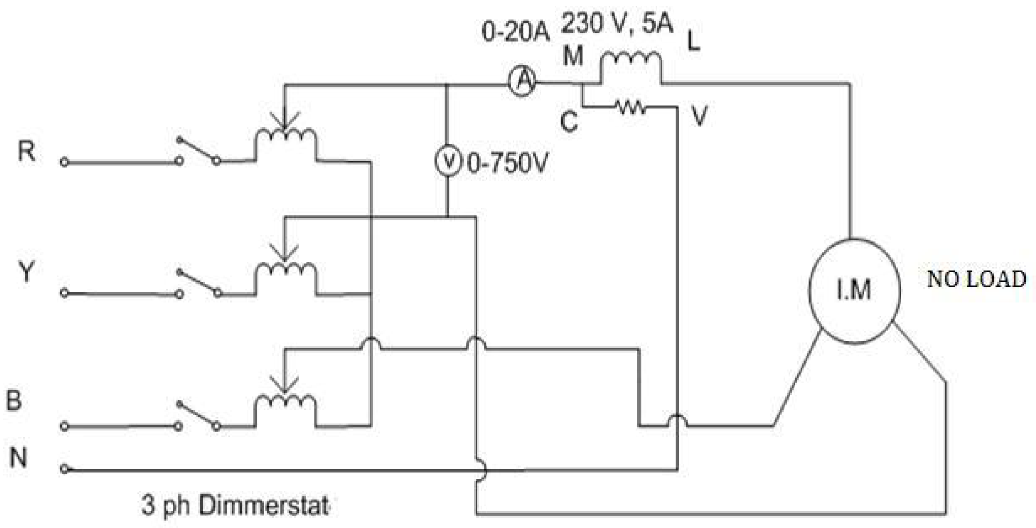


Figure 9. No load test connection diagram (Naik et al., 2017, p. 1746).

Blocked rotor test is performed to obtain short circuit current and its power factor angle (Naik et al., 2017, pp. 1746-1747.). The test can be performed as seen in Figure 10.

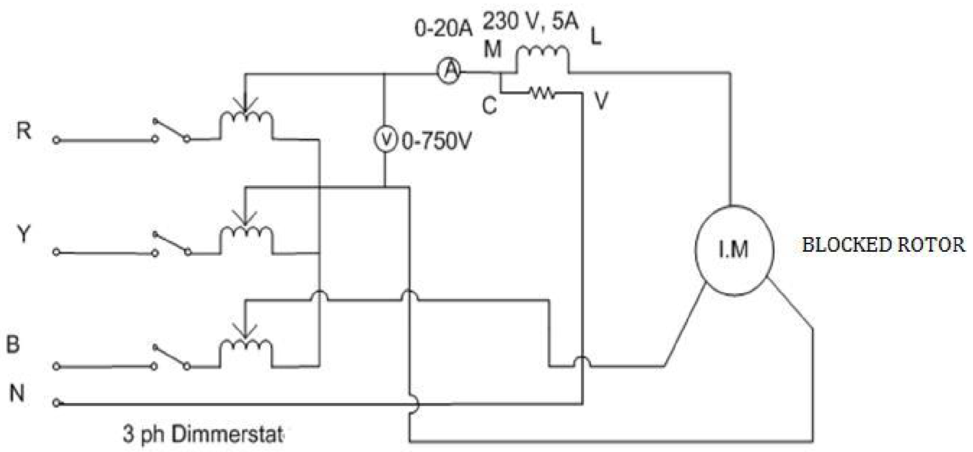


Figure 10. Blocked rotor connection diagram (Naik et al., 2017, p. 1747).

According to Naik et al. (2017, p. 1748) phase sequence test is carried out to verify the correct direction of rotation for the rotor. According to IEC 60034-8 standard the motor rotates clockwise seen from the drive end of the motor when the phases of the supply are connected to the terminal block in order L1, L2, L3 → U, V, W.

Winding resistance test is performed to verify the quality of the winding and to check for possible issues such as broken or short-circuited coils or coil to ground leakages (Naik et al., 2017, p. 1748). It is also important to ensure that the motor is correctly connected to delta or star connection according to the manufacturer specification.

Insulation resistance test is performed to verify the quality of insulation and to ensure that it endures the typical stresses applied to it during operation (Naik et al., 2017, pp. 1747-1748). In motor winding there are several different insulation materials such as the resin or stator slot insulations.

Vibration test is made to verify the operating and mechanical condition of equipment (Naik et al., 2017, p. 1750.). The key characteristics of vibration are frequency, period, acceleration, displacement, amplitude, velocity and phase.

Temperatures are tested because they are very important factors in motor operation (Naik et al., 2017, p. 1750). Changes in temperatures can reveal abnormalities before potential damage occurs. Bearing temperatures and winding temperature are the most common temperatures that are monitored (Naik et al., 2017, p. 1750). High winding temperatures may damage the insulation which will eventually lead to failure.

Besides the tests suggested by Naik et al. (2017) there are other tests suggested by Soukup (1989) and these include for example reed critical frequency & performance tests. However, Soukup (1989) reminds that individual tests can never replace maintenance and long-term testing programs.

3.2 Routine test standards

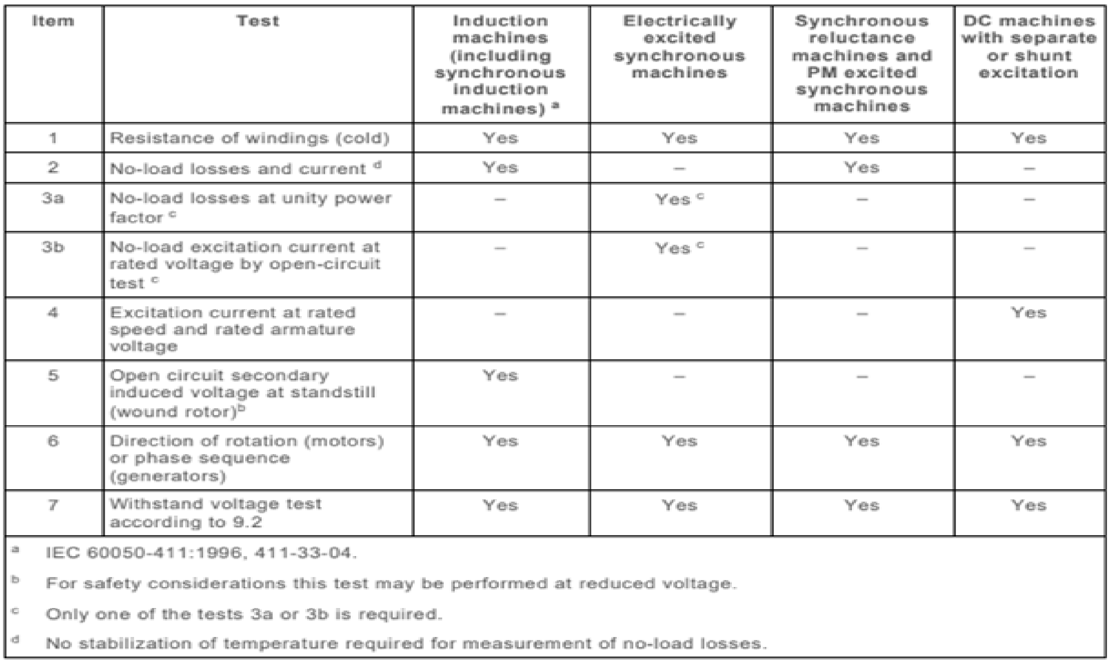
There are four relevant routine testing standards. Next, I´ll go through them and explain why they are important for routine tests. The first one includes phases which should be included in the routine test. The second one defines vibration level limits. The third one focuses on terminal markings and the fourth one defines the winding resistance value and other topics concerning the testing of three-phase AC motors, such as equations to calculate certain losses. It is important to test the motor according to these standards to ensure quality and safety of the motor.

