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Improvement of electronics cooling fans' ALT testing project

Master's thesis

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Elektroonika jahutusventilaatorite ALT testimisprojekti täiustamine

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Author’s declaration of originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature, and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

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Abstract

This thesis work is completed for the Reliability Engineering Team of an Electronics Company located in Estonia. The main purpose of the thesis is seeking improvements in the Accelerated Lifetime Testing procedure for the component-level testing project.

Electronics Company is continuously developing its testing projects and the search for improvement possibilities of electronics cooling fans' Accelerated Lifetime Testing project has been initiated. This thesis is reviewing the general construction of electrical drives, the main failures observed in electrical drives, the role of cooling fans in electrical drives, and available in the industry lifetime testing techniques which can be or are applied for such testing projects. Based on such knowledge and understanding, cooling fans are reviewed as a separate component of the system (electrical drive), together with an in-depth analysis of the applicable standards for the fan manufacturing and testing processes available in the industry. The detailed review of one main applicable standard and comparison of the standard requirements with the Company's needs and requirements for testing helps to derive improvement possibilities for existing fans' testing setup and procedure. Improvement possibilities, which are the main outcomes of this thesis, have been derived and proposed for the Electronics Company and the Reliability Engineering Team for review. Some improvement possibilities have been implemented in frames of thesis work and some have been proposed for future implementation with the action plan and need justification, according to applied standards and Company's needs.

This thesis is written in English and is 66 pages long, including 12 chapters, 21 figures, and 11 tables.

Annotatsioon

Elektroonika jahutusventilaatorite ALT testimise täiustamine

Käesolev lõputöö on valminud Eestis asuva elektroonikaettevõtte töökindluse insenerimeeskonna vajadustest lähtudes. Lõputöö põhieesmärk on komponendi tasemel läbi viidavate kiirendatud eluea testimise protsesside täiustamine.

Elektroonikaettevõtte arendab pidevalt oma testimisprojekte ning otsib viise oma elektroonika jahutusventilaatorite kiirendatud eluea testimise täiustamiseks. Käesolevas lõputöös käsitletakse elektriajamite üldist ehitust, elektriajamites täheldatud peamisi tõrkeid, jahutusventilaatorite rolli elektriajamites ning tööstuses saadaolevaid eluea testimise tehnikaid, mida saab kasutada sellistes testimisprojektides. Sellistele teadmistele ja arusaamadele tuginedes vaadeldakse jahutusventilaatoreid süsteemi (elektriajam) eraldiseisva komponendina koos tööstuses saadaolevate ventilaatorite tootmis- ja testimisprotsessidele kehtivate standardite põhjaliku analüüsiga. Ühe peamiselt kasutatava standardi üksikasjalik käsitlemine ja standardinõuete võrdlemine ettevõtte vajaduste ja testimisnõuetega aitab selgitada välja parendusvõimalusi olemasolevate ventilaatorite testimise seadistuste ja protseduuride jaoks. Täiendusvõimalused, mis on käesoleva lõputöö peamised tulemused, on pakutud elektroonikaettevõttele ja töökindluse insenerimeeskonnale läbivaatamiseks. Lõputöö raames on mõningaid parendusvõimalusi juba rakendatud ning osa on pakutud edaspidiseks elluviimiseks koos tegevuskava ja põhjendustega, mis toetuvad kehtivatele standarditele ja ettevõtte vajadustele.

Lõputöö on kirjutatud Inglise keeles ning sisaldab teksti 66 leheküljel, 12 peatükki, 21 joonist, 11 tabelit.

List of abbreviations and terms

R&D	Research and Development
ALT	Accelerated Lifetime Testing
PLC	Programmable Logical Controller
PC	Personal Computer
ADC	Analog-to-Digital Converters
MCU	Microcontroller Unit
mm	Millimeters
V	Volts
AC	Alternating Current
DC	Direct Current
PCB	Printed Circuit Board
HALT	Highly Accelerated Lifetime Testing
RDT	Reliability Demonstration Test
HASS	Highly Accelerated Stress Screening
ANSI	American National Standards Institute
AMCA	Air Movement and Control Association
ISO	International Organization for Standardization
CPU	Central Processing Unit
PWM	Pulse-Width Modulation
RPM	Revolutions Per Minute
AABUS	As Agreed Upon Between User and Supplier
IEC	International Electrotechnical Commission
MTTF	Mean Time To Failure
ºC	Degrees Celsius
MIL-HDBK	Military Defence Handbook
FMEA	Failure Modes and Effects Analysis
DUT	Device Under Test
A	Amperes

Ω	Ohms
LAN	Local Area Network
LXI	LAN eXtension for Instrumentation
AF	Acceleration Factor
HW	Hardware
SW	Software
€	Euros
JIS	Japanese Industrial Standard

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1 Introduction

The topic for this work originates from the Reliability Engineering team with the support of colleagues from the Research and Development (R&D) department of the Electronics Company in Estonia, which produce electrical drives and other power electronics devices. The topic of reliability of electrical drives and their components is a topic of high interest in the company, as it influences customer satisfaction level and the general rating image of the company directly. As a part of the components' reliability testing projects, a dedicated project concentrated on Accelerated Lifetime Testing (ALT) of cooling fans has been initiated. The cooling fan is an important component of electrical drive, as it provides operability of electrical drive in a long-term perspective, by decreasing the temperature-related aging of other electronic components of the drive and by minimizing the risk of overheating or burning of other product's operation-critical components.

The project covers the topic of reliability of cooling fans, which the Company is using in electrical drives produced by it, and verification of the reliability through the application of the pre-defined stress factors, which have a direct influence on the controlled aging of components. The project has been developed more than 5 years back in time, by the product quality team from another country, where the Electronics Company is also represented. Recently, the project has moved to the Estonian team with the request for searching possible improvements to the existing testing procedure and testing chambers.

Existing test setup and procedure have several main points which have been reviewed in the thesis work:

- whether all stress factors applied to fans in the existing test setup are monitored and have defined metrics or are there any additional factors that physically exist but are not controlled and measured anyhow
- verification of standards compliance of the existing test procedure and test setup
- comparison of the existing testing approach to the standard and fan manufacturers testing and fans' reliability estimation

- are there any additional reasonable measurements that should be conducted in frames of the test procedure to improve the quality and significance of testing results for analysis
- verify how the test can be automated and whether the automation of the existing setup is meaningful
- verify whether test results can be compared to field failures and whether such knowledge can have potential influence on future improvements of the testing.

In the following thesis work, the research has been completed to seek improvement possibilities of the testing procedure and setup. Work done in the thesis can be divided into several main steps:

- review of components of electrical drives and description of the role of fans in this structure
- providing the general idea of the ALT concept and similar testing concepts
- providing a general idea of fans' reliability concept and standards, that can be or are already applied
- review of the fan structure, fan failure mechanisms, and requirements for testing
- deep analysis of the existing test procedure and setup
- finding improvement points based on the standardization and requests from Company's engineers
- implementation and reasoning of improvements
- proposals of long-term possible improvements in the testing project to increase the efficiency of the testing.

Possible outcomes of this work together with further financial evaluation, which has not been discussed in this thesis work, potentially can have a global influence on processes inside the Company and the quality of the final product, manufactured by the Company.

2 Electrical drives, their reliability, and testing

This chapter aims to generally describe the main constituents of electrical drives, describe faults, that might be encountered in drives' applications, and provide the concept of reliability verifications used by the Electronics Company. Electrical fans, which are the main topic of this thesis work – are an important part of the electrical drive, providing the cooling for the whole electrical drive and other its components. Therefore, for a further understanding of the importance of fans' reliability in the system, it is important to describe the testing process of electrical fans in Electronics Company facilities. To provide an overview of the stress tests, which are applied to electrical drives, and as a result to electrical fans, as a part of the system, this chapter is presenting several examples of test strategies and an explanation of their importance for the reliability evaluation of electrical drive and its components, including electrical fan. Failures and resulting faults on the drive might happen in different components of the system, including the cooling fan and its internal components, which can potentially lead to the overheating of other components. Based on that reason the testing of fans as a separate component is important.

Figure 1 describes the block diagram of all main components of an electrical drive and helps to visualize everything described below in this chapter and understand that the operational capabilities of the main components of the electrical drive, depend on cooling, which is provided by the electrical fan.

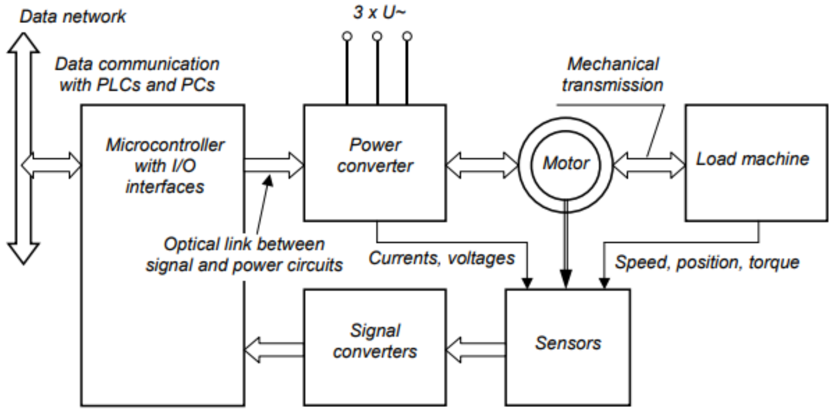

Figure 1. Simplified structure of electrical drive [1].

2.1 What is an electrical drive

Nowadays, electrical motors are utilized in different applications. Those motors are controlled by the input power received from the power supply. However, in between, there is a control part of such a system, which allows more complex and powerful utilization of the available resource. This control part might be built on a simple relay logic and be controlled with the help of humans, or this control can be performed with the help of modern technologies. The system is responsible for safe and precise control of motor and, as a result, control of traction, or other mechanical movements in the system, where it is needed to perform a specific operation.

Power supply. It is an essential part of the electrical drive’s system. Exists several ways how the electrical drive is supplied with power, but the two most used ways are the following: one way is to supply the electrical drive from the same power source, as the motor is supplied, with the help of power conversion schematics and another way is to use the separate supply for control part. The control part uses lower power, compared to the power, required by the motor. The choice depends on the specific application and available sources.

Data network. As the drive has logic, it should be controlled. Thus, the device should be connected to external devices, which are used to be programmed, such as Programmable Logical Controllers (PLCs) or Personal Computers (PCs).

Microcontroller unit. The brain of the system enables different ways of control for the user. Various electronic devices are used to give power of control to the user: timers, Analog-to-Digital Converters (ADC), pulse-width modulators, Microcontroller Units (MCUs), etc.

Power converter. As it is stated by the name, the device converts the power from the supply to the form, required by the motor. The power converter is connected to the microcontroller unit. What exactly gives the user the control over the motor, is not related to mechanical parts, but the control of the power using the preferred logic. With that, the user can set the speed or torque of the motor, required by one or another application.

Motor. It is the electrical equipment that is completing work tasks based on the requirements of the system, in which it is implemented. This equipment is directly dependent on the functionality of the electrical drive, as any operation of an electrical motor is controlled by an electrical drive.

Load machine. The device is moved or driven by the motor. It is another subsystem, which is not reviewed in the frames of this thesis work.

Feedback loop. This part consists of sensors and signal converters. Sensors gather data from the power converter, motor, and load machine. This data is gathered not only to perform proper control but to perform safety-related actions in case of emergency. Signal converters are interconnection between the MCU and sensors, performing translation of the gathered data.

Electrical fans. Electrical fans are not described as a part of the system. The reason is that several separate blocks of the system might need the cooling provided. The location of the cooling element depends on the dimensions of the drive and the mechanical design of the cooling system. In case the electrical drive is used in the home application, components of the system which require active cooling are located in one encasement which is mechanically designed to have a small capacity of space, which needs to be actively cooled, one small fan with the width of 40 millimeters (mm) and height of 40 mm would be enough to fulfill cooling needs. However, in the case of electrical drive implemented into a system like a wind turbine, the mechanical and electrical dimensions of the system are changing. That gives a situation, where several subblocks of electrical drive can be located in separate encasements and require separate active cooling devices of different dimensions, starting from the same 40mm by 40 mm fan, supplied by 24 Volts (V) of Direct Current (DC) and finishing by large dimensions fan of 175mm by 175mm supplied by 230V of Alternating Current (AC).

2.2 Faults classification in electrical drives

Due to the fact, that electrical drives consist mainly of various electronics components, faults observed in such systems are related to electronics of different levels. The majority of faults in electrical drives are related to the defective or malfunctioned parts of the power conversion process. The minority of faults are related to motor, motor feedback, sensors, sensors' signal processing, MCU, and its' programming bugs. Faults can be divided into several main groups [2], [3]:

- Power conversion faults
- Electrical motor faults
- Sensor faults
- MCU and programming faults

Table 1 divides listed faults into two different subgroups: faults that can be identified through measurements and faults which can be noticed visually.

Table 1. Example of failures in electronic subparts of electrical drives.

Measurable	**Visually identifiable failures**
Short circuit	Overheating/burning of components
Open circuit	Delamination of Printed Circuit Board (PCB) layers and other structural failures
Intermittent overheating of connections	Voids

2.3 Drives reliability concept used in industry

Reliability may be generally described as the useful lifetime expectancy of the product on the customer site. Reliability of the single unit of equipment can be evaluated numerically as 1 – Probability of failure = Reliability. However, the reliability of large populations of one or another product will need additional statistical analysis of occurring failures and deriving probabilities, with which one or another device will fail in some amount of time. Companies sometimes assign different meanings to the reliability of their products, so the customer does not usually understand what stands behind the word "reliable". Additionally to that, companies sometimes are stating that reliability is a measure of products' quality. To clarify the term reliability a bit more, it is needed to look at Figure 2, where the typical bathtub chart example for the expected lifetime of the electrical drive, is presented. It is possible to say, that the term "reliability" describes the life of the electrical drive through its expected or estimated lifetime. The frequently met value of the expected lifetime is close to 10 years, if generalized. Drives, designed for particular applications, with a harsh environment or operating cycles might have much less value for the expected lifetime [4].

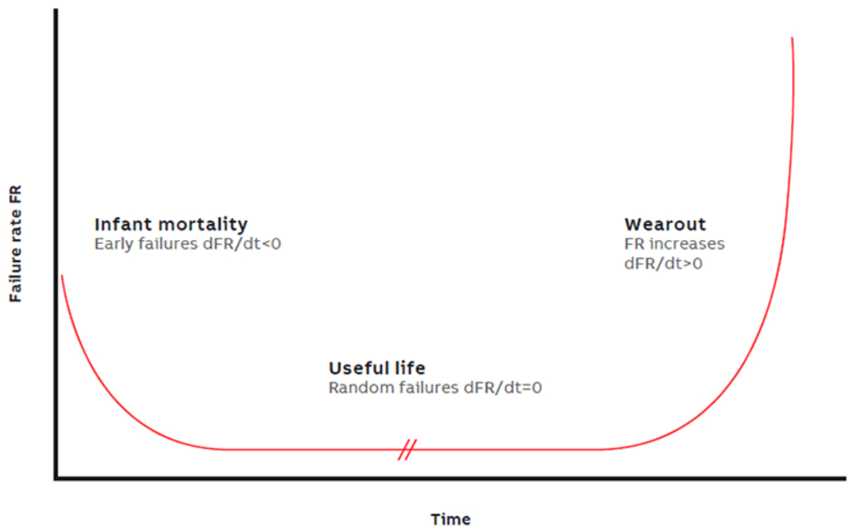

Figure 2. Bathtub curve for expected derives' lifetime [4].

During the infant mortality step, various manufacturing, transportation, storing, or installation-related faults can appear and once the early failures have happened, the failure rate is decreasing (dFR/dt <0 in Figure 2). Useful life is the period when drives are operating without faults and show a high-performance rate. During useful life, the failures are most commonly random failures, and the failure rate remains constant (dFR/dt = 0 in Figure 2). The wear-out period is the step of the lifetime, where the drive may start failing due to the end of the lifetime of some components of the system. As the drive approach, its end of life the failure rate increases with time (dFR/dt > 0 in Figure 2). Reliability plays a big role in power electronics and methods on how to implement more and more "reliability practices" into usage, are discussed. Nowadays, the reliability of power electronics systems and drives particularly was estimated and designed using several general techniques [5]:

- Reliability block diagrams
- Failure modes and effects analysis
- Fault trees
- Markov models

The objective of the thesis is not to describe all the techniques, used for estimating reliability but is aimed to show how the reliability is checked and proven using particular techniques. Proving the reliability of the product is a large topic that requires investments, but the return from these investments can be quite huge and cover all investments for one or another reliability testing project. Such testing helps companies to understand the weakest points of their products and potential places, where financial or time resources can be lost. Companies might have different expectations of their products and different relations with their customers. Based on these two factors lies their desire to run reliability testing projects. One good example of drive manufacturers, whose products are estimated as high-quality electrical drives, is one international company, approaches of which, are represented in this thesis as an example of different reliability testing techniques. Reliability testing techniques can be represented as follows [4]:

- **Highly accelerated lifetime testing (HALT).** This kind of testing is aimed to define the stress level, which the product can withstand, or in other words, the product's operational range. Based on the results of such tests, companies are making specifications for their products.
- **Reliability demonstration test (RDT).** Such a test helps to verify that a product can survive on the customer site under some average conditions, without exceeding limits, as stated by the HALT test for the target time stated by the company.
- **Accelerated lifetime test (ALT).** This test is pretty similar to RDT. The company checks the lifetime of the product, but by applying additional stress factors and waiting for a product not to reach the target but failed (dead state).
- **Highly accelerated stress screening (HASS).** Such type of testing is a part of the production process and the aim behind it is to pass the "infant mortality" step of the product life on the production site, not in the customer's hands.
- **Ongoing reliability test (ORT).** Sense of it is quite similar to the ALT testing, but the aim is not to wait until final failure. The procedure of test is such, that lifetime is accelerated by stress factors for the samples of product, taken out from production with some specific frequency, to define that production does not have any quality issues and is working properly, to catch possible variation in components' quality.

Why those tests are needed and how they influence the lifetime of the product is possible to see in Figure 3 below. With the applied stress factors, the bathtub curve, seen earlier, squeezes in time, and the company can observe failures from different steps, earlier than in real application. And accelerated testing is needed because companies can't wait until full lifetime testing before product launch. What is more, such tests are allowing verification of nominal and defective products.

However, when applying aging acceleration tests, the one, who is defining test conditions, has to be careful during this process and consider that no new failure mechanisms should be introduced with the elevated stress, meaning that the failure mechanisms and modes should be identical between testing and real-life application.

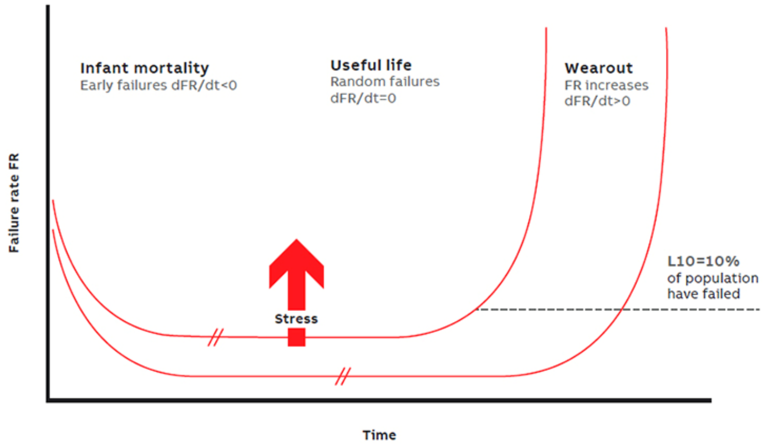

Figure 3. Bathtub curve change with applied stress factors [4].

Nominal and defective products have different ways of acting in overstress and wear-out conditions:

- **Nominal product and overstress conditions.** Ideally, failures in a nominal product should occur only when excessive stress is applied to the product.
- **Nominal product and wear out.** Faults occur after a long operating time and are related to the wear out of inner components of the drive. Such faults should be taken into account during the design step so that customers will not face unacceptable wear-out times.
- **Defective drive and overstress.** The fault is appearing quite soon when stress is applied. The product can not survive a specified time under specified conditions.
- **Defective product and wear out.** Wear-out happens faster than in normal products, faults start to occur earlier than expected.

Based on such parameters and knowing the failure mechanisms of products, the company sets the testing profile for the product. Testing profiles for defining nominal and defective products are chosen according to the matrix, presented in Figure 4 below.

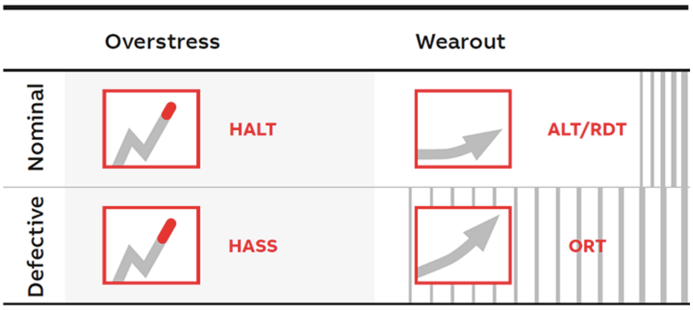

Figure 4. Matrix of test profiles [4].

The last point, important for understanding in choosing test profiles, which is derived from failure analysis is the failure mechanism of components and electronics components particularly. A generalized table describing failure mechanisms and electrical drives is presented in Figure 5.

	Overstress	Wearout
Mechanical	Yield Fracture Interfacial de-adhesion	Fatigue Creep Wear
Thermal	Glass transition (Tg) Phase transition	Stress driven diffusion voiding (SDDV)
Electrical	Dielectric breakdown Electrical overstress Electrostatic discharge Second breakdown	TDDB Electromigration Surface charge spreading Hot electrons
Radiation	Single event upset	Radiation embrittlement Charge trapping in oxides
Chemical		Corrosion, ECM Dendrites & whiskers Depolymerization Intermetallic Growth

Figure 5. Failure mechanisms of electronics devices [4].

2.4 Need in fans ALT testing in Electronics Company

Electronics Company, for which this work is initiated, is working on several component-level test projects. Such projects are meant to get a deeper and more thorough understanding of products’ expected lifetime. Most of the tested units are ready-built products in prototype versions or units randomly taken from production.

There are several main reasons, based on which testing projects of final products’ components are done:

- **New design.** The main reason for reliability testing in Electronics Company is the creation of new product designs and the need for verification of such products.

- **New components vendors.** Vendors of the company are changing from time to time based on specific financial reasons and availability challenges. Products of new vendors should be checked for compatibility with the final product of the company and their influence on the lifetime of the final product overall.
- **New design of components from vendors.** Components vendors might make changes to the designs of components used by the Company. Therefore, the new design of components needs verification.
- **Finding faults before the customer will find them.** The earlier the defect, incorrect design, or faulty components are noticed on Company's side, the more financially efficient such finding will be for the company.
- **Withstanding environmental conditions.** Products of the company might and will be used in various for one product type environmental conditions. The company aims to understand and ensure customers that the product can withstand customers' specific conditions.

The reasons above are described generally for the product. However, reasons for component-level testing and specifically for fans ALT testing can be scaled from the reasons above and will be the same with the minor specifications, based on the specification of components that need to be tested.

3 Fans as electronics equipment

Plenty of standards are used to define and describe fans as the system, their operating conditions, and testing principles according to the classification of fans. Several standards which are discussed further in this thesis and on which the thesis is based, are the following: The American National Standards Institute (ANSI) and Air Movement and Control Association (AMCA) 210 standard (ANSI/AMCA 210), International Organization for Standardization (ISO) 13347, ISO 14694, ISO 14695, ISO 10302, European Computer Manufacturers Association (ECMA) for Standardizing Information and Communication Systems ECMA 275, IPC International IPC-9591 [6] – [14].

3.1 Standards for fans in industrial applications

Out of the standards, mentioned above, ANSI/AMCA 210, ISO 13347, ISO 14694, and ISO 14695 are involving discussions about fans used in industrial applications. An industrial fan, according to the classification of these standards, is an air or gas moving device, which uses power to rotate an impeller, which creates movement. The main parameter of industrial fans is the pressure increase between the inlet and outlet of the machine, which should not increase 30-kilo Pascals (kPa).

Procedures described in those standards are helping with the testing and regulating the quality of fans in industrial applications. Regulations of noise, balancing, and methods for the determination of vibration levels are discussed there. What is more, those standards are used by test engineers for verification of critical parameters in newly developed fans.

3.2 Standards for fans in electronics applications

ISO 10302 and ECMA-275 standards are concentrated on small air moving devices. Small air moving devices are considered fans, the pressure difference of which, on the inlet and outlet is not exceeding 750 Pa. Those standards are concentrated on the description of methods of testing and analyzing the noise and vibrations produced by fans during their lifecycle. Some manufacturers are considering an increase in noise and vibration of the fan as one of the failure criteria based on the standard, which are described further in this chapter, and based on the specific application of manufactured fans.

The next and main standard, which has been reviewed in frames of this thesis work and is directly used by manufacturers, is the standard IPC-9591. This specific document is taking into consideration small air-moving devices which are meant for a specific application – cooling of the heat radiating components in electronics devices. Fans, which are related to the described category are used in electrical drives for cooling aims. Therefore, this standard is the main reference point, used for the research, data analysis, and comparison, aimed to seek possible improvements of component (fan) lifetime testing procedure in frames of the Electronics Company testing project.

3.3 IPC-9591 definition of Air Moving Devices

3.3.1 Main points of the standard

According to the IPC-9591 standard, Air Moving Devices, are devices meant for the cooling of electronics equipment, with the installation directly near the heat-radiating components of electronics systems, such as Central Processing Units (CPUs), radiators, resistors, etc. Another way of installation of the fan in the system, according to the standard, is the installation on the inlets or outlets of cooling channels of specific mechanically designed encasement of the device, cooling of which the fan is providing. The performance of the fan is defined by several main parameters:

- **Mechanical.** The first parameter describes requirements for the internal mechanical components and their design, based on other relevant standards. Mechanical components include bearings and grease. What is more, mechanical parameter undertakes the specific technical parameters of fan performance such as rotor balancing, characteristics of air moving and direction, size and shape of the fan, wiring color protocol, the orientation of the fan, and materials used during the manufacturing of the fan.
- **Electrical.** This parameter defines modes, in which the fan will be operating. Three modes of operation can be derived: Alternating Current (AC), Direct Current (DC), and Pulse-Width Modulation (PWM) modes. Based on these three

modes, the supply voltage level, supplied current level, feedback, and the control loop is chosen and the decision of any other applicable or electrical interface is defined.

- **Environmental.** The third parameter includes a definition of use conditions of the air-cooling device at the customer side and the logistics chain conditions between manufacturer and customer: environmental conditions of storage at the manufacturer side, transportation, and storage at the customer side.
- **Quality and/or Reliability assurance.** As stated in Chapter 3.2, the standard is providing conditions and requirements for manufacturers, based on which the evaluation of the manufactured fan should be done by the producer and allows customers of electrical fan vendors to verify the reliability based on the potential use conditions and products.

3.3.2 Mechanical requirements stated by the standard

Standard IPC-9591 describes mechanical parameters, standards, according to which the documentation of mechanical parameters should be listed, and standards, which describe testing methods of mechanical parameters listed. Table 2 represents the list of mechanical parameters and the main requirements of the parameters listed which shall be provided by the fan manufacturing company to its customer. It should be noted that the testing of mechanical parameters standards should be followed by the manufacturer, but they are not mandatory to be provided to the customer without the customer’s request.

Table 2. Mechanical requirements for the fan according [14].

Parameter	**Requirements**
Bearing Design	Bearing manufacturer information and specification for the exact fan model should be provided to the customer of the electrical fan manufacturer.
Lubrication System	Relevant information about the lubrication technology for the specific fan model should be provided to the customer of the fan manufacturing company by the company.
Rotor Balancing	Evidence of Rotor Balancing results should be presented to the customer of the fan manufacturing company. Quality grade information stated by ISO 1940-1 and the balance speed of the dynamic balancing machine used in the process shall be provided to the customer. Balancing should be done to the complete build model of the fan, not only to the parts of the fan separately.

General Airflow Configuration	The axial, radial, or crossflow airflow configuration of the fan should be described to the customer.
Form	Dimensions and tolerances of the fan should be specified to the customer in form of the technical documentation and engineering drawings by the fan manufacturer.
Orientation	Shaft vertical, inlet up; Shaft vertical, inlet down; Shaft horizontal; Operational orientation not restricted – are orientation modes. The mode of orientation shall be specified for each fan by the fan manufacturer.
Air movement	Airflow specification in form of the “Static Pressure vs. Airflow” curves according to the standard ANSI/AMCA 210 shall be provided to the customer by the manufacturer.
Acoustical	Acoustical noise emission should be provided in the technical document describing the fan specification shall be provided by the fan manufacturer.
Materials	Information about materials out of which the fan is manufactured, and their main technical characteristics shall be provided by the fan manufacturer at the customer’s request.