3.2.1 IEC60034-1

IEC60034-1 applies to all rotating electrical machines with some exceptions given in the standard. It also defines minimum test schedule for routine tests. It also provides instructions concerning the withstand voltage test and other test related subjects, such as the tolerances for certain values. IEC60034-1 (International Electrotechnical Commission 2022: 58) standard defines routine test as follows:

´´Routine tests are always factory tests. They shall be performed on all machines which are assembled at the factory of the manufacturer. The machines need not be completely assembled. They can lack components which are not significant for the testing. Routine tests do not need the machines to be coupled except for the open-circuit test on synchronous machines. The minimum test schedule is listed in Table 1 and is applicable for machines with rated output ≤ 20 MW (MVA) that are assembled and tested in the factory. Additional routine tests may be performed especially on machines with ratings above 200 kW (kVA). The term synchronous machines includes brushless permanent magnet machines. For DC machines, depending on size and design, a commutation test under load may be performed as a routine test.´´

Table 1. Minimum routine tests for machines assembled and tested in the factory of the manufacturer (International Electrotechnical Commission 2022: p. 60).



Item	Test	Induction machines (including synchronous induction machines) [a]	Electrically excited synchronous machines	Synchronous reluctance machines and PM excited synchronous machines	DC machines with separate or shunt excitation
1	Resistance of windings (cold)	Yes	Yes	Yes	Yes
2	No-load losses and current [d]	Yes	–	Yes	–
3a	No-load losses at unity power factor [c]	–	Yes [c]	–	–
3b	No-load excitation current at rated voltage by open-circuit test [c]	–	Yes [c]	–	–
4	Excitation current at rated speed and rated armature voltage	–	–	–	Yes
5	Open circuit secondary induced voltage at standstill (wound rotor)[b]	Yes	–	–	–
6	Direction of rotation (motors) or phase sequence (generators)	Yes	Yes	Yes	Yes
7	Withstand voltage test according to 9.2	Yes	Yes	Yes	Yes

[a] IEC 60050-411:1996, 411-33-04.

[b] For safety considerations this test may be performed at reduced voltage.

[c] Only one of the tests 3a or 3b is required.

[d] No stabilization of temperature required for measurement of no-load losses.

3.2.2 IEC60034-14

IEC60034-14 specifies vibration level limits for three-phase AC motors which are included in the scope. It also specifies other limitations concerning the vibration and testing of three-phase motors.

IEC60014-14 (International Electrotechnical Commission 2018: p. 6) defines the scope as seen below:

´´This part of IEC 60034 specifies the factory acceptance vibration test procedures and vibration limits for certain electrical machines under specified conditions, when uncoupled from any load or prime mover. It is applicable to DC and three-phase AC machines, with shaft heights 56 mm and higher and a rated output up to 50 MW, at operational speeds from 120 min–1 up to and including 15 000 min–1. This document is not applicable to machines mounted in situ (on site), three-phase commutator motors, single-phase machines, three-phase machines operated on single-phase systems, vertical waterpower generators, turbine generators greater than 20 MW and machines with magnetic bearings or series-wound machines.´´

3.2.3 IEC60034-8

IEC60034-8 mainly provides instructions to terminal markings and how to check the direction of rotation for motors in the scope of the standard. The rotation has a clockwise direction when observing the shaft from drive-end of the motor. IEC60034-8 (International Electrotechnical Commission 2014b: p. 8) defines the scope as seen below:

´´This part of IEC 60034 applies to a.c. and d.c. machines and specifies a) rules for the identification of winding connection points; b) marking of winding terminals; c) direction of rotation; d) relationship between terminal markings and direction of rotation; e) terminal marking of auxiliary devices; f) connection diagrams of machines for common applications. Turbine-type synchronous machines are excluded from this standard.´´

3.2.4 IEC60034-2-1

IEC60034-2-1 defines the winding resistance value and other topics concerning the testing of three-phase AC motors, such as equations to calculate certain losses. IEC60034-2-1 applies to every motor within the scope defined in the standard.

IEC60034-2-1 (International Electrotechnical Commission 2014a: p. 7) defines the scope as seen below:

´´This part of IEC 60034 is intended to establish methods of determining efficiencies from tests, and also to specify methods of obtaining specific losses. This standard applies to d.c. machines and to a.c. synchronous and induction machines of all sizes within the scope of IEC 60034-1.´´

4 Routine testing process for IEC LV motors

According to the final testing procedures the purpose of routine testing is to check and verify that the performance and properties of a motor fulfills the requirements of a customer, relevant standards and the manufacturer, ABB Oy, IEC LV Motors, Vaasa (Vieri, 2021, p. 1). The routine test is made for every motor at the end of assembly line. All the motors for safe areas and hazardous areas are verified and tested according to the relevant rules of IEC and EN-standards. The content of routine test program is described in Table 2.

Table 2. Content of test program for routine test. (Vieri, 2021, p. 2–3).

Routine test process	Inspection phase
Visual inspection	1
Terminal markings and direction of rotation	2
Resistance measured at the ambient temperature	3
No load point at 50 Hz	4
Vibration level test	5
Short circuit point at 50 Hz	6
Withstand voltage test	7
Insulation resistance measurement	8
Surge comparison test	9
Comparing test results to control values	10

Next, I´ll go through the different phases included in routine testing to demonstrate different ways how any issues in quality can be discovered concerning the rotors. This also creates a basis on what types of measurements concerning the quality can be developed to discover potential quality issues more accurately in the future.