3.3.3 Electrical requirements stated by the standard

Standard IPC-9591 describes electrical parameters and methods using which the documentation of electrical parameters should be listed. Table 3 represents the list of electrical parameters and the main requirements for the listed parameters, which shall be provided by the fan manufacturing company to its customer, with the reference to Annex 2 of this document, which shows the list of parameters, required to be identified.

Table 3. Electrical requirements for the fan [14].

Parameter	**Requirement**
Power Waveform Type	As described in Chapter 3.3.1, electrical fans can be powered by an AC, DC, or PWM source. The supply source required for the specific fan type shall be provided by the fan manufacturer.
Voltage, current, frequency	Operation ranges of three parameters listed, for the specific fan type, shall be stated by the manufacturer to the customer. The customer in its turn, shall not operate the electrical fan outside the rated values of these three parameters.
Fan Speed Control	Various fan models might have a built-in speed control feature. If the presence of the feature is specified by the fan manufacturer, then parameters of the speed control should be specified correspondingly. Fan manufacturer shall provide the speed dependence curve depending on the parameter, which determines the speed control. The curve must include at least 10 points of dependency and shall be provided to the customer.

Tachometer signal specifications	Output type of the tachometer, pulses per revolution, rotational speed output of the tachometer in the range of ±1% of the actual Revolutions Per Minute (RPM), and the “locked rotor” sensor parameters (if such is present in the fan) shall be provided to the customer by the fan manufacturer.
Summary of Electrical Requirements	The document, compiled as the summary of electrical parameters described in standard IPC-9591 is presented in Appendix 2 of this thesis. The list of parameters specified in the Appendix is the real representation of the electrical specification of the fan, which shall be provided by the fan manufacturer to the customer.

3.3.4 Environmental requirements stated by the standard

Standard IPC-9591 describes operational parameters and methods using which the documentation of environmental parameters should be listed and proven. Table 4 represents the list of nonoperating (storage and shipping phases) and operating environmental parameters and the main requirements of the parameters listed which shall be provided by the fan manufacturing company to its customer.

Table 4. Environmental requirements for the fan [14].

Parameter	**Requirement**
Nonoperating shipping and storage requirements	The manufacturer of the fan shall provide requirements for temperature and humidity ranges allowed for the storage or shipping of the fan. General requirements provided by the standard are presented in Figures 6 and 7 below. Additionally, the manufacturer shall test limits for the altitude, shock, and vibration with no less than five units from the batch and shall provide results of testing to the customer, in case of such request. After two years of storage/shipping environment, units of the product must be requalified (retested). Only one requalification round for another two years of such conditions is allowed. Fans shall meet specific nonoperating shock, nonoperating shock, and vibration limits. These limits can be used for the simulation of the environment to which fans have been exposed while being in the shipment or storage phase.
Operating environmental limits	Operating temperature and humidity limits should be stated in the fan’s technical specification. The fan should stay operating and withstand such an operating environment for a stated by the manufacturer lifetime. Information about limits should be provided to the customer. Corrosion and dust protection levels should be provided by the fan manufacturer As Agreed Upon Between the User and Supplier. If the dust protection of the fan has not been discussed with the customer, then it shall be provided according to the dust category description in the standard by International Electrotechnical Commission (IEC)-60529.

Figures 6 and 7 represent requirements stated by the standard IPC-9591 for the temperature and humidity ranges, in which it is allowed to store or ship the fans from the manufacturer to the customer. What is more, those limits can be used for the simulations of the nonoperating environment in case of such need.

Temperature Ranges Equipment & Peripherals	-40° to 70°C [-40° to 158°F]
Temperature Gradient Maximum per 60 Min.	20°C [36°F]

Figure 6. Nonoperating temperature ranges for storage and shipping of fans [14].

Humidity Percent Ranges Noncondensing (Wet bulb max = 38°C)	5 to 95%
Humidity Gradient Maximum per 60 Min.	20%

Figure 7. Nonoperating humidity ranges for storage and shipping of fans [14].

All the described requirements for fan manufacturing, fan operation, transportation and storage conditions, and testing requirements, discussed in IPC-9591standard have been taken into consideration during the preparation of improvements to the existing test procedure and setup.

4 Fans’ construction and reliability concept

The typical cooling fan consists of the impeller, electrical motor, bearing, and small electronics control unit, which typically is a Printed Circuit Board (PCB). The testing of fans is needed to define whether one of those components influences the reliability of the whole system (fan) and what are possible outcomes in case of unreliable components’ presence in the system. Fan as a system is part of a larger system. In the frames of this work, this system is an electrical drive. Interest in the project is conditioned by the need to verify that the cooling of the system (electrical drive) is efficient enough and has a reasonable influence on system reliability.

4.1 Fan structure overview

An example of the typical fan motor structure is shown in the schematic cross-sectional drawing in Figure 8. As it is represented in Figure 8, it is possible to derive seven main constituents of the motor: rotor, stator, hall sensor, ball bearing, stator winding, permanent magnet, and the commutating electronics which are designed as the small PCB unit and placed inside the fan.

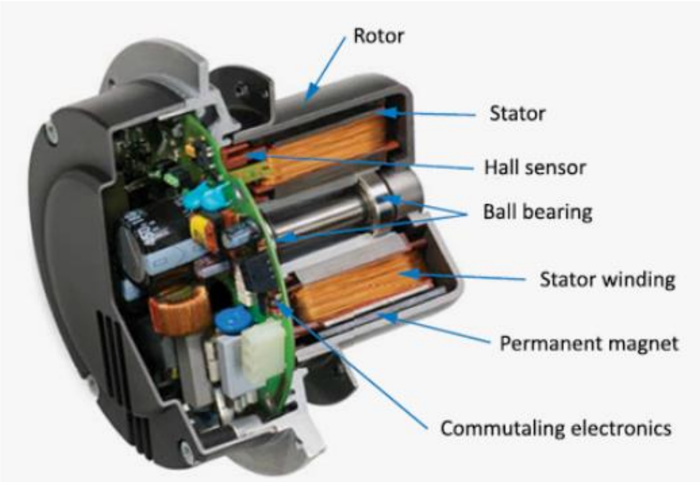

Figure 8. Typical structure of fans’ motor [15].

In the frames of the testing project and this thesis, several fan samples have been disassembled for the overview, comparison, and analysis of the fan’s components. An example of the disassembled fan, used for the electronics equipment cooling, is presented in the following figures.

Figure 9 shows the fully assembled fan example from the top and bottom sides. Further assumed that the left part of the figure represents the bottom side of the fan, right part represents the upper side. “Top” and “bottom” markings have been assigned based on the airflow direction of the fan, markings of which are stated in the datasheet and housing of the specific fan model. The “Bottom” side is the air inlet side of the fan. The “Top” side is the air outlet side of the fan.

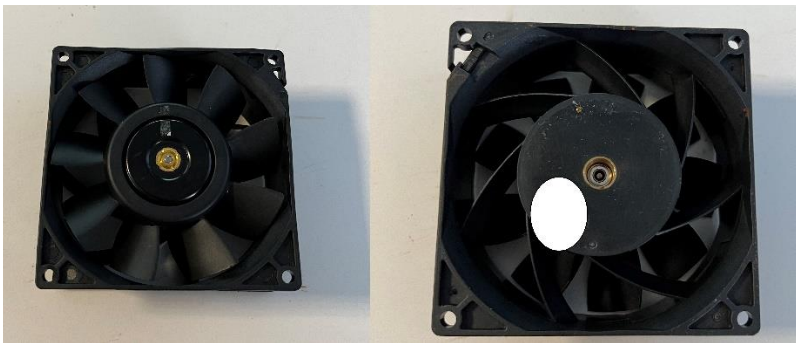

Figure 9. Example of the assembled fan.

Figure 10 represents the disassembled fan and part of the components, marked on the picture.

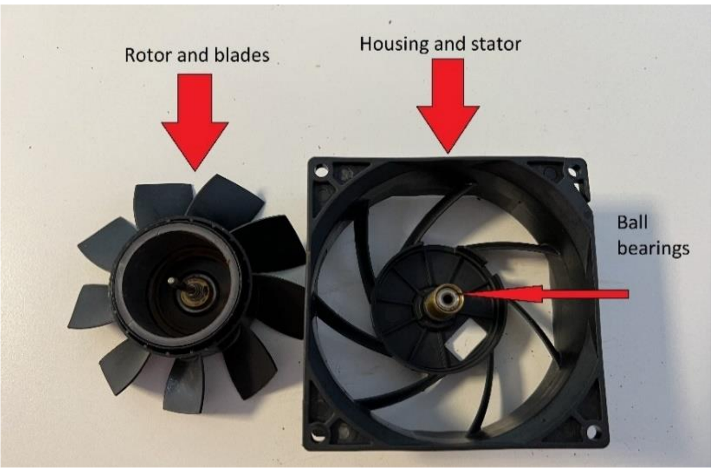

Figure 10. Components of the disassembled fan.

Figure 11 shows the more detailed view of the stator of the fan, and its winding, together with the commutating electronics circuit mounted on PCB.

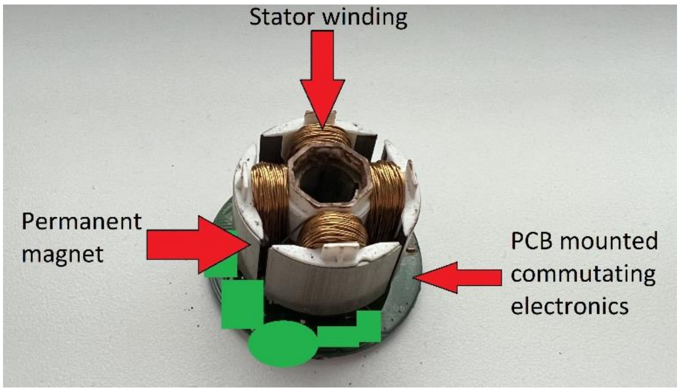

Figure 11. Stator winding, permanent magnet, and electronics of the fan.

4.2 Fans' reliability concept

Reliability term in terms of electronics cooling fans generally has the same meaning as for the whole concept of electronics reliability. In simple words, the reliability concept of electronics components or systems represents the time, during which the component or system can operate normally, without faults in specified environmental conditions. The reliability of components or systems is a function of time, which represents how frequently failures are appearing in one or another product [16].

According to the main standard, discussed in this thesis, IPC-9591, four main points should be specified and provided by the manufacturer to the fans' user. These four points are described in Table 5 below.

Table 5. Lifetime estimation requirements for the fan [14].

Parameter	**Requirements**
Reliability oriented design	The estimation of the reliability of the manufactured fan, including its mechanical and electronic components of it, shall be provided and explained in the best way for the user of the fan by the fan manufacturer.
A lifetime of bearing used in the fan production	The supplier is responsible for estimation and providing to the customer the corresponding results of the bearing's grease life calculation and bearing load rating life approximation. Bearing load rating life approximation should be completed based on the standard ISO 281, 12-1, "Rolling Bearings – Dynamic Load Ratings and Rating life".
Lifetime of electronics	As a measure of the lifetime of fans' electronics components, the Mean Time To Failure (MTTF) metric is used. The estimation of the MTTF is the responsibility of the fan manufacturer. The MTTF estimation should be calculated for the following usage conditions: 40 degrees Celsius (ºC) of surrounding temperature at nominal input voltage specified for the fan model. Such estimations should be done according to the standard Military Defense

	Handbook (MIL-HDBK)-217 or Bellcore/Telcordia SR332. Fan manufacturer shall specify the quality level used during the estimation to the customer.
Derating of used components	Fan manufacturer is responsible for the assuring inappropriateness of the derating of all electronic and mechanical components. Mechanical and electrical designs including relevant materials shall be provided by the fan manufacturer to the customer in case of such request. The method used for derating components is chosen based on the fan manufacturer's estimation if no other conditions have been discussed by the manufacturer and customer.

4.3 Fans' components failures

Fans for electronics cooling purposes, like any other electro-mechanical devices, have failures related to components, described in part 4.1 of this chapter.

Failures in fans can be categorized into two main categories: mechanical and electrical. Each of these categories has its failure modes, causes, and mechanisms. In tables 6 and 7 below, the most critical failure modes for fan components are described. Failure Modes and Effects Analysis (FMEA) represented in the following tables is the result of the analysis of research available on the fans' reliability topic and based on the analysis of testing results conducted by the author. Table 6 represents FMEA for mechanical components of electronics cooling fans. Table 7 represents FMEA for electrical components of fans [17], [18].

Table 6. Main failure modes, mechanisms, and causes of fans' mechanical components.

Components	**Failure modes**	**Failure mechanisms**	**Causes of the failure**
Blade	Cracking of component	Fatigue	Cyclic thermal and mechanical loads
	Unwanted growths on the surface	Adhesion	Dust, presence of various particles in usage conditions
	Disbalance	Adhesion	Unwanted particles, cracks on the blade surface
Stator	Winding wire film cracking and peeling	Aging of insulating materials related to thermal cycling	Cyclic thermal and mechanical loads

	Displacement of the stator	Aging of the glue between the inner components of the fan	Thermal cycling in addition to mechanical loads
Housing (frame)	Cracking of component	Fatigue	Cyclic thermal and mechanical loads
	Friction	Blade touching frame during the operation	Cyclic thermal and mechanical loads, aging of other inner components
	Unwanted growth	Adhesion	Dust, presence of various particles in usage conditions
Ball-bearing	Brinelling	Yielding	Mechanical overload
	Seizure	Lubricant degradation	Cyclic thermal loading/overloading
	Furrows occurrence	Corrosion	Moisture
	Spalling damage	Fatigue	Cyclic thermal and mechanical loading

To summarize Table 6, it is needed to say that most of the causes of fans' failures are related to mechanical (operating) and thermal stressing of the devices. Another popular cause is the presence of dust and other external particles inside the fan. The least spread cause of failure for mechanical components, but a reasonable cause, is the moisture present in the system. Failures related to the design or manufacturing process, which make fans not operational from the zero time, have not been discussed in this FMEA.

Table 7. Main failure modes, mechanisms, and causes of fans' electrical components.