4.1 Visual inspection

Vieri (2021, p. 4) describes that in the first phase of the routine testing process the test personnel checks that the motor is made according to the work card. Work cards are motor specific and include all the necessary information about the motor and order, such as component list and structure of the motor and information about the different work phases. The work card includes information about which type of motor it is (for example BP/AA/GP/JP/KP), how the motor should be connected, which kind of rotor and shaft the motor has, and a list of all other components needed to manufacture the motor and the information about the calculation number of the motor. Motor specific calculation includes all the necessary information about the active components of a motor such as the stator and rotor. The calculation includes information about the material of the rotor and stator sheets, dimensions of the active components, the amount and type of the slots and information about how much of the stator slots are fulfilled with copper wires (Vieri, 2021, p. 4.). It also includes information about the insulation and dimensions of copper wires used in the stator among many other technical information. Once it is verified that the motor is manufactured according to the work card, the test personnel checks that all the other points according to the FIMOT0067 instructions (Vieri, 2021, p. 4).

The visual inspection continues by checking the rating plate values of the main motor and the separate cooling motor if it was included in the order (Vieri, 2021, p. 4.). One also needs to check that main terminal boxes, terminal block and that other auxiliary devices are of correct type (Vieri, 2021, p. 4). The shaft and key are also visually inspected to detect scratches and possible fractures. In the last phase of the visual inspection the painting color, cable glands and international mounting (IM) code is checked to ensure that the motor has the correct components (Vieri, 2021, p. 4). No external requirements for the visual inspection can be found from standards. The acceptance criteria are based on the verification that the construction of the motor is made according to the order.

4.2 Terminal markings and direction of rotation

In this phase of routine testing process the terminal markings and direction of rotation of the motor is checked (Vieri, 2021, p. 4.). According to IEC 60034-8 standard the motor rotates clockwise seen from the drive end of the motor when the phases of the supply are connected to the terminal block in order L1, L2, L3 → U, V, W. The requirements for the phase markings and direction of rotation comes from IEC standards 60034-1 & 60034-8. The motor fulfills the acceptance criteria if the markings can be found from the stator phases and the motor rotates clockwise with the connection described before.

4.3 Winding resistance measured at the ambient temperature

According to Vieri (2021, p. 4) during the production line routine test the resistance values of the standard terminals are measured between terminals U1-U2, V1-V2, W1-W2 regardless of the Y or D connection of the motor. Vieri (2021, p.4) also describes that in this phase the resistance of the winding is measured at ambient temperature. This measurement is done to check that the connections of the windings are made correctly and to find out unbalances between phases. It is also important to measure the accurate ´´cold´´ resistance so that the temperature rise can be determined after a possible temperature rise test conducted in possible type tests (Vieri, 2021, p. 4.). Resistance values reported in the routine test report are according to Y or D connection depending on the actual connection used in the no load test. The requirement for this test comes from IEC standards 60034-1 & 60034-2-1. At the end of the test the measured resistance values are compared to the calculated control values. Acceptance criteria is defined by the manufacturer and the test is passed if the measured value is according to the control value considering the manufacturing tolerance defined by the manufacturer (Vieri, 2021, p. 4).

4.4 Resistance measured from accessories at the ambient temperature

Resistances of all ordered accessory components (for example PT100, PT1000, PTC thermistors and space heaters) are measured at ambient temperature from motor terminal blocks on routine tests performed at production line (Vieri, 2021, p. 5.). There are no requirements for this type of test from standards and thus the acceptance criteria are defined by the manufacturer. At the end of the test the resistance values are compared to the control values according to the type of the accessory (Vieri, 2021, p. 5).

4.5 No load point at 50 Hz

Vieri (2021, p. 5) describes that the motor is supplied with voltage defined in the control values by electrical designer and with 50 Hz frequency. Control values are specified for each individual electrical calculation and thus they are always same for motors having identical electrical design. The no-load voltage defined in the control values is not necessary the same nominal voltage stamped to the rating plate of a motor. The standard voltages available for each manufacturing lines are 220/230 V, 380/400 V, 500 V and 660/690 V (Vieri, 2021, p. 5). For motors which have rated voltage corresponding to 60 Hz frequency an equivalent voltage is selected for 50 Hz supply. During the test no-load current, power factor, voltage and power are measured and compared to the calculated control values (Vieri, 2021, p. 5.). The requirement for this test comes from IEC standard 60034-1. Acceptance criteria is defined by the manufacturer and the test is passed if the measured values are according to the control values considering the manufacturing tolerance defined by the manufacturer and if the vibration levels are acceptable (Vieri, 2021, p. 5).

4.6 Vibration level test

The vibration level test is made during the no-load test where the motor is free of suspension (Vieri, 2021, p. 6.). The state of free suspension can be achieved when the motor is fixed to a wooden pallet or is placed on a rubber mat or if the motor is hanging on a crane. The vibration level test is performed for all motors in horizontal position. It does not consider the actual mounting arrangement of the motor. The vibration levels are measured from five different places as shown in Figure 11. Only the highest value is reported in the routine test report (VC 148). All five values are reported if vibration level report (VC 760) is ordered. The vibration level test is not reliable for motors equipped with angular contact ball bearings and thus in those cases, the values are not available. (Vieri, 2021, p. 6.)

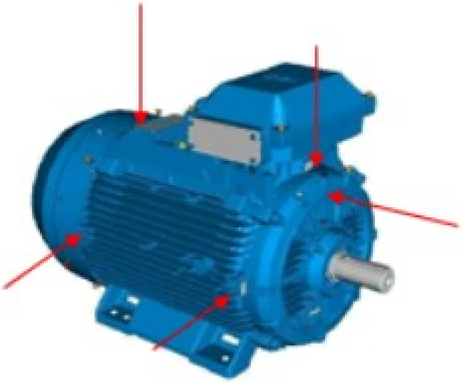


Figure 11. Directions of vibration measurements (Vieri, 2021, p. 6).

The requirements for vibrations level tests come from IEC standard 60034-14. The acceptance criteria are defined in the standard and can be seen in Table 3 below. The relationship between displacement and velocity for single-frequency harmonic component is defined in the standard ISO 10816-1 (Vieri, 2021, p. 6).

Table 3. IEC standard 60034-14 limits of maximum vibration magnitude in displacement and velocity (International Electrotechnical Commission 2018, p. 12).