Components	**Failure modes**	**Failure mechanisms**	**Causes of the failure**
Fan's control circuit PCB	Short circuit	Dendritic growth	Voltage bias, moisture, corrosive gases
		Interconnection of components	Unwanted growth, side particles present on components, dust, usage environment, insulation cracking
	Open circuit	Interdiffusion	High-temperature environment
		Corrosion	Moisture or corrosive gases

	Solder joints cracking	Fatigue	Thermal and mechanical cyclic loading
Wiring	Open circuit on wire bond	Delamination	Thermal or mechanical shock
	Short circuit	Interconnection of components	Insulation cracking, de-adhesion, wire braking
	Insulation cracking	Fatigue	Thermal and mechanical cycling/overload
	Wire breaking	Delamination	Thermal or mechanical shock
		Fatigue	Aging of material due to cyclic mechanical and thermal stress

Table 7, same as Table 6 presents the thermal and mechanical stresses as the main cause of failure in electronic components of fans. Moisturized environment has an impact on a larger number of failures in electronics components than it has been in mechanical components. What is more, in both tables it is possible to notice that the causes of some failure modes are results of other listed failure modes. Such tendency has been noted during the analysis of test results. It has been noticed that some failure modes, like wire insulation cracking, are not influencing the performance of the fan directly, but in the long run, it becomes the cause of the short circuit failure mode.

The FMEA is derived based on the research and analysis of failures, completed in frames of work on this thesis, in this chapter of the thesis shows the main failure modes and their causes. Analysis of failure mechanisms is the basement for the explanation of the need in ALT testing and how those failure mechanisms are or can be applied later in the testing process. Effects of all the listed failures, both mechanical and electrical components related, in this specific case of use of cooling fans, are generalized to one local effect - loss of cooling or decrease in cooling effectiveness in the electrical drive. Specific next higher level effects are discussed in other testing projects of Electronics Company, out of the scope of this work.

5 Fans' reliability and endurance testing

This chapter of the thesis aims to describe the requirements set by the IPC-9591 standard for the reliability assessment of fans used by Electronics Company and electronics company vendors. What is more, test strategies of Electronics Company vendors are briefly discussed to give the reader an understanding of that and to provide the comparison of test strategy used in Electronics Company. Such comparisons provided in later chapters of the thesis are delivering points of improvements to the test strategy used by the Electronics Company.

5.1 Fans' reliability assessment based on IPC-9591

The standard IPC-9591 clearly describes requirements for the test conditions and test facility in which the reliability assessment of electronics cooling fans shall be completed. Table 8 concludes such requirements into one list.

Table 8. Test and measurement requirements for fan-testing [14].

Parameter	**Requirement**
Failure criteria	Rotational speed reduction of ≥15% of initially measured RPM shall be considered a failure.
	Increased current consumption of ≥15% of initially measured current shall be considered a failure.
	Acoustical noise emission with an increase of more than 3dB over the initially measured sound level, under specified operating conditions, shall be considered a failure.
	The malfunctioning electronic interface of fans shall be considered a failure.
	Visible cracking of the housing, impeller, or guards shall be considered a failure.
	Noticeable leakage on greased/oiled components and/or not tight bearing seals shall be considered as a failure.
Test chamber	The temperature in the test chamber, on the inlet of each separate Device Under Test (DUT), which is the fan, in this case, shall not be different from the average temperature in the test chamber in the range of ±3.0ºC.

	Test chamber dimensions are reasonably large, to allow testing of the larger amount of population and to avoid the influence of DUTs on each other.
Fans operating orientation	All possible fan operational orientations, specified for the fan model, shall be tested and the test results together with the test data for specific orientations shall be provided by the fan manufacturers.
Sample size and life test time	The sample size (population) of the test is defined by the manufacturer or by the party which is completing the testing. Sample size directly affects the confidence level of the life test and life test duration. With the larger sample size, test time can be shorter, and it gives better visibility of component-to-component variation.
Temperature stress and test time	Test time is related to the applied temperature stress in the following way: the higher the temperature stress, the lower can be testing time, and vice-versa. Standard recommends an acceleration factor that should be applied when using the L_{10} test strategy, which is discussed further in this thesis work.
Measurement conditions	Fan manufacturers or the party conducting the test shall conduct measurements of all parameters listed below before the testing (at time zero). All the listed parameters should be measured after each restart of the DUT within 15min.
	Speed measurements shall be conducted each 200h of testing or monitored continuously.
	Current measurements shall be conducted each 200h or monitored continuously during the testing.
	Acoustic noise measurements require additional start/stop cycles, the number of which shall be specified. Measurements shall be conducted each 1000h or as agreed between manufacturer and customer.
Periodic start/stop operation	Start/stop cycling should be performed once per 24 hours of testing. DUT should be powered “off” for 5min and after that powered back “on”.

Understanding and clarifying the requirements mentioned in the standard are important for the further understanding of the quality of vendors testing and applying test principles on the Electronics Company site.

5.2 Fans’ reliability assessment by vendors

In frames of the improvement of the existing test procedure which is in usage in the Electronics Company, discussions with the fans’ vendors and a review of their test specifications have been completed. Based on the analysis of provided confidential materials and discussions, it is possible to conclude that several main fan vendors of the company are actively using and providing testing of their production based on the IPC-9591 testing requirements.

IPC-9591 standard gives room for adjusting test conditions, and measurements based on specific customer needs. For that reason, after analysis of the provided material, it has been concluded that vendors have some conditions, applied in the test differently. The main difference lies in measurement frequency and way of measurement. Different vendors use different time gaps in measuring frequency or continuity of measurements. Those time gaps are acceptable by the standard range and the standard does not specify the influence of the measuring frequency on the quality of results of testing.

To conclude everything stated above, it is needed to say that vendors are complying with the required standards of testing. Such testing stresses the fan as the system with all its components. However, when using the life test calculations, for analysis of test results, provided by the standard IPC-9591, the testing party metrically evaluates the influence of temperature as of acceleration factor, without evaluating other acceleration factors which might be applied during the testing, and which influence the lifetime of bearing and other mechanical components of the fan. For that reason, the estimation of the lifetime of the fan based on the testing results, used by the Electronics Company, includes additional acceleration factors which reflect the influence of other acceleration factors on mechanical and electrical components' theoretical aging on the fan testing time on the Company site.

6 Description of the existing test setup and procedure

The history of the development of the test setup and test procedure is relatively long, and some improvements have been completed without the participation of the author of the thesis work. Chapter 6.1 aims to briefly describe the status of the test chamber and procedure from the begging and until the last test chamber update in 2019, from where the main improvement points implemented as the result of this thesis work have been later derived. Chapters 6.2 and 6.3 aim to describe the status of the test chamber, its features, and the status of the test procedure after the last update in 2019 and as of the moment of the beginning of the work on this thesis and as a result derive the weak points of that.

6.1 The first milestone of the testing project

The design of the first version of the test setup has been introduced about 8 years before the first updates have been initiated. The representation of the first model of the "fan-tester" is shown in Figure 12.

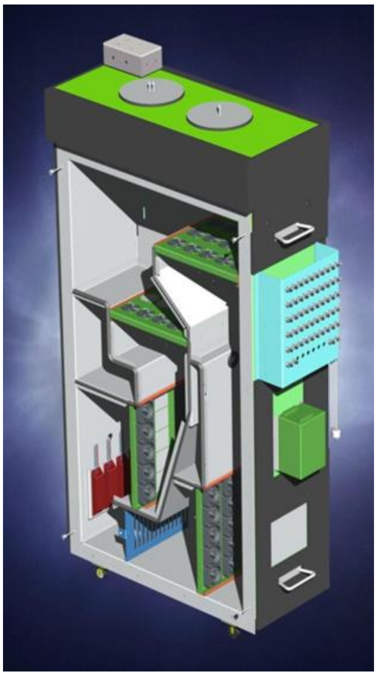

Figure 12. Example of the first model of the fan-testing test chamber.

A test chamber can be generally described as a metal chamber, thermally insulated to avoid temperature losses inside the cabinet during the testing, with an enclosed air-moving contour, visible if looking at the cabinet physically, the air inside of which is moved by the DUTs. Cabinet has had 4 places for the installation of “test jigs” or “test stands”, on which, depending on the size of tested fans, have been installed a specific number of fans. The enclosed air-moving contour between stands with DUTs is represented in Figure 15 later in this chapter.

Cooling of the cabinet, to keep the stable temperature inside the cabinet during the test has been done by two fans, mounted on top of the cabinet, providing the air movement inside the enclosed contour. The walls of the cabinet are metal, and the mentioned enclosed air contour has been passing between the outer wall of the cabinet, which has been thermally insulated, and the inner wall of the cabinet, another side of which is located in the enclosed contour with DUTs located in it. As the mentioned walls are metal, the cabinet cooling fans have allowed cooling of the inner wall with the cooled air by pushing this air into the close contour, when they are operating. The process of the operating cooling fans based on the signal of the temperature controller is described further in this chapter.

Control of the DUTs and the test procedure have been realized manually, except for the temperature control inside the test chamber. The equipment, which has been used has been the following:

24V power supply. A usual power supply, which has been powered from the 230V AC from the socket and has been able to produce an output of 24V DC and a current of up to 32 Amps (A), without the possibility to regulate the output voltage of the power supply.

Manual two-pole switches. Each DUT in the test chamber has been connected to the 24V power supply through the two-pole electrical switch. Availability of switches in the test setup allowed to control each of the DUTs separately to comply with the IPC-9591 standard requirement of stop/start cycling of fans during the testing, discussed in Table 8 of Chapter 5.1.

Resistors inside the cabinet. Resistors, placed at the bottom of the test cabinet have been used as a heating element which has provided a stable high-temperature condition inside the test cabinet. Totally 8 resistors have been used, with 4 resistors on each wall of the cabinet. All of them have been connected in series and connected to the same 24V power supply of the system. A resistor of each of the components is equal to 3.3 Ohms (**Ω**).

Temperature controller of the cabinet. To keep the temperature level stable throughout the test, the temperature controller has been used the control the cabinet cooling fans. The temperature controller used in the test setup has been powered by 230V AC from the same power supply and had a 24V DC output channel, output on which have been controlled by the specific option module of the controller. The specific model of the option module, which has satisfied the need for temperature control in the testing, has been acting as the system's cooling fans voltage regulator. The temperature inside the cabinet has been measured by the thermocouple of J-type inside the test cabinet. When the temperature exceeded the temperature setpoint (85 ºC, used in the test) for more than the set temperature value (>3ºC has been used as a value in the test), the controller have been starting gradually outputting voltage on the earlier mentioned 24V DC output channel, directly connected to the supply channels of fans used for the cooling of the cabinet. The output voltage has been at 10V DC, which have been the minimum required voltage for the cabinet colling fan to start rotating with the minimal speed and cool down the cabinet back to the setpoint temperature. In case the minimum rotational speed of cooling fans has not been enough for cooling, at a specific time moment, and the temperature continued rising, the supply voltage of the fan has been linearly increasing to increase the fan rotating speed and make cooling more effective.

Measurements during the testing. Out of three important measurements, which have been described in Table 8 of Chapter 5.1 and which should have been conducted to verify fan failures, only one has been applied. Current measurements have been conducted once per agreed unit of time, which have been less than the minimum required time by the standard. To complete measurements, the test has been stopped and the current has been measured on all DUTs separately. Measurements of the speed of the fan and the noise level have not been conducted.

6.2 Updates of the cabinet in summer 2019

During the summer of 2019, the modification of the test chamber was initiated and completed. The reasons for the modification have been related to the increased need for testing new fan models and the automation of the test in possible ways with the existing test chamber to increase the repeatability of the testing. During the traineeship completed at Bachelor level studies, the author of the thesis has been participating in consultation meetings aimed to discuss possible ways of automation the setup and later have been completing the building of the setup based on agreed schematics.

From the cabinet and its features described in Chapter 6.1, the chamber itself left without mechanical improvements, and the temperature control system, with the used temperature controller, cabinet cooling fans, and the enclosed air contour meant for the cooling of the cabinet stayed the same as in the first version of the setup. What has been improved is the electrical and control part of the test chamber. The main improvement points have been the following:

The power supply of the cabinet. During the modification, the test chamber has gotten two separate power supplies with a regulative output voltage of up to 32V DC, one of which is controlling the test chamber electronics, and a second one is responsible for supplying only DUTs. That has been solving two main problems: the influence of the power consumption of the test chamber on the DUTs and allowing for regulating the supply voltage level of DUTs. Regulating the DUTs' voltage level has been discussed as one of the stress factors: an increase of 10% compared to the nominal supply power level is influencing the acceleration of the lifetime of fan electronics. The power supply level of the test chamber has stayed at the level of 24V, as required by the components used in the electrical setup.

Electronics protective circuitry. Due to the increased amount of the new electronics components in the setup, the protective circuitry has been designed and implemented. What is more, additional protective circuitry has been designed for DUTs, to protect them and minimize the influence of possible hysteresis in the network on DUTs. 24V circuit breakers have been installed for each of the DUTs (amount of DUTs and description of their installation and connections are discussed further in the chapter).

Timing logic. Thanks to the built-up relay logic implemented into the system timer, the need for the temperature cycling control has been fulfilled. The need for temperature cycling has been based on the developed test specification and strategy used for lifetime estimation, which is discussed in Chapter 7.

Measurement circuitry. The circuitry, which allows the continuity of current measurements during the test has been designed and implemented. For the continuous time-adjustable current measurements the Keysight Local Area Network (LAN) extension for Instrumentation (LXI) Data Acquisition/Data Logger Switch unit 34972A has been taken into usage. This device allowed to continuously monitor the current consumed by DUTs. In a later built setup newer Keysight Data Acquisition System (DAS) DAQ970A has been taken into usage, due to the obsolesce of the previously used model and extended list of data gathering opportunities [19], [20].

6.3 Description of the DUTs installation and airflow in the test chamber

This chapter is aimed to describe the construction of the test chamber in detail and discuss some of the aspects of the test procedure, which are needed for an understanding of improvement points, the implementation of which is described further in this thesis.

6.3.1 Test jigs and amount of DUTs

The first step in the DUTs installation process is defining the fan dimensions and choosing the test jig appropriate for fan model dimensions. Several specific dimensions of used fans have been derived from the Electronics Company's product portfolio and testing needs. Corresponding test jigs have been designed for the test chamber. Depending on the dimension of the tested fans, each test jig has a corresponding amount of test places. The dependency of the DUTs sample size from the DUTs dimensions is described in Table 9 below.

Table 9. Size of DUTs and amount of DUTs in one testing round.