Shaft height [mm]		56 ≤ H ≤ 132		H > 132	
Vibration grade	Mounting	Displacement [μm]	Velocity [mm/s]	Displacement [μm]	Velocity [mm/s]
A	Free suspension	45	2,8	45	2,8
	Rigid mounting	-	-	37	2,3
B	Free suspension	18	1,1	29	1,8
	Rigid mounting	-	-	24	1,5

4.7 Short circuit point at 50 Hz

During the short circuit test the rotor of the motor is mechanically locked. The motor is supplied with voltage defined in the control values by electrical designer and with 50 Hz frequency. Control values are specified for each individual electrical calculation and thus they are always same for motors having identical electrical design. The short circuit voltage with 50 Hz frequency is defined in a way so that it gives approximately the rated current during short circuit test (Vieri, 2021, p. 7.). Short circuit current used in the test and defined in the control values is not necessarily the same as nominal current stamped to the rating plate. The test will be done with a lower current if it exceeds the capacity of the power source. During the short circuit test current, power factor, voltage and power are measured and compared to the calculated control values (Vieri, 2021, p. 7.). No requirements for this test can be found from the standards. Acceptance criteria is defined by the manufacturer and the test is passed if the measured values are according to the control values considering the manufacturing tolerance defined by the manufacturer. Some of the possible rotor quality issues can be found during the short circuit test, for example poor casting in rotor slots is usually found from motors which measure a lot lower short circuit current compared to the control value (Vieri, 2021, p. 7).

4.8 Withstand voltage test for winding

The main purpose of withstand voltage test is to ensure that there are no weak points in winding insulation (Vieri, 2021, pp. 7–8.). For standard motors and windings, where the star point is available, the windings can be tested separately as seen in figure 12. For windings with internal connection the phases are tested together as seen in Figure 13.

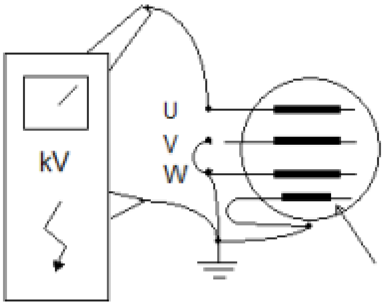


Figure 12. Withstand voltage test connections for the stator phase U (Vieri, 2021, p. 7).

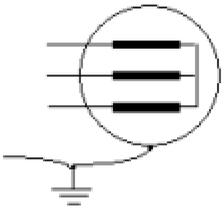


Figure 13. Withstand voltage test connections for the winding with internal connections (Vieri, 2021, p. 8).

The test voltages used are defined in IEC standard 60034-1. The test voltage of winding is 2400 V (2x690 V + 1000V) if the winding is designed for nominal voltage of 690 V in all motor sizes and the duration of the test is 60 seconds (Vieri, 2021, p. 8). The 60 second test may be replaced with a test of 1 second with 120% of test voltage during the routine test process for motors with power of up to 200 kW (Vieri, 2021, p. 8). The withstand voltage test with full voltage shall not be repeated for already tested and accepted windings. If second test is ordered by the customer, the test voltage shall be 80% of the full test voltage (Vieri, 2021, p. 8.). The requirements for withstand voltage test comes from IEC standard 60034-1 and the winding is considered accepted if it passed the test without short circuit.

4.9 Withstand voltage test for accessories

Withstand voltage test for accessories can be made if it is separately ordered (VC 149) (Vieri, 2021, p. 8). Withstand voltage test for all ordered accessory components installed in the winding (for example PT100, PT1000, PTC thermistors and space heaters) is made with 1500 V and the duration of the test is 60 seconds (Vieri, 2021, p. 8.). The test for accessory components installed outside the winding (for example bearing temperature detectors) is made with 500 V and the duration of the test is 15 seconds (Vieri, 2021, p. 8.). The requirements for withstand voltage test comes from IEC standard 60034-1 and the accessory component is considered accepted if it passed the test without short circuit.

4.10 Insulation resistance measurement for winding

According to Vieri (2021, pp. 8-9) the main purpose of insulation resistance test is to verify that the insulation level of winding is high enough to ensure safe operation of the motor. The test voltage is 1000VDC (Vieri, 2021, pp. 8–9.). The measuring process is stopped when acceptable values has been reached or when the final value is measured after 60 seconds (Vieri, 2021, pp. 8–9.). The test is done at ambient temperature for routine tested motors. The measured value is highly dependent on winding temperature. The reference standard for insulation resistance measurement is IEC60034-27-4. The acceptance criteria for windings at ambient temperature is defined by the manufacturer to be 2000 MΩ if ambient relative humidity is below 40% and 1000 MΩ if ambient relative humidity is 40% or higher (Vieri, 2021, pp. 8–9.). The measurement process of insulation resistance of stator winding is shown in Figure 14.

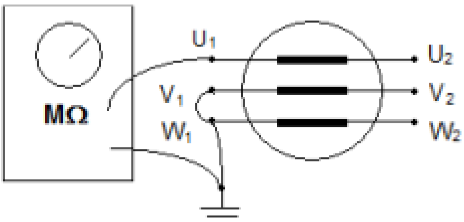


Figure 14. Stator winding insulation resistance measurement (Vieri, 2021, p. 9).

4.11 Insulation resistance measurement for accessories

Vieri (2021, p. 9) describes that insulation resistance measurement can also be done for accessory components if it is ordered separately (VC 149). The test voltage is 1000 V and the duration is 60 seconds for accessory components installed in the winding (for example PT100, PT1000, PTC thermistors and space heaters) (Vieri, 2021, p. 9). The test voltage is 500 V and the duration is 60 seconds for accessories installed outside the winding (for example bearing temperature detectors) (Vieri, 2021, p. 9.). The measurement is performed between all accessories and with winding connected to frame. No requirements for this type of test can be found from standards and thus the manufacturer has defined the minimum acceptance criteria to be 1000 MΩ (Vieri, 2021, p. 9).

4.12 Surge comparison test

According to Vieri (2021, p. 13) surge comparison test is made for two of the phases of a motor which are fed with 3000 V surge peaks. The voltage curves of the test are checked with oscilloscope and compared visually (Vieri, 2021, p. 13.). This test will be done only once for each motor. The test is done during routine test on production line.

The main purpose of this test is to find out if turn-to-turn failures are present in the winding (Vieri, 2021, p. 13.). No requirements for this test can be found from standards and thus the acceptance criteria are defined by the manufacturer. The winding is passed if there is no unbalance between phases.