DUTs dimensions	**Amount of DUTs on one test jig**	**Number of fans of one size in one test chamber**
40mm width by 40mm heigh	20 DUTs	40 DUTs or 80 DUTs with the installation of an additional current measurement device (Data Logger or DAQ)
60mm by 60mm	15 DUTs	40 DUTs or 60 DUTs with the installation of an additional current measurement device (Data Logger or DAQ)
80mm by 80mm	9 DUTs	36 DUTs

92mm by 92mm	6 DUTs	24 DUTs
120mm by 120mm	4 DUTs	16 DUTs

The amount of the DUTs in one test chamber is directly dependent on the dimensions of the tested model. The amount of the DUTs or so-called population of the test, as discussed in Table 8 of Chapter 5.1, directly influence the testing time, a calculation example of which is provided in Chapter 7.

6.3.2 Preparation of DUTs

As the next step of the DUTs installation process is the preparation of DUTs and installation onto test jigs.

Preparation of DUTs is meant for the preparation of wiring of DUTs. First of all, the length of the wiring should be checked and verified whether that length is suitable for connecting DUTs inside the test chamber. In case the length is not suitable, wires should be extended through soldering. That process can be divided into three steps: DUTs' wires stripping and preparation of extension wires, soldering extension wires to DUTs wires and covering soldering points with the heat shrink tube to avoid possible short circuit caused and failure of the test caused by the test setup (later called as setup-related failure). The process is visualized in Figure 13.

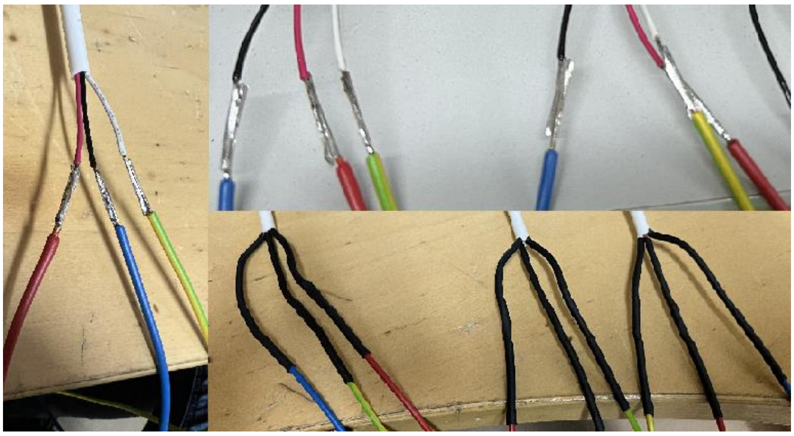

Figure 13. Soldering and heat-shrinking step of preparation.

In case the wire's length is enough long for making connections inside the test chamber, wires should only be prepared through wire stripping and installation of conductive wire end caps of the proper size on the ends of each wire, which will be connected, to the DUT.

6.3.3 Installation of DUTs

The last step is the installation of DUTs on test jigs and the installation of test jigs into the test chamber.

Installation of each DUT on the test jig should be done carefully, using the screwdriver with adjustable torque and the torque should be adjusted according to the value, specified by the fan model's datasheet or the assembly manual of the product, in which the fan is used. An example of the installation of the fan on the test jig is presented in Figure 14.

Fans on the test jig should be fixed with screws suitable for one or another dimension of the fan. Orientation of the fan should be chosen based on the number of test jigs and its further allocation in the test chamber. The direction of wiring should be adjusted in such a way, that wires will not face additional tension and will have a suitable length for the connectivity inside the test chamber.

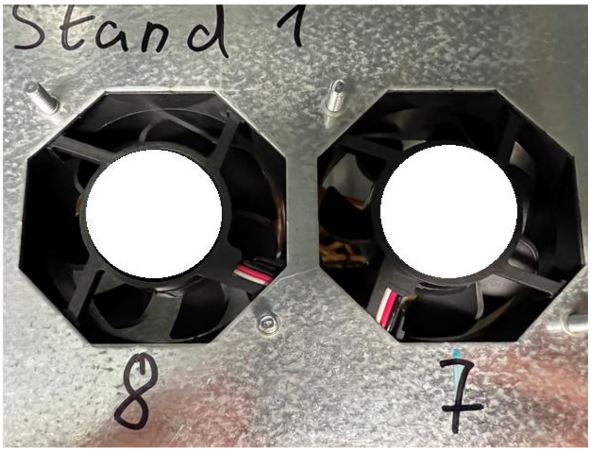

Figure 14. Fans installed on the test jig.

After installation of DUTs on one test jig, the test jig should be placed into the test chamber, into the slot with the corresponding number.

6.3.4 Test chamber, slots' location, and airflow direction

An important point during the installation of test jigs into slots is the installation of jigs into corresponding test slots, which are marked on each test jig and each test slot of the test chamber. Depending on the slots and orientation of blowing fans installed on each test jig, the correctness of the airflow direction inside the chamber is determined. Figure 15 represents the location of test jigs' (stands') slots and corresponding numbering inside the test chamber, together with the desired airflow inside the test chamber.

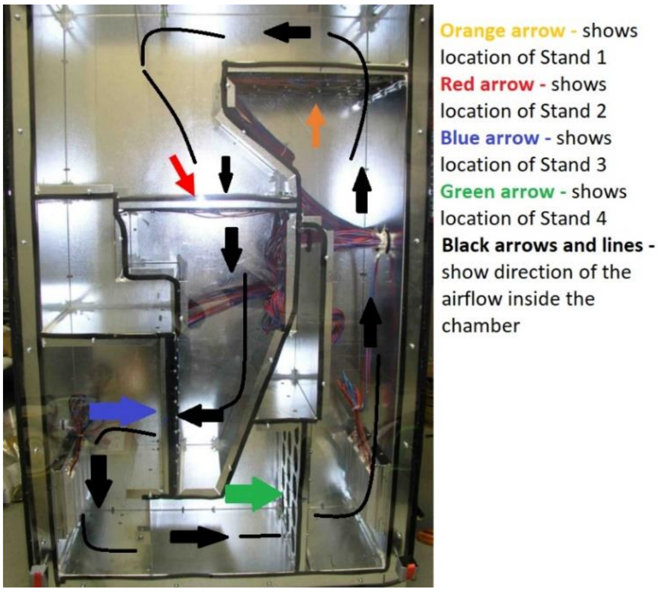

Figure 15. Test jigs' location and airflow direction representation.

Such pre-determined airflow direction gives an understanding of how the DUTs should be installed on each test jig and determines the variation of blowing orientation used in the testing, which is required by the standard and is discussed in Table 8 in Chapter 5.1.

Test jig 1. Fans' blowing orientation should be directed upwards, jig located horizontally in the slot, which gives a possibility to test fans' vertical upward orientation.

Test jig 2. Fans' blowing orientation should be directed downwards, jig located horizontally in the slot, which gives a possibility to test fans' vertical downward orientation.

Test jig 3. Fans' blowing orientation should be directed upwards on the test jig, jig located vertically, directed to the left, which gives a possibility to test fans' horizontal orientation directed to the left.

Test jig 4. Fans' blowing orientation should be directed downwards on the test jig, jig located vertically, directed to the right, which gives a possibility to test fans' horizontal orientation directed to the right.

Such orientation of fans and specification of the airflow direction inside the chamber gives compliance with the standard IPC95-91, which states that fans shall be tested in all possible directions specified by the datasheet of the fan model.

7 Aging principles

This chapter of the thesis work is aimed to describe and analyze principles, of aging estimation described by the standard IPC-9591, aging estimation used in the testing in the Electronics Company, and one Fans-Manufacturing company taken as an example. Standard requirements for the testing environment and reliability verification, stated in IPC-9591, describe two ways for estimating the reliability of electrical fans: MTTF and/or L10. All three examples of aging calculations, derived in the following sub-parts of this chapter, are based on L10 metrics. The used metrics allow having the 10% failed DUTs out of one whole test population, tested in the common environment.

7.1 Aging estimation according to IPC-9591

The acceleration factor, proposed by the IPC-9591, is equal to 1.5 per each 10 ºC increase. This recommended factor shall be used by fan-manufacturing companies in datasheets provided to the customers, to describe the reliability of fans. To evaluate how much the lifetime of the fan has been accelerated, during testing, four main parameters are used: test time, test temperature, and expected operating conditions.

Expected operating conditions, is the temperature (To) at which the fan is expected to be operating during the whole stated expected lifetime. For the example calculations, a 50ºC value is taken. Test time is the time, during which the DUT has been operating in conditions, more extreme than stated by the datasheet, typically temperature-wise, also noted in calculations as the lifetime at the test temperature ($L10_{Test\ temperature}$). For the example calculations, a 15000h value is used. Test temperature (Tt)– is the temperature value of conditions, under which fans have been operating during the testing. This temperature value should not exceed the maximum allowed temperature design value stated in the datasheet of the fan. For the example calculations, an 80ºC value is used.

An example for calculations is the following. The fan has been subjected to testing in conditions of constant 80ºC temperature - T_t. The time, during which the fan has stayed operational, based on its functionality and criteria stated by the IPC-9591, 15000h - $L10_{80}$.

Calculation aims to project the lifetime from the test to the fan's real operating conditions of 50ºC – T_o. As it is stated at the beginning of this chapter, the recommended acceleration factor is 1.5 per each 10 ºC, from which, the formula for calculations is derived. Lifetime at the test temperature should be multiplied by the acceleration factor of 1.5 in the power of difference, between test temperature and operating temperature, divided by 10. Final formula is following: $L10_{To} = L10_{Tt} \times 1.5^{(Tt-To)/10}$, which for derived example is giving following result: $L10_{50} = L10_{70} \times 1.5^{(70-50)/10} = 15000 \times 1.5^2 = 33750h$. The result of example calculations shows that the fan, designed to work in specific temperature conditions, will work for the estimated time, in case it has passed the testing in stated testing conditions.

7.2 Aging estimation used for example fan-manufacturing company

An example of one electronics manufacturing company, components of which can be met in various electronic devices, and which has the fan-manufacturing, as a part of its portfolio, shows how the company is evaluating and calculating the lifetime of fans based on design and ALT testing. The company states that the tests, held by it are standardized according to IPC-9591. That gives a background that L10 metrics are also applied in the ALT testing done by this company together with the parametric evaluation of failure modes utilizing RPM and current measurements, to verify that reduction or rise of values of those parameters have not happened during the testing. For the prediction and evaluation of the lifetime of fans and cooling devices, the company uses the Arrhenius relation. Equation (1) represents the general Arrhenius life-stress relationship, where L – represents a quantifiable life measure, which is a scale parameter, V – represents the stress level applied to the component, C - is an aging model parameter defined by test specification, B – is another aging model parameter defined by test specification, e – is the activation energy. Such a relationship is used for an estimation of the simulated lifetime of the cooling fan by the Electronics Company, with applied modifications, which are described in Chapter 7.3 [21] – [23].

$$\eta = L(V) = C \cdot e \frac{\beta}{V} \quad (1)$$

7.3 Aging estimation used in Electronics Company

The Electronics Company's engineers have developed a test time calculator and the lifetime calculator as tools for the more effective evaluation of the lifetime of fans provided by vendors and proven by the results of the testing described in this thesis work.

As can be noticed in Figure 16, which represents the test time calculator, Electronics Company has derived three Acceleration Factors (AF), named in the figure as A, B, C, and D.

Target lifetime		years	Test temperature		°C
Target reliability	90	%	Use temperature		°C
Sample size	48		Temp. Coefficent	1.5	
Component beta	3		AF	3.38	Simple version (A)
Confidence level	95	%	Power switching freq use	1	
Characteristic life	0	hours	Power switching freq test	270	
Acceleration factor	3.50	D	Power on time ratio	92.8125	%
Required simulated life	0	hours	AF	6.00	Including power switching and power on time ratio (B)
			Activation energy	0.8	eV
Test time	0	hours	Boltzmann constant	8.62E-05	eV/K
	0	days	AF	1.00	Arrhenius (C)
	0	weeks			
Test run hours per day	24	hours		3.499377	B and C average (D)
Test run days per week	7				

Figure 16. Representation of the test time calculator derived by Electronics Company.

AF A – a simple version of life and test time evaluation has been derived using the acceleration factor calculation proposed by the IPC-9591 standard and is similar to the example calculations provided in Chapter 7.1, with consideration of specific test temperature conditions and specific fan model use temperature requirements.

AF B – is the factor, derived based on the research done by Company's engineers in cooperation with fan vendors. This AF numerically describes the influence of the start/stop cycling (power cycling), described in Table 8 of Chapter 5.1, on DUTs as the acceleration factor for bearing and other mechanical components of fans. In calculations of this AF, the calculations of AF A are included, which means AF B is the combination of the acceleration factor defined by the IPC-9591 standard and the power cycling acceleration factor. Calculation of this AF is based on the "power on ratio" of the test, meaning the ratio of time when the fan is supplied by the voltage and time when the fan is not supplied by the voltage. Additionally, calculations include the number of start/stop cycles of fans in real application of the Company's products, during the same number of hours as one test cycle test, and several start/stop sub-cycles used in the test cycle. All the values have been derived internally in the company. Another stress factor, which is applied in the testing, is the fan power supply voltage. It is increased by a certain number of per-cents from the nominal supply voltage, to stress the electronics of fans, according to test specification. During the review of applied acceleration factors used in the Electronics Company, it has been found that the influence of this specific factor has not been considered in AF calculations, and this question has been delivered for further investigation, which will be completed out the scope of this work.

AF C – is the factor calculated based on the Arrhenius model, which uses such parameters as predefined activation energy, derived for Company’s products internally, and Boltzmann’s constant influence on fans. This AF has been used to evaluate the aging of only electronic components of the fan.

AF D – is the AF that has been derived as the result of Company internal discussions and is an average of B and C factors. As the result, test time calculations, lifetime calculations, and analysis of testing results are based on this derived AF.

Other parameters used for the evaluation of the expected test time are the following: population of the test (sample size), target reliability, which is derived from the earlier described L10 metrics, predefined components beta, and confidence level. For the evaluation of lifetime, based on the testing parameters and results, the calculator same as presented in Figure 19 is used, only the logic of calculations is reversed.

7.4 Evaluation parameters exclusions from the thesis

This thesis work is not aimed to describe the lifetime evaluation parameters used by the Electronics Company or fan-manufacturing companies. However, this chapter provides an overview and general understanding of the standardized approach and differences between lifetime evaluation strategies applied in the industry. Understanding of the evaluation criteria is needed for the verification of the standardization level of the existing setup and possible improvements to the existing test procedure, which can raise the efficiency of evaluation of test parameters and test setup needs for the high-quality reliability assurance, suitable for the products of the Electronics Company and its customers. What is more, this review gives an understanding, that reliability assurance approaches used in the industry have advanced standardized techniques and depend on the exact field of usage.

8 Test setup after implemented improvements

This chapter is aimed to describe the improvements to the measurements of fans' parameters, crucial for the evaluation of the reliability of fans during the ALT testing, completed in the frames of this thesis work. In Chapter 8.1, the test procedure existing at the moment of the beginning of the work on this thesis is reviewed to later explain how the procedure itself has changed during the work on this thesis and define outcomes in Chapter 10. In Chapters 8.2 and 8.3, improvement of measurements' quality, which have been applied in frames of this thesis work, are reviewed, together with the review of additional possible measurements, discussed in Chapter 8.4. Improvements done in the measurements' quality have a direct influence on the test procedure, a new version of which is one of the main outcomes of the thesis work and is discussed in Chapter 10. As the measurement quality improvements, further improvements in the measurements accuracy and reproducibility are discussed, together with possible automated measurement approaches review.

8.1 Test procedure at the beginning of work

The existing test procedures, at the beginning of the work on this thesis, have been based on the test setup after the update of 2019, described in detail in Chapter 6.2, with the automation part realized during that update and data-logging tools added during the update.

A test procedure that has been implemented based on the update of the testing cycle and automation updates in the 2019 summer has been the following:

Receiving of fans. The first step of the procedure has been receiving the DUTs for testing and the visual inspection aimed to verify that fans have not been damaged during the transportation or storage.

Pre-conditioning. The pre-conditioning (or pre-treatment) means the storing of half of the population of fans, which will be exposed to testing, in specific conditions, defined by the test specification to simulate the transportation and storage conditions for the new fan models, which are arriving directly from the manufacturing site and have not been impacted by the transportation or the storage conditions for the long time (months). Such simulation has been initialized based on the possibility given by one of the requirements, stated by the IPC-9591 standard and described in Table 4, Chapter 3.3.4 of this work. Such simulation has not been evaluated numerically and has been implemented due to experimental interest, to verify that such conditions will not have a crucial influence on the fans' lifetime. Continuous analyses on this topic are ongoing constantly, out of the scope of this thesis work.

Fans installation. The next step has been the installation of fans on the test jigs, using applicable installation tools. Then is coming the installation of test jigs with fans into the test chamber and the connection of fans inside the test chamber. Adjusting the fan power supply voltage according to test specification and fans' model.

Initial measurements. Fans current intake measurement was conducted using the Datalogger or DAQ, in the enclosed chamber, at the increased by 10% voltage, at room temperature (20ºC).

Test running. Current measurements have been done continuously during the test but without stated intervals. Maximum current observed on each DUT during the measurement period with measurement intervals of 5mins have been recorded. Tests have been stopped to remove the DUT in case its current level has been exceeding a 15% rise compared to the initially measured current or if DUT has stopped operating. DUT has been analyzed internally or sent to the vendor for analysis in case of some earlier unknown faults or design-related failures.

Test stopped. If the defined testing time has passed, tests have been stopped and DUTs removed. DUTs with the highest current rises, but not exceeding the failure limit of 15%, have been analyzed separately in case of such need.

8.2 Improvements in measurements quality

8.2.1 Current measurements during the test

Continuous current measurements have been implemented after the test setup update in 2019. However, several improvement points for these measurements have been found and implemented by the author of this thesis work.

Continuity of measurements. The process of continuity of data gathering has been improved with the implementation of Datalogger/DAQ units into the test setup. However, the time frames, and in which format the data should be stored have not been specified.

Time gaps between measurements have been assigned to 5mins at the existing test procedure. However, with such time gaps, the problem of measuring the fan intake current every 5mins has been resulting in measuring decreased intake current or zero intake current due to overlapping of measurement and stop stage of the fan sub-cycle. The reason for that is the presence of start/stop cycling each 5mins (fan operating for 5mins and stopped for 10s) in the general test cycle, according to the test specification. That problem has been partially fixed by analysis of measurement gaps and assigning a new time value of 4min and 50s between measurements. The reason for such adjustment has been an aim, to minimize elapsing of the measurement period with the stop stage of the fan. Further analysis of test data has shown that the measurements of reduced and zero current measurements have been minimized and have happened in a negligible number of rows of datasets. After such changes, it has been noticed that measurements are bringing new results to the datasets. Increased current rates, with the increase of more than 100%, on some DUTs have been noticed during measurements.

Continuing analysis of test data, it has been found and confirmed, that such current peaks are related to the start-up current of DUTs, meaning that measurements have been done at the first milliseconds of fans' operation after the stop stage of the cycle. From one point of view, the appeared problem has canceled the possibility to analyze the data based on >15% current rise criteria, given a large number of peak values in datasets, at least using singular measurement points. A possible solution is to set the failure criteria as "X consecutive measurements are >15% higher than the initial measurement". Such a number X of allowed consecutive measurements will be reviewed out of the scope of this thesis work. From another point of view, such data allowed new analysis of fans and how they will be acting in the product, conclusions of which are presented in Chapter 9. Further adjustments in setting suitable time gaps between measurements have been postponed with the priority to investigate the current peaks problem and understand the meaning of that for the testing.

To conclude everything stated above, it is needed to say that further investigation on suitable measurements time gaps will be continued in further work on the testing project, and several main aspects will be considered. Shifting time gaps after each measurement, because of the time required for Datalogger/DAQ for measuring and recording the data, is one of such aspects. A time gap of 4mins 50s is the gap between the end of the last measurement and the beginning of the next measurement. Measuring time itself is not verified precisely. As it depends on the number of DUTs in the test and delays during the measurements, a difference of nano- or milliseconds can be added to the time gaps. As the further improvement, out the scope of this work, it is needed to verify the data measuring time and delays caused by measuring equipment and consider that together with verification of which amount of data can be considered as negligible or allowed.

Data gathering and analysis time gaps have not been clarified in the existing test setup. Due to that reason, the data gathering time, meaning the time of downloading data from the measuring devices of the test setups, has been set equal for all test setups and arranged once per week. From the data point of view, it means that amount of data (amount of measurements cycles) is equal for all setups and the continuity of analysis of the data is going sustainably in a long run, with the possibility to easily trace the needed time frame of testing of some fan models, in case such interest arises, which has been complicated to complete without the specified continuity of measurements. As the process of data gathering is not automated yet, it happens that some of the gathering steps are missed, but this number and shifting have been decreased in comparison to the previous procedure.

Data processing quality. In the new procedure, the data processing pattern has been taken from the existing setup. However, the time frames for analysis of one dataset have been assigned and the pattern has changed as the result of improvements. A clear correlation between measuring channels and DUTs has been derived, the table with the test summary data has been updated to be presented in a form, more convenient for the operator, and additional parameters have been added to the summary data tables.

8.2.2 Speed measurements during the test

Fans' speed measurements have not been considered as the part of testing procedure in its initial version. However, as it can be derived from the applied standard IPC-9591 failure criteria, stated in Table 8 of Chapter 5.1, the speed measurements are crucial for understanding whether a fan can be considered operational or not. Measured fan speed directly shows the changes in the fans' cooling capabilities and the speed-current dependency.

Speed measurements in the existing setup. For the implementation of speed measurements in the setup several available solutions have been reviewed:

- Solution 1. Inside the chamber measurements
- Solution 2. External fan controlling devices
- Solution 3. Measurements with the oscilloscope
- Solution 4. External handy tachometer

Reviewed Solution number one, is measuring the RPM of the fan using the non-contact (laser) tachometer, installed inside the test chamber, for each stand and each DUT separately, with its output wiring connected to the dedicated terminals in the test chamber control cabinet. This option had its pros and cons. Positive sides of the solution are the possibility of measuring fan speed continuously during the testing and with additional preciseness caused by the stable location of the sensor relative to the fan, on which speed is measured, meaning the minimization of uncertainty caused by human error during the measurements. Negative points of such a setup have overtaken the positive sides of it. Due to the scalability of fans, tested in the test chamber, the variety of fans sizes in the setup, and the fans population changing between testing rounds, it is time-consuming to install and reinstall such tachometers between tests and financially inefficient to provide each DUT with the separate measuring unit. Additionally comes up a need for a physical update of the test chamber and its electrical cabinet, which is already fully equipped with electrical components, meaning the need to creation of additional space and changes in the design of the chamber, and review the priorities of the Reliability Team. Based on the listed negative points considering this fan speed measurement solution, it has been decided to use another available solution.

Another reviewed Solution number two is the speed measurements using fan controlling devices manufactured by the Electronics Company for some models of their products, where the fan controlling solution is required due to the dimensions of the system. Advantages of such a solution are the usage and additional verification of fan controlling equipment and compatibility of Hardware (HW) and Software (SW) solutions used in this equipment with fan models in products, where they will be potentially used. Another positive point of this solution is the adjustable continuity of measurements. The disadvantages of this solution are similar to the previous solution. Firstly, fans sizes and models' variety in testing leaves a need for adjustment and man-hours spent between testing rounds. Secondly, approximately 90% of fans, based on models tested at the moment of completion of this thesis work, in all of the test chambers, do not have the control possibility, and about 20% of the whole test population, based on already finished tests, does not have any feedback loop, only two wires – which are 24V supply wire and supply minus wire. Based on the listed reasons, it has been decided to use this solution only when it is required by the product engineering team, as it is done now in one of the test chambers, for the experimental reasons and in case of further development of the testing project.

Solution number three is the idea of measuring the frequency of rotations using the oscilloscope and feedback wires of fans. Feedback wiring is also connected to terminals in the electrical distribution box of the test chamber and the oscilloscope can be connected directly to those terminals. Advantages of such measurements have been the high precision of measurements and the possibility to adjust the continuity of measurements. Disadvantages are related to scalability, the same as in the two previous solutions. A large number of DUTs at the same time will require financial investment into at least 10 oscilloscopes, to partially satisfy the needs of each test chamber separately, additionally to the man-hours required for data processing and recalculation of frequency into the real speed value. Based on mentioned reasons, it has been decided to implement measurements with the oscilloscope only in case of such requirements and specific project needs for verification of fan operation parameters in high-temperature conditions inside the test chamber.

Solution number four has been figured out as the simplest solution, with suitable precision of measurements and satisfying required needs. This solution is the simple handy tachometer that allows contact and non-contact measurements. Both, the contact measurements, and non-contact measurements approaches have been tried in practice. Contact measurements can be done using the rotational mechanical part of the device, the rotational speed of which is measured in the device by the laser internally and translated to the RPM value of the measured speed. That method has shown low precision as it has been dependent on the force of pushing of the measurement element (roller) applied during the measurements to the moving part of the fan. With the application of low force, the roller has not been rotating fast enough to show the real speed of the fan. When applying a higher pushing force to make the contact better, it happened that the applied force has been influencing the fan's rotational speed and decreasing it because of the friction between the roller and the moving part of the fan. For that reason, a non-contact approach, using the laser of the device and the reflective element attached to the rotating part of the fan has been applied. This approach allows making measurements on all DUTs in different chambers when the time gap is upcoming, without the need for additional test setup updates, measuring the fan speed at different voltage levels used in the testing, according to the test requirements specification. What is more, this approach is more efficient in sense of one-time financial investments, compared to others: the handy tachometer average price on the market is 150 euros (€) compared to the minimal price of 1000€ for 1 unit of similar, lower quality, measuring devices same to mentioned as Solutions number two and three. Additional saving is a man-hour required to operate the data in Solutions number two and three. From 40 to 60h of personnel time should be spent for required updates of the test chambers and adjustments to set up measurements in all available testing chambers and DUTs, which is a one-time resource investment. An approximate estimation of 10h should be considered for adjustments of devices between testing rounds, where the size and population of DUTs are changing, which is done at least two times per year for each chamber. The last, time resource issue, is the data processing time, which will require from 2 to 4h weekly, from one person to collect and check the measurements data, depending on the population size. The handy tachometer which is finally has been taken into usage, the Extech RPM33 device, saves the man-hours resource, as it is the “plug-and-play” solution, for which all required preparations, are only attaching the reflective element to all DUTs used in the chamber at the beginning of the testing round, which requires up to 30mins of time and one-time measurements conduction, requiring 10mins of work for measurements and 5mins of work for recording results [24].

In conclusion, it is needed to say, that the Extech RPM33 device is successfully used in the test procedure, to complete measurements of DUTs speed at the beginning and the end of the test round, and in the minimum time intervals between measurements, required by the standard IPC-9591 and discussed in Table 8 of Chapter 5.1. Based on the results of measurements which has been analyzed before, after, and during previous testing rounds, it has been found that the most observable failure criteria in the testing are the current consumption increase or fan’s operation stopping. The failure criteria of fans’ speed have been observed only in several cases. However, in those cases, the abnormal increase or decrease in the fan’s speed has been following the increase or decrease in the current consumption rates. Based on these additional reasons and reasons mentioned above for all the options, it has been decided to use Solution 4 for continuous measurements, applying the minimal time intervals between measurements required by IPC-9591 or lower if abnormal current consumption of fans has been noticed. Solutions 2 and 3 can be used in case of such request from the product engineering team, who ordered the testing, for example, to check the speed of fans during the hot stage of the test cycle and how are current and speed are acting in such conditions in specific fan model.

8.3 Before and after test measurements

In frames of analysis of one of the fans models’ population after the testing round for the population has been finished, additional “after test measurements” have been conducted in experimental frames. Reasons for such interest have been mostly related to the fact, that the company is analyzing only the failed according to criteria fans, using Company’s or Vendors’ resources for analysis. However, for a better understanding of the influence of the components aging into fans operation it has been proposed to conduct “before” and “after test” measurements, based on the available results of one “after test” measurement conducted in frames of this thesis work. Results of such measurements for one of the Vendors’ fans are presented in Table 10 and discussed below. All the results, marked with red color on the table in Table 10, are meaning that they are not satisfying the failure criteria established for fans and that fans have failed the testing or results of the testing should be discussed in detail based on all the conclusions derived from testing and additional measurements.

Table 10. Results of “after test” measurements in test summary table of 40mm fans.