4.13 Comparing routine test results to control values

Kuusisto (2012, p. 22) describes the calculation of control values by describing how they are based on electrical values which are stator and rotor specific. Control values are calculated for the optimal supply frequency and voltage based on the winding design (Kuusisto, 2012, p. 22). Calculated control values are compared to tested routine test values. The motor is rejected if the measured values differ from the control values. There is also manufacturer´s own production tolerance values for each specific control value.

In this section the equations for calculating routine test control values are explained. The magnetizing current part of the no load current I_0 can be calculated as

$$I_{Q0} = \frac{\pi p m_0}{\sqrt{2} m_1 2 N_{1t} \xi_1}, \tag{1}$$

where I_{q0} means magnetizing current, p means pole pair number, m_0 means the magnetomotive force of the whole circuit, m_1 means phase number, ξ_1 means winding factor of the stator and $2N_{1t}$ means effective wire factor for phase. (Kuusisto, 2012, p. 19). The magnetizing portion of the no load current comes primarily from the airgap and lamination magnetization.

The reactive part of the no load current I_0 can be calculated as

$$I_{p0} = \frac{P_{Fe} + P_p}{m_1 U_{v1}}, \tag{2}$$

where I_{p0} means the reactive part of the no load current, P_{Fe} means iron losses in the stator, P_p means friction losses and U_{V1} phase voltage. (Kuusisto, 2012, p. 19). The reactive part of the no load current comes primarily from iron and friction losses.

No load current I_0 can be calculated as

$$I_0 = \sqrt{I_{Q0}^2 + I_{P0}^2}, \tag{3}$$

where I_0 means no load current (Kuusisto, 2012, p. 20). No load current consists of the magnetizing current and the reactive current part.

No load power factor can be calculated as

$$cos\ \varphi_0 = \frac{P_0}{\sqrt{3}U_0 I_0}, \tag{4}$$

where cos φ_0 means no load power factor, P_0 means no load power and U_0 means no load voltage (Kuusisto, 2012, p. 20). All the variables are calculated when the motor is in no load condition.

No load power can be calculated as

$$\mathrm{P}_0 = \sqrt{3}U_0 I_0 cos\ \varphi_0 \tag{5}$$

No load power is based mainly on stator-winding loss at no-load, excitation-loss, friction, windage, and stray losses (Kuusisto, 2012, p. 20). It´s the power taken from the grid by the motor when no load is attached to it.

Short circuit current can be calculated as

$$I_k = \frac{U_N}{U_{km}} I_{km}, \tag{6}$$

where U_N means nominal voltage, U_{km} and I_{km} are reduced values for voltage and current in short circuit test (Nyblin, 2002, p. 47). Short circuit current means current with locked rotor.

Short circuit power can be calculated as

$$\mathrm{P}_k = \sqrt{3} U_{km} I_{km} cos\ \varphi_k, \tag{7}$$

where cos φ_k means short circuit power factor (Mäenpää, 2016, p. 21). All the variables are calculated when the motor is in locked rotor conditions.

5 Analysis of rotor quality deviations

The research started by investigating routine test results of motors manufactured in KK -factory (frame sizes 71-250) in 2021 to answer the first research question. The purpose of the research was to identify which rotor cores had the most quality deviations and what those deviations might have been. By researching the routine test results from 2021 it was found that 85 different types of rotor cores had quality deviations. It was also discovered that the most defected rotor core had approximately 18% of all the quality deviations. Because of that reason, this 112-frame size rotor core 11-17 became the focus of the study. The list of all the defected rotor cores can be found in Appendix 1. Figure 15 shows how the quality issues are divided into different frame sizes.

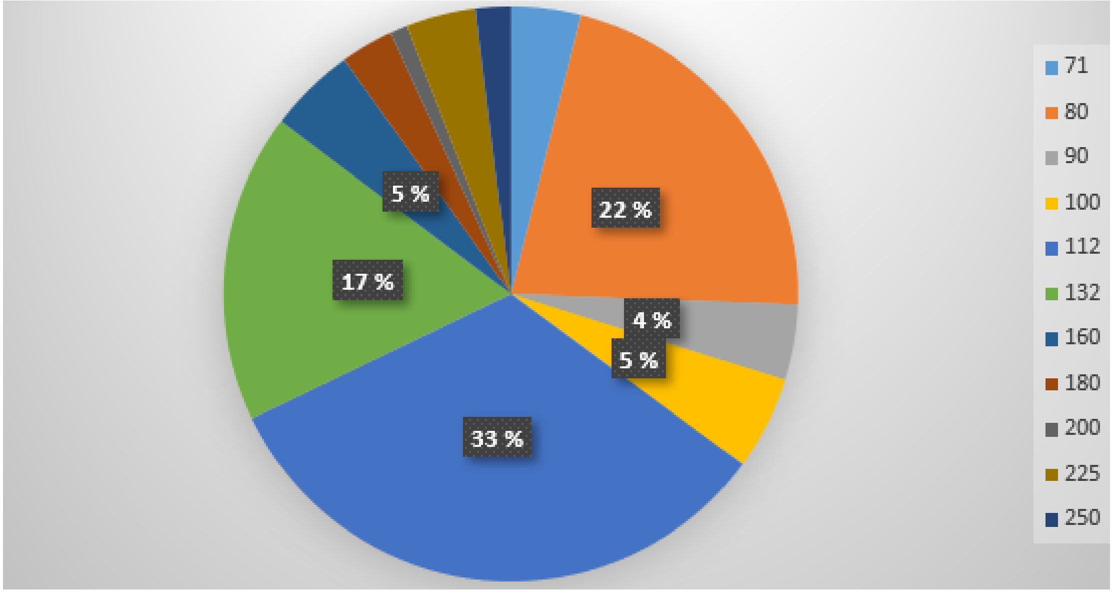


Figure 15. Defected rotor cores divided to frame sizes.

Based on the routine test results it was also discovered that 48% out of the defected 11-17 rotor cores tested too low short circuit currents I_{km} compared to the rotor specific control values meaning that approximately half of the defected rotor cores might have similar quality deviations. Based on the previous routine testing data and experience on rotor testing it would seem possible, that too low short circuit currents in routine testing might be having problems with poor casting quality in the rotor core slots. A couple of rotors made with 11-17 rotor cores which had failed the routine test were cut to verify the casting quality in rotor slots. The results from the tests can be seen in Figures 16, 17 and 18. Figure 16 shows that the aluminum has not fulfilled the whole rotor slot causing interruption of the bar in the rotor slot. Figure 17 shows the short circuit rings having air bubbles and porosity defects at the end of the rotor. Figure 18 shows an uneven distribution of the aluminum in couple of the rotor slots.