Fans	Initial current	Current measured on each unit separately	Current change in %, respective to initial current (average current measured with 26.4 has been taken for this comparison)	Measured RPM	Nominal RPM	Difference between measured and nominal RPM in %	Current measurements with 24V				Current measurements with increased voltage			
							Min current	Average current	Start-up current	Difference in % between min and max currents	Min current	Average current	Start-up current	Difference in % between min and max currents
_40mm_1_1	0.035749716	0.04271169	19.47420827	8061	7500	7.48	0.034406173	0.037496	0.097794	184.2343349	0.03928	0.04271	0.10049	155.8595963
_40mm_1_2	0.035066589	0.037816387	7.841646731	7959	7500	6.12	0.031517	0.034039	0.088215	179.8963734	0.03435	0.03782	0.09818	185.8502709
_40mm_1_3	0.035706661	0.040470553	13.34174598	7776	7500	3.68	0.034024277	0.036361	0.086265	153.5382662	0.03818	0.04047	0.09571	150.7017421
_40mm_1_4	0.033381105	0.041939737	25.63915156	7761	7500	3.48	0.034625179	0.037338	0.082415	138.021158	0.03823	0.04194	0.09218	141.080384
_40mm_1_5	0.03426273	0.038645698	12.79223014	8097	7500	7.96	0.031752004	0.034006	0.089974	183.3650689	0.03552	0.03865	0.10007	181.7409519
_40mm_1_6	0.034932187	0.041625493	19.16085769	8183	7500	9.1066667	0.034128501	0.0366	0.08295	143.0517883	0.03898	0.04163	0.09603	146.3572386
_40mm_1_7	0.03358152	0.036046217	7.339446316	7901	7500	5.3466667	0.029456289	0.032238	0.08118	175.5959313	0.03355	0.03605	0.09423	180.8423083
_40mm_1_8	0.032815034	0.03831213	16.75175904	7875	7500	5	0.031420885	0.03419	0.076389	143.1167868	0.0358	0.03831	0.09429	163.4096986
_40mm_2_1	0.035083626	0.037370456	6.518225357	7997	7500	6.6266667	0.031395551	0.033759	0.080409	156.114438	0.03444	0.03737	0.08275	140.2878391
_40mm_2_2	0.034294493	0.039144758	14.14298521	7949	7500	5.9866667	0.032700249	0.035326	0.091726	180.5042004	0.03687	0.03914	0.09898	168.4309071
_40mm_2_3	0.033493583	0.037070104	10.67822511	6112	7500	-18.506667	0.031082878	0.033392	0.074728	140.4144977	0.03465	0.03707	0.08811	154.2744569
_40mm_2_4	0.035599091	0.038482091	8.098520173	8218	7500	9.5733333	0.030663315	0.033261	0.087058	183.9155258	0.03531	0.03848	0.08959	153.734453
_40mm_2_5	0.035667326	0.038902078	9.069230575	7821	7500	4.28	0.030875541	0.033922	0.08373	171.1864385	0.03504	0.0389	0.08988	156.4917069
_40mm_2_6	0.03346083	0.037761079	12.85158892	7872	7500	4.96	0.03067587	0.032896	0.075817	147.1536944	0.03414	0.03776	0.09347	173.7622341
_40mm_2_7	0.031746025	0.038439249	21.08366028	7674	7500	2.32	0.032542135	0.034787	0.08503	161.2912675	0.03617	0.03844	0.08286	129.1000363

In the “after test” measurements, the current measurements have been completed with the application of a nominal voltage of fans, 24V, and the increased voltage, stated by the test specification and used in the test as an operational voltage of fans. Minimum, maximum, and derived average current consumption are results of the interest of those measurements. Measurements have been conducted when fans have been removed from the test chamber, using the same approach for current measurement, as used in the test chamber, using the power supply with adjustable voltage.

Average current consumption has been derived from the minimum and maximum observed current consumption during continuous measurement of each DUT separately, during the specified amount of time, compared with the standard IPC-9591 requirement for the time which should be applied during the testing. The average current, derived from the increased voltage measurements has been compared to the initially measured current of each DUT, which has been measured before the test round, in the test chamber, with the same ambient and power supply conditions.

What is more, the speed of DUTs has been measured and compared to the datasheet value. The datasheet value has been taken as the nominal, due to the fact of absence of the improvement which included speed measurements before the test at the time when this round of testing started. Ideally and in all further analysis, initial DUTs’ speed, measured at the beginning of the test based on earlier described conditions and used tools, should be compared against measurements conducted at the end of the testing round.

All the measurements conducted in frames of this analysis have been done due to the fact of noticed increased intake current of fans during fans’ start-up after the “off” step of the testing cycles, which is described in Chapter 9 of this thesis. Results of these measurements have been useful in further negotiations with the Vendor and analysis of fans. Additionally, such results have shown that the more detailed analysis of the tested fans might be useful for improving the knowledge and proving or disapproving some of the ALT strategies derived in the Electronics Company. Not all the results have been compared to the initially measured values, but even though have been useful for deriving results of the analysis.

To conclude everything described above, it is needed to say, that the results of such analysis have appeared to be interesting for product/project engineers, and the request to make such measurements at the beginning and the end of testing rounds for all tested fans as a part of the test procedure has been received.

8.4 Proposed and possible measurements

This chapter is aimed to describe and evaluate the possibility of implementation of required and additional possible measurements, proposed in the frames of this thesis work. Possible results and planning of such measurements have been discussed internally in the company and appeared to have an interest in the competence improvement and test setup future improvements for increasing test capacity and quality.

8.4.1 Noise measurements

Noise emission of fans is considered to be one of the failure criteria of fans under the test, according to IPC-9591, discussed in Table 8 of Chapter 5.1. Additionally, increased noise emission level is stated to be a sign of the fans' mechanical components degradation and a sign of failure modes discussed in Table 6 of Chapter 4.3. Based on these facts, it has been proposed to conduct noise measurements, in frames of the improvements for the testing procedure. Implementation of such measurements requires a specification for such measurements, which is discussed in this chapter together with an estimated investment cost analysis.

When looking into the IPC-9591 standard, it is possible to notice that the standard states requirements for measurements and refers to other standards, which should be reviewed for establishing the most precise measurement results. The table in Figure 17 below represents the operating modes in which the fan acoustical noise emission levels should be measured and reported to the fan manufacturing companies' customers, for each specific fan model.

Operating Range	Flow
Maximum voltage or PWM	Free flow
Highest Voltage or PWM	80% of flow
Highest Voltage or PWM	20% of flow
Center Voltage or PWM	Free flow
Center Voltage or PWM	80% of flow
Center Voltage or PWM	20% of flow
Lowest voltage or PWM	Free flow
Lowest voltage or PWM	80% of flow
Lowest voltage or PWM	20% of flow

Figure 17. Fans' noise level measurement modes [14].

Based on that table, it is possible to derive the mode, in which the fan should be tested in frames of the test procedure. As this table describes all the required modes for testing on the fans manufacturer side, which should be delivered in the fan model's documentation to the customer, and the IPC-9591 does not specify in which modes the fan should be tested in frames of measurements in ALT testing, it has been assumed that measurements must be done at normal room temperature ~20ºC, with the nominal operating voltage and free airflow. In case of special requirements from the product/project engineering side, measurements must be done at elevated operating voltage, at which fan is operating in the test chamber according to the test specification.

Time intervals between the measurements are stated as 1000h of testing or AABUS, based on IPC-9591. Based on this, it has been concluded that the suitable time for measurements will be at the beginning and the end of the testing round before fans are placed into and after fans are taken out from the test chamber unless nothing is specified by the product/project engineering side. Additional time intervals depend on the need of the project and the typical application of the final product of the Electronics Company in which the fan is used.

The IPC-9591 standard is referring to several other standards: ISO 103102, ISO 3741, and ISO 3744, which are discussing the procedures of acoustical measurements and methods, which shall be used for the determination of the sound power levels. However, discussions with Vendors of the Electronics Company, conducted to verify how they are conducting noise measurements, have shown that different Vendors are referring to different standards for conducting measurements. For example, one of the vendors refers to a standard, which defines the location of the microphone during the measurements relative to the fan and states that the microphone should be located one meter away from the fan input airflow direction side. The same approach is recommended by the IPC-9591 standard. Referring to the anechoic chamber for measurements, Vendors apply the standard ISO 7779 [25] – [27].

One of the side fan manufacturers, which has been taken as an example for analysis of the problem, describes noise measurements, referring to Japanese Industrial Standard (JIS) C9603. That standard proposes the same distance of one meter for measuring the noise level of the fan but states another position of the microphone relative to the fan during the measurement. The proposed position is one meter from in front of the side of the fan's housing, not in front of the impeller part, as was described in the different standards above. The position of the microphone, proposed in the JIS C9603 standard is represented in Figure 18 [28].

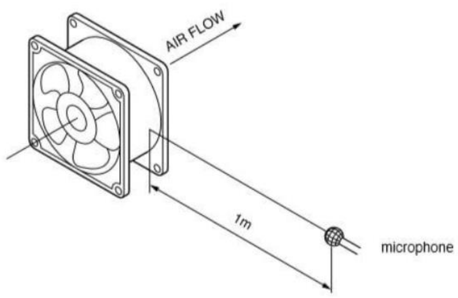

Figure 18. Position of the microphone according to JIS C9603 [21].

General requirements for the noise measurements discussed in this thesis work will be stated in an official document in Company's format to present the topic for discussions and further investigation on this topic is ongoing out of the scope of this thesis work, aiming to deeply analyze the standards mentioned in this chapter and compare them to available measurement solutions for conducting measurements in frames of the improved test procedure.

Price negotiations and comparison have been based on a discussion of lately formulated measurement requirements with one of the external acoustic measurements service providers and based on the approximate price estimation of the cost of noise measuring setup done earlier in the Electronics Company. Considering the smallest possible number of samples, or population of the test, for which measurements should be completed, 16 DUTs (120mm-by-120mm fans, according to the Table 9 from the Chapter 6.3.1), the cost of the noise measurement setup will be depreciated after 3 rounds of testing of 120mm-by-120mm fans, comparing to the price of the external acoustic measurements service, and the number of test rounds, for the cost depreciation reduces with the higher number of DUTs in the test round. Additionally to the cost analysis, the deeper analysis of measurement standards proposed by external service provider solutions, which are based on several main standards for acoustical measurements: ISO 10140:2010, ISO 354:2003, and ISO 11654:1999, should and will be conducted as the future development of this project, but out of the scope of this thesis work.

8.4.2 Pressure and vibration measurements

The idea of the test chamber internal pressure measurements has risen from one of the failures, related to mechanical braking of wiring in the test setup, which is described in Chapter 9. The idea of DUTs vibration measurements has risen due to the fact, that the vibration is one sign of wear-out of bearing components. There are no related requirements discussed in the testing requirement part of the IPC-9591 standard, however, the possibility of such measurements has been reviewed in the frames of this thesis work and has been proposed for further discussions.

Standard IPC-9591 states that the fan manufacturer shall present to the customer the Static Pressure vs Airflow curves for a specific fan model at nominal operating conditions. An example of such a curve is represented in Figure 19. The airflow of the fan depends on the static pressure, against which the air should be moved by the device. From that, it can be assumed that with the change of the operational conditions, the increase or decrease of the pressure can affect fan operating modes, the speed of fans, and for example, higher current consumption required to reach a certain speed level at high-pressure conditions.

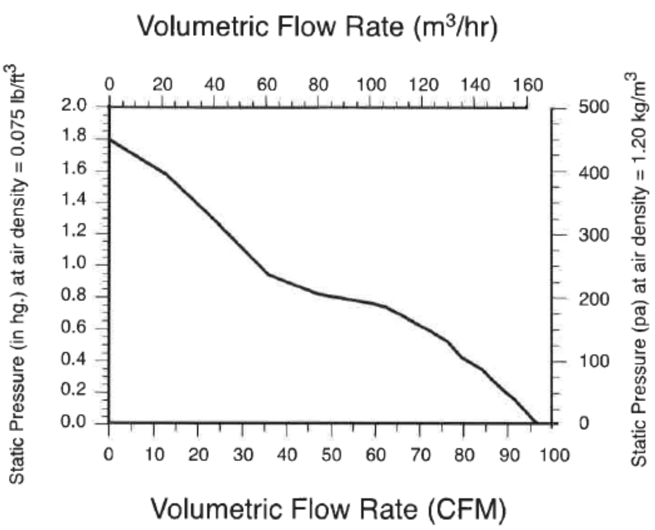

Figure 19. Fans’ Static Pressure vs Airflow curve example [21].

High pressure operating conditions can potentially have an additional stress influence on fans’ electronic components and circuitry. The pressure has not been evaluated in the test setup, for different fan models and operating conditions earlier. However, the setup has the pressure regulating plate in its mechanical design, which allows working on this topic further. Numerical evaluation of the pressure might allow reviewing how the increased pressure conditions will influence the aging of components and which components might be the most subjected to such stress. Initial steps for such understanding have been completed in frames of this thesis work, by preparing measurement points in the existing test setup and conducting the air-flow measurements during the testing of specific fan models. Further actions planned on this topic will be completed out of the scope of this thesis work but will include pressure calculations based on measured air-flow results and knowing the dimensions of the airflow channels. Such evaluation will not give a possibility for a precise evaluation of the pressure on each DUT separately but will give a good overview of the test chamber conditions and room for improvements in the future. What is more, such evaluation will give an understanding of the possibility and reasonability of mixing populations of different fan types, of different sizes, or different speed characteristics in one test chamber, to fulfill the testing needs of several orders simultaneously.

Allowed vibration level to which fans are induced during operations and storage, and vibration levels of the fan itself shall be stated in fan models’ datasheets according to IPC-9591. The same standard does not discuss the possibility of testing fans in increased vibration conditions or evaluating vibration levels produced by fans in the testing process. Fans have their own allowed operational vibration levels limits stated in the technical documentation, but the influence of the vibration, as a stress factor has not been reviewed for testing in Electronics Company. Fans’ vibration has not been evaluated numerically either. The proposal of development of such idea has been done in frames of this thesis work and initial research on vibration influence has been started and in its current stage requires discussions with vendors, with a goal, to verify if such ideas have been reviewed or implemented in their facility and if they are considering increased vibration as the acceleration factor for fans lifetime. Development of this idea will be continued out of the scope of this thesis after corresponding discussions will be completed.

9 Testing results

This chapter aims to describe several examples of fan testing success stories, which have happened after analysis of testing results and tested DUTs in the frames of this thesis work. These stories are the success cases, in the sense that thanks to the fans' ALT testing and developed procedure failures in fans have been found and delivered to the product responsible engineers inside the company and which have not propagated to the field, resulting in final product failures on the customers' side. Such results of the testing are showing and confirming the importance of the testing for the product and customers and motivating the testing quality improvements, verification and application of new stress factors, and excellence in measurements and test data tracing.