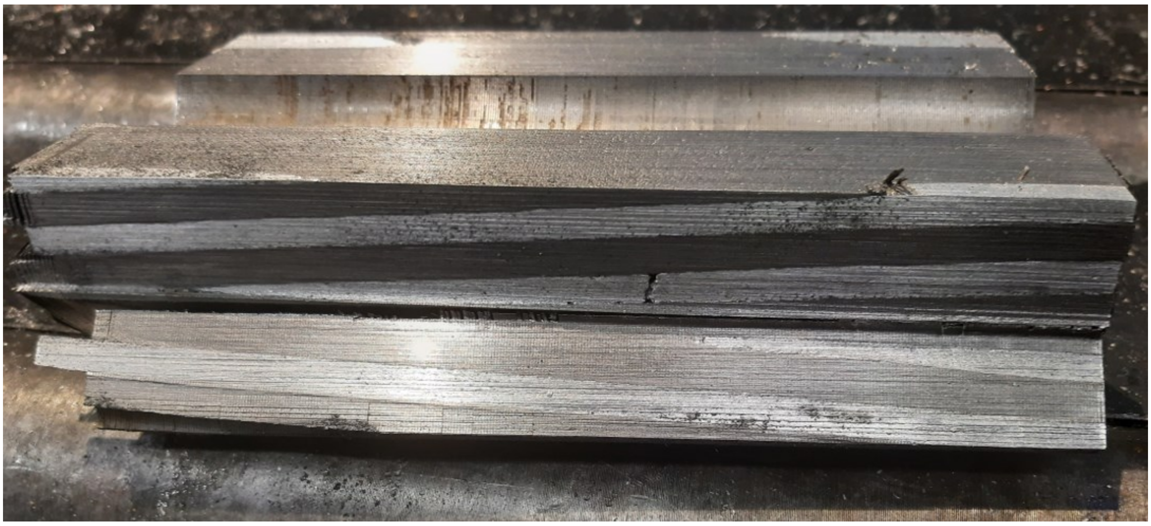


Figure 16. Close up of casting defect found from one of the slots of studied rotor core 11-17.

Figure 17. Casting defect found from one of the short circuit rings of studied rotor core 11-17.

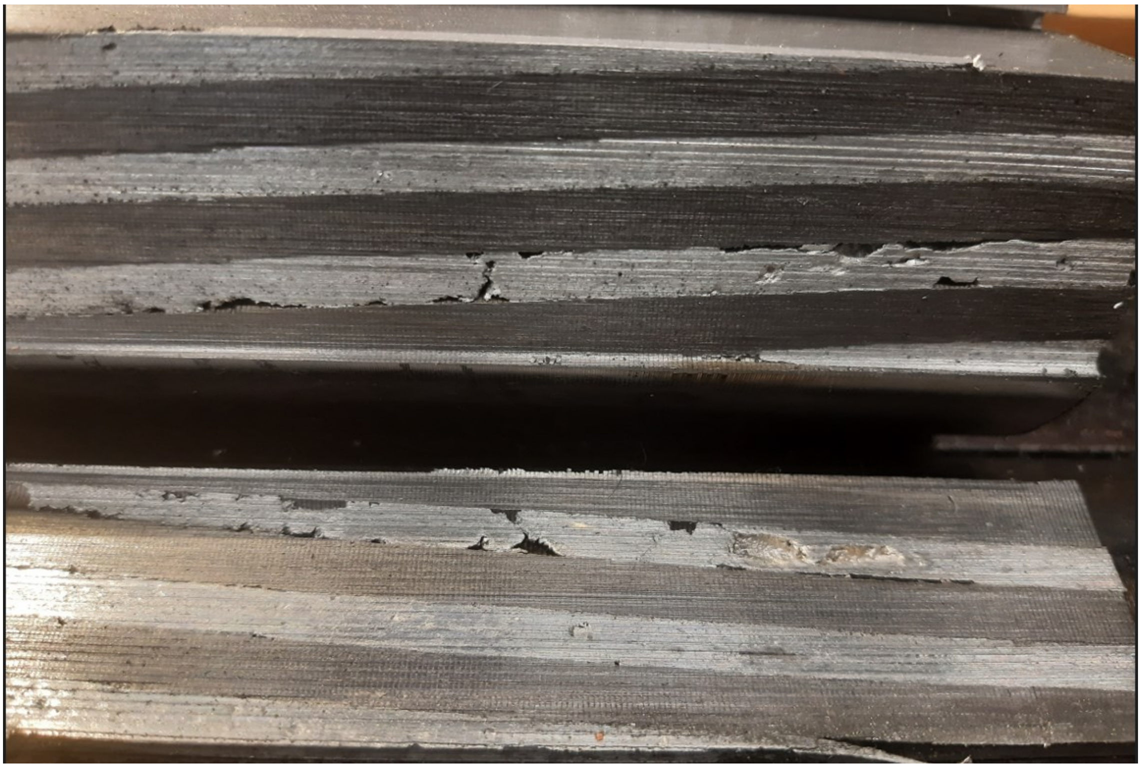


Figure 18. Uneven distribution of aluminum in couple of the slots on studied rotor core 11-17.

Some of the ways researched to detect poor casting quality included measuring the weight of the rotor, measuring the balancing weights used in the rotor and measuring the aluminum conductivity of the rotors. The values measured from the defected 11-17 rotor cores can be seen in Table 4.

From the research it became clear that some of defect’s, such as a defect seen in Figure 16, can´t be found from measuring the overall weight of a complete rotor since the amount of missing aluminum in the rotor slot can sometimes be smaller than the weight tolerance of all the components used in complete rotor (such as bearings and shaft).

Table 4. Measured sample rotors.

Test sample	Rotor core	Balancing grade	Rotor weight [g]	Balancing weight [g]	Aluminum conductivity [MS/m]
1	11-17	G1	11928	18.8	35.15
2	11-17	G1	11712	11.3	34.44
3	11-17	G1	11767	16	35.52
4	11-17	G2,5	11699	3	34.64
5	11-17	G2,5	11693	10.5	34.94
6	11-17	G2,5	11713	7.5	34.74
7	11-17	G2,5	11745	0	35.53
8	11-17	G2,5	11757	14.4	34.76
9	11-17	G2,5	11739	12	35.23
10	11-17	G2,5	11703	7.5	34.90
11	11-17	G2,5	11682	7.5	35.26
12	11-17	G2,5	11879	4.5	35.20
13	11-17	G2,5	11732	3	34.74
14	11-17	G2,5	11726	7.5	35.42
15	11-17	G2,5	11775	15.2	34.74

The most promising way to detect casting faults from defected rotor cores was to measure the balancing weights used to balance the rotor, but this would require more research and information about the used balancing weights on a specific rotor type to determine what should be the control value for the maximum amount of allowed balancing weights. Now this information is not gathered in the system. It would also require balancing weight comparison between rotors passing and failing the routine test, so to conduct this research it would require a process change so that this information is gathered from every rotor and maximum balancing weight value determined based on that data.

This would also require that the shaft is inserted in the rotor core and the rotor is balanced before the defect could be detected, so it wouldn´t be the most optimal phase of the rotor manufacturing process to detect the defect.

The aluminum conductivity test was also one of the ways researched to detect the defects in a rotor. During the tests it was found out that the value can vary 0.5 MS/m even when measuring from the same point due to impurities. It would require specific test instructions to get reliable test results from the aluminum conductivity. It would also require more research and information about the aluminum conductivity on a specific rotor type to determine what should be the control value for it. Now this information is not gathered in the system. It would require a process change to gather the data to make a comparison between rotors passing and failing the routine test and to determine the control value.

Based on the routine testing data it was not always possible to find the root cause of the quality deviation related to the rotor. Cause-and-effect diagram was made to analyze possible causes of quality defects present in squirrel cage rotors and to answer the second research question. Other possible quality issues might be for example that the rotor has not been balanced correctly or that the shaft is not pressed to the correct dimension or that the skew of the rotor slots is not correct. This cause-and-effect diagram can be seen in Figure 19.

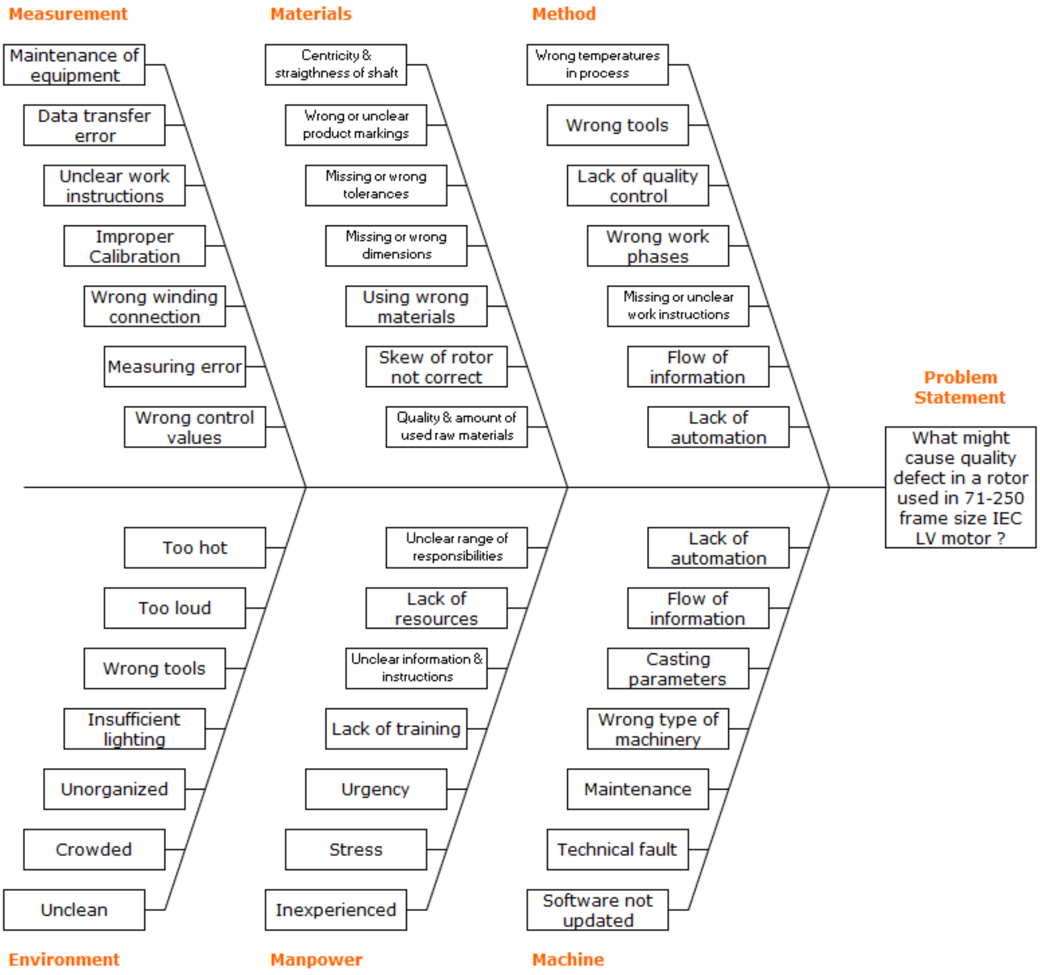


Figure 19. Cause-and-effect diagram for quality defect in rotor in 71-250 frame size IEC LV motor.

The final part of the research was to figure out ways to detect quality issues at the earlier stages of the supply chain. Based on the results of the tests for rotors made with 11-17 rotor core, two ways were found which would help to detect the casting defect right after the casting process. The best way to detect the casting defects in the rotor slot would be to use cage verification testing equipment right after the casting to measure the quality of the cage bars of asynchronous motors. The equipment displays waveforms corresponding to the interaction between the electromagnet and the cage bars (Figure 20).

Figure 20. Cage verification equipment. (Risatti global, 2022).

The other way would be the same as described in Section 3.3, The rotor core manufacturer can measure the weight of the rotor core before and after the casting to ensure that the correct amount of aluminum is used on the rotor core. At this point there is no additional components added to the rotor and the possible weight difference is much smaller than of complete rotor. This would also be the best and most optimal part of the rotor manufacturing process to detect possible casting faults because the rotor has not been fully assembled yet. Rotor cores made with 11-17 should have approximately 1087 g of aluminum in the rotor slots after the casting process.

6 Conclusions and future recommendations

In this chapter conclusions are drawn, and future recommendations are presented. Discoveries are based on studies conducted on previous chapters as well as discussions concerning the cause-and-effect diagram.

6.1 Conclusions

In this study first research question was figuring out what are the most common rotor cores where quality deviations are present. By researching the routine test results from 2021 it was found that 85 different types of rotor cores had quality deviations. It was also discovered that the most problematic rotor core had approximately 18% of all the quality deviations. The list of all the defected rotor cores and their defect percentages can be found in Appendix 1.