9.1 Increased intake current of fans

One of the problems, which has been noticed during the testing and is under continuous analysis for different test chambers and fan models, is the problem of increased intake current. The problem has been noticed during the adjustment of measurement time gaps, described in Chapter 8.2.1. Such increased current has been noticed during the start-up of fans after the power-off step of the cycle. Further analysis has shown that after a few seconds of fans' operating state, the current intake level normalizes and reaches back to the acceptable intake rates, which satisfies the failure criteria requirement. However, the increased start-up current levels of DUTs in some cases are exceeding 100% of intake current compared to the initially measured current. One of the charts, completed during the analysis of one of the fans models' test data, is presented in Figure 20.

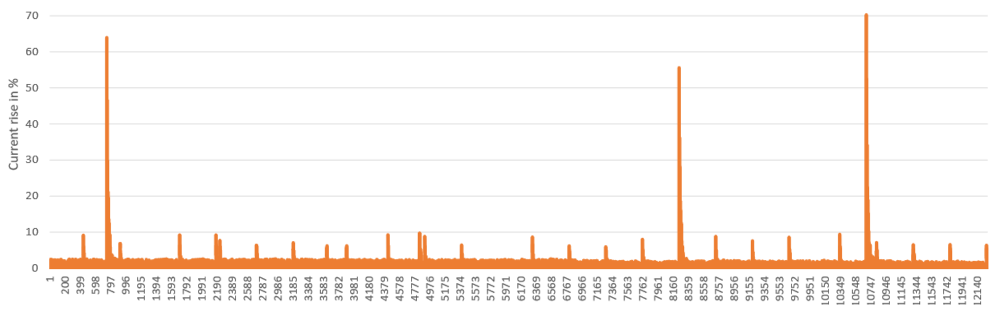

Figure 20. Increased intake current example.

From the presented chart, it is possible to notice that most of the time during the measurements current intake level stays allowed by the standard failure criteria boundaries. However, in three measurement series, the intake current rise of 70% compared to the initial current has been noticed.

Such a problem has appeared on several tested fan models, not depending on the vendor of the specific model and size of the model. One of the initial theories has been related to the problem of the test setup. However, probability has minimized, after the same increase in start-up current has been noticed in “after test” measurements of some models which have been having problems in testing. Another theory that is being worked on is the influence of components aging. But the increased intake current is noticed in the fans, which have been under testing for a relatively low time to have aging problems.

Therefore, the problem has been addressed to product engineers and vendors of fans. Communication about this specific topic with vendors has not brought useful results at the moment of the completion of this thesis work, but the vendors have been interested in further investigation. The problem has been discussed with product engineers and had several main outcomes. It has been agreed that engineers should verify whether the power supply and protection circuitry of the final product has capabilities and are designed in a way that they can handle the high intake current of fans and not cut fans from the power supply.

9.2 Internal fan’s fuse burning

Another relevant problem, interesting for further research and knowledge-gathering, has been the problem of internal fan protection fuse burning. Conditions, under which the fuse has been damaged are unknown because that has happened between the measurements of current intake, during the defined gap of time. One of the theories is the increase of the intake current, to which internal protection reacted faster than the external protection (fuses on the input channels of fans’ power supply lines) of the fan. Another theory is the effect of the aging on electronic components of the fan. Thanks to the fan’s vendor and their part of the analysis, it has been verified that the fan is operating normally after fuse replacement. What is more, standard measurements completed on the fan after fuse replacement have shown that the fan is operating within allowed boundaries when compared to initially measured DUT values and checking them against standard requirements.

9.3 Aging of the gluing

The results of aging of the glue between internal fans' components have been noticed when fans have stopped operating totally. The initial symptoms of the failure – have been broken/cut wires of the fans on their input. Failure has been observed in the early stage of testing in one specific model of fans and on a test jig with the same fan allocation in two different test chambers. The first theory during analysis has been the bad quality of soldering, which caused wires to detach from their pins. However, a closer look at pins using the zooming devices has shown that wires are not detached from soldering points but are cut or torn off by some external force. The theory has been questionable until a certain point in analysis because the installation of fans has been completed according to fans specification and no additional stress has been applied to wires. Fans have been sent for analysis to the vendor. The first results of analysis by vendors have confirmed the theory, that wires have been cut or torn off by external force. However, there where no external force in the testing and verification if that has been completed. Further investigation has shown the fan control circuitry, located on PCB has changed its position compared to other DUTs which has not failed. Based on this fact, it has been asked from the vendor to continue analysis and verify whether the internal movements in the fan are possible and if they are tolerable.

The final results of the investigation have shown that the glue on internal components has degraded faster than it has been expected and that caused the possibility of internal movements between components. Torn wires have been the result of the tension force caused by PCB movements. The outcome of the investigation has been proposed improvement points to the mechanical design of the specific fan model, to satisfy Electronics Company's needs and assignment of an additional round of testing for an improved model, which is happening at the moment of completion of this thesis work.

10 Conclusions of the test setup and procedure improvements

This chapter aims to summarize and derive bullet points, describing changes that have been implemented and proposed for future review, in the frames of this thesis work to the electronics cooling fans' ALT testing procedure, completed by the Reliability Engineering team in Electronics Company. The table, which will be formed into an official Electronics Company standard document after completion of this thesis work, is proposed for review in this chapter. The table describes the test procedure step by step and states the requirements which should be followed during the test in different steps of the testing procedure. Such a way of presenting improved and formalized test procedure have been completed because of the easiness of representation of requirements and because it potentially can be used as an official part of testing documentation, can be followed by engineers to prepare fans for the testing, run testing rounds efficiently, and analyze results in the required time after testing. The efficiency of the testing procedure means the quality of testing, which directly influence the product, finally delivered to the customer and is important for engineers from Reliability Team, because actions in the table are described step by step, which saves time for new engineers spend less time on education process and save time for all other engineers by organizing their work according to an already-created plan of the process.

10.1 Implemented changes in the test procedure

The changes, implemented in the test procedure based on the results of work completed in the frames of this thesis are the following:

- **Improved measurements quality.** The quality of current measurements conducted through the testing and data processing has been improved through the practical adjustment of timing gaps, between time measurements, needs which are based on the IPC-9591 standard and which have been adjusted to specific needs discussed in Electronics Company internally. Such adjustment influences the testing data quality, which will make the test results analysis, failure analysis, and tracing easier for the responsible engineer. Additionally, the requirement on the time gaps for testing data analysis has been implemented into the test procedure requirements to decrease the time of reacting to failures that occurred during the testing. Improvements to the test summary documentation have been done, which will help to track the testing and reporting status and make the data tracing easier for involved engineers.

- **Additional measurements implementation.** Based on the results of the analysis of the applied, to such kind of ALT testing, standard IPC-9591, the fans' speed measurements have been implemented. Several main approaches for measurements have been reviewed and one of them has already been fully implemented. Two other approaches have been partially taken into use based on specific fan testing project requirements in cooperation with product development engineers. The airflow measurements have been partially integrated to verify pressure levels occurring in the test chambers. The aim of pressure levels verification is the estimation of the possible influence of the pressure on fan operating modes during the testing and the influence of aging of fan's components. Results of pressure level verification have not been discussed in the frames of this thesis work. "Before" and "After" test measurements have been implemented and appeared to be useful during the fan analysis after testing and when reporting the test results, with the request to include such measurements into the testing procedure.
- **Additionally proposed measurements.** The need and possible approaches for measurements of the noise levels of fans during their operation mode have been proposed for review and further planning, aiming to make these measurements a required part of the test procedure to comply with the IPC-9591 standard. Vibration level measurements have been reviewed based on the IPC-9591 standard and proposed for future negotiation and analysis of the need for such measurements in the scope of the ALT testing procedure. Vibration levels are considered not only as of the parameter which can be evaluated but also as the external stress factor which can have a potential influence on testing results.

10.2 Proposed formalized test procedure

This chapter presents a formalized test procedure, presented as the table checklist, to be followed from the beginning, which is the initiation of fans ALT testing need in Reliability Teams facilities, until the end of the testing round, which can be defined as the review and discussion of the test report together with product and project responsible engineers, for whom the testing has been completed.

Table 11. Test procedure and requirements checklist.

№	Action to be completed	Applied requirements
1	Planning of the testing round	Assignment of the test chamber to be used, the definition of the fan model to be tested, verification of the responsible person from the product engineering side, completing records to corresponding documentation (Test tracking table and Test summary table).
2	Estimating test time	Making a record of planned test start time, calculating an estimated test time considering specific model requirements, estimating test end time, and completing records to corresponding documentation.
3	Pre-conditioning of DUTs	Pre-conditioning can be done upon the request of the test ordering side by themselves or in the Reliability Team's facilities, to be agreed between sides, completing records to corresponding documentation about pre-conditioned DUTs and pre-conditioning environment.
4	Receival of DUTs	The test ordering side should be notified when DUTs arrived at testing facilities. This step might be interchanged with the position of the previous step during the process, based on the decision on where the pre-conditioning will be completed.
5	Before the test measurements	Current and speed measurements, in the free airflow, with nominal and increased (used in the test) voltage levels, should be completed on each DUT separately and results should be recorded in the Test summary table.
6	Installation of DUTs	Installation of DUTs on the test jigs should be completed with the allowed screwing torque, specified by the assembly manual of the product.
7	Connection of DUTs and installation into the test chamber	The wiring of DUTs should be installed in a way with the adjustable fixation inside the test chamber, to avoid additional stress on wiring.
8	Parametrization of the test chamber	Temperature limits of the test chamber, protection circuitry for DUTs, and supply voltage level should be adjusted according to the fan model's technical specification or the standard test specification,

		adjusting time measurement gaps on the testing measurement equipment.
10	Conducting intake current measurements of DUTs in the enclosed test chamber	After enclosing the test chamber, initial current intake measurements, conducted utilizing test chamber measurement equipment should be completed and recorded into the Test summary table, to later be compared with the current measurements conducted along with the testing round.
12	Test start	Starting the temperature cycling the test chamber, making a record of the test start time in the Test summary table.
13	Test running, monitoring data	The current measurement series during the testing is completed with an interval of 4.50mins. Current measurement results should be gathered weekly, with noting the test cycle number and reviewing the data, to verify whether failures have occurred in the testing, filling the Test summary table. Speed measurements should be conducted after each 200h of testing, or in shorter time gaps if requested by the test ordering side.
14	Test stop in case of failure	In case of observing failure, the test should be stopped immediately, for the verification of failure and removing failed DUT from the testing. After test restart, the failure should be reported to the test ordering side, required analysis of data and fan should be completed and noted in the Test summary table.
15	Test stop	After the test stop, the current intake on DUTs should be measured for the last time in an enclosed chamber, at in-room temperature. After measurements are done, fans should be removed from the test chamber and test jigs. The date of the test end should be noted in the Test summary table.
16	After test measurements	Current and speed measurements, in the free airflow, with nominal and increased (used in the test) voltage levels, should be completed on each DUT separately and results should be recorded in the Test summary table.
17	Reporting the test results	After all, measurements have been completed, test reporting to the test ordering side should be completed and presented for initial discussion within two weeks after the test end. The report should be filled according to the reporting template and made publicly available in the resources of the Company.

11 Future possibilities

This chapter aims to describe the possible proposed improvements to the test procedure, through the automation, data gathering methods, and improvements in Electronics Company's communication aspects which potentially will help to get a deeper understanding of field failure in products related to the cooling devices. Such possibilities have been reviewed and proposed for further discussions in the frames of this thesis work, but the implementation of proposals will depend in the future on the priority of these tasks in the tasks list of the Reliability Team.

11.1 Automation of the test

11.1.1 Microcontroller based automation

At first, the simpler the point of view of implementation, the approach has been reviewed. The idea of the approach is to use the microcontroller, such as some model of Raspberry Pi, which potentially will serve the needs and will be efficient enough to perform required actions in the test system and interconnect test chambers between each other and establish communication with servers used for data storage. As the amount of test chambers in the testing project (system) is large enough and potentially can be increased in the nearest future, the possibility of implementing the master-slave system has been reviewed. Idea is to have one master microcontroller which will be going through all the slave microcontrollers and collecting data files, recorded on them, in specific time gaps. Slave microcontrollers will be placed in each test chamber separately and will be responsible for the test logic control and data gathering from the data logger or DAQ devices. Such a layout gives a possibility to implement new test chambers into a general system easily, by connecting additional slave devices to the system. However, this idea has not been taken into further search on possible solutions for automation because of several main points. The first disadvantage is a need for additional adjustments in each cabinet, to establish wiring and logic in a planned and required way, which potentially can take from 20 to 40 hours of work from the personnel, for modification of one test chamber. The second disadvantage is the programming of the device and establishing all needed connections, which potentially can take from 60 up to 90 hours of work, considering additional learning needs to complete the project. The third disadvantage is the need to spend time verifying whether such a system will be compatible with the standards followed by the company in creating such systems. The fourth disadvantage is the need for implementation of such a system, into the whole system used in the company for testing monitoring, and data gathering, which might require resources from other teams to establish the required connection with the databases and general network. Based on these reasons, it has been decided to continue reviewing the possibility of implementing the fully automated system, based on the PLC automation approach.

11.1.2 PLC automation

The PLC automation approach has been chosen as the most probable approach to be implemented based on several main aspects. The first aspect is related to the fact, that all the test systems in Electronics Company and its Reliability Team are based on the PLC automation approach. That fact gives a possibility for the fast solution of implementation of fan testing system into the general network and tackling the occurred problems based on already existing knowledge. Another aspect is the availability of the PLC controller which can be used for building up this test system in the team’s stock, which reduces investment costs and time of completion of the project by canceling components' lead time from the scope. The third main aspect is the easiness of physical and programmable interconnection of the test chambers with PLC. PLC will require only several signals to control one test chamber because of the presence of needed time and voltage relays in the design of the test chamber, meaning that they will need only additional, more precisely regulated signals from outside, to be controlled. Programming time will decrease compared to what is required for programming a microcontroller because different parts of logic can be taken and programmed in the same way, as it has been done in other test systems. The reasoning for the need for automation is following:

- **Lower required time for data processing.** Due to the fact, that data gathering will be automated and automatically saved to the database, less time weekly will be required for data gathering, processing, and finding of data for malfunctioned fans in the testing, thanks to the opportunities of data analysis in database systems.
- **Improved time synchronization.** Using an automated approach will improve the times and cycles synchronization and reduce the time required for tracing the data

from one or another test cycle. As the synchronization of cycle numbers and data sets is done manually as of now, it is in some cases impossible or time-consuming to trace out specific data rows in a specific time frame. Additionally, it will be possible to regulate time gaps between current measurements more efficiently and filter out the “stop” cycle data from the datasets.

- **Decreased reaction time on fault.** The possibility of establishment of various alarms and triggers in the PLC system will potentially decrease reaction time on possible test chambers’ failures and fan