Second research question was inspecting what might be the cause for those quality deviations. Cause-and-effect diagram (Figure 19) was made to analyze possible causes of quality defects present in squirrel cage rotors and to answer the second research question. The diagram can be used to figure out what could be the root causes of a certain quality deviation. For example, the most probable causes for casting related quality deviation would be that wrong temperatures are used in the process or that the casting parameters are not set correctly or that the quality and quantity of used raw materials are not correct. Quality deviations related to the shaft insertion can be a result of missing or wrong information, such as dimensions or tolerances, in the rotor core drawings. There can also be wrong temperatures in the process or wrong tools used to fit the shaft into the rotor core.

Final research question tried to resolve what would help to detect quality deviations at the earlier stages of the supply chain. One possible solution to detect rotor quality issues is using cage verification equipment such as Risatti. The equipment displays waveforms corresponding to the interaction between the electromagnets and the cage bars. The equipment might have some limitations concerning the rotor size and it also might require that the shaft is inserted in the rotor core before it can be tested, depending on the used equipment.

The other way to detect casting faults in rotor would be, as said in Section 3.3, to measure the weight of the rotor core before and after the casting to ensure that the correct amount of aluminum is used on the rotor core. This would be the best and most optimal part of the rotor manufacturing process to detect possible casting faults because the rotor has not been fully assembled yet. Rotor cores made with 11-17 should have approximately 1087 g of aluminum in the rotor slots after the casting process.

Possible casting defects can also be detected at the rotor balancing process, as stated in paragraph 3.3. This would require more research and information about the used balancing weights on a specific rotor to determine what should be the control value for the maximum amount of allowed balancing weights. This would be the second most optimal phase of the rotor manufacturing process to detect possible casting quality issues, because the balancing process can only be done after the shaft has been inserted to the rotor core and thus some amount of resources are already used in the rotor before detecting the problem.

The least optimal phase of the whole motor manufacturing process is to detect the rotor quality defects during routine tests of the motor. At this point not only, the whole rotor is assembled but also the motor, requiring the dismantling of the motor to change the defected rotor, wasting the resources to fix the issue.

6.2 Future recommendations

One of the best ways to improve the casting quality of rotor cores is to contact the subcontractor and work with them to recheck the overall casting process to see if something could be changed to improve the quality, such as casting parameters. This process was also started because of this thesis with the manufacturer of 11-17 rotor cores to see if we can work together to find the final solution to improve the overall quality of these rotor cores. This same kind of procedure should always be used if considerable amount of new rotor cores starts to fail the routine test. In those cases, also a further analysis is needed to first try to find the root cause of the problems and then communicate with the relevant subcontractor.

Maximum rotor balancing weight and aluminum conductivity limits could be set for the rotors, but it would require further research and information about what the values would be for the good quality rotors and then make the comparison between the data gathered here and the new values. Now this balancing weight data or aluminum conductivity data is not gathered in the systems in any way, so it would require a process change to gather this information for a while until more detailed limits could be set.

From the sourcing perspective it could also be considered if it would be possible to manufacture complete rotors with using only one subcontractor, meaning that the rotor core manufacturing, shaft insertion and balancing would all be made by the same subcontractor. It would make the rotor manufacturing process smoother and provide more opportunities for quality control for the subcontractor.

Other topic to consider is the work phases of the whole rotor manufacturing. Now rotors are balanced after the shaft is inserted into the rotor core, but for example bearings or fans are not included in the rotor when it is balanced. Balancing phase should be the last phase after every component is added to the rotors such as bearings, fans etc. The added component after the balancing phase always contributes a little to the overall unbalance of the rotor.

In literature there has been some recent suggestions on how to detect rotor defects using more advanced methods, such as MRA combined with BPNN which is suggested as one potential method for diagnosing the rotor bar defects of motors (Lee et al., 2020). However, this method requires more research, and it should be considered whether it is applicable for ABB purposes.

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Appendix

Appendix 1. Defected rotor cores in 2021.

Rotor core product code	Defects [%]	Rotor core product code	Defects [%]
07-13	1.97 %	11-28	5.57 %
07-25	1.31 %	11-29	3.93 %
07-8	0.33 %	11-62	0.33 %
08-11	0.33 %	13-126	0.33 %
08-14	2.62 %	13-130	0.33 %
08-3	0.66 %	13-137	0.33 %
08-5	5.90 %	13-24	1.97 %
08-50	0.33 %	13-25	1.97 %
08-7	0.98 %	13-26	1.64 %
08-8	3.61 %	13-35	0.66 %
09-13	0.33 %	13-36	0.98 %
09-15	0.33 %	13-37	0.98 %
09-26	0.66 %	13-66	0.66 %
09-28	1.64 %	16-119	0.66 %
10-12	0.66 %	16-64	0.33 %
10-29	0.33 %	16-69	0.33 %
10-98	0.33 %	18-60	0.33 %
11-17	17.70 %	20-111	0.33 %
11-18	2.62 %	25-16	0.66 %

Rotor core product code	Defects [%]	Rotor core product code	Defects [%]
45-H	0.33 %	53-F	0.66 %
45-J	0.33 %	53-G	0.66 %
45-U	0.33 %	54-U	0.66 %
46-J	0.66 %	54-X	0.66 %
48-G	0.33 %	55-N	0.33 %
48-J	0.33 %	56-D	0.33 %
48-K	1.31 %	57-A	0.33 %
48-M	0.33 %	57-H	0.66 %
49-A	0.33 %	57-J	0.66 %
49-F	0.33 %	58-C	0.33 %
50-E	0.33 %		

Rotor core product code	Defects [%]	Rotor core product code	Defects [%]
74-B	0.33 %	84-A	0.66 %
82-B	0.66 %	84-B	3.28 %
82-C	1.64 %	92-A	0.33 %
83-D	0.66 %	93-C	0.33 %
83-F	0.33 %	93-FV	0.33 %

Rotor core product code	Defects [%]	Rotor core product code	Defects [%]
02-CV	0.66 %	34-H	0.33 %
03-A	0.66 %	35-B	1.31 %
03-K	2.30 %	35-C	0.66 %
03-KY	0.33 %	35-F	1.31 %
34-C	0.33 %	35-G	0.66 %
34-G	0.33 %	35-I	2.62 %

Rotor core product code (other codes)	Defects [%]	Rotor core product code (other codes)	Defects [%]
09-1D	0.33 %	11-B	0.66 %
18-2	1.97 %	11-E	1.97 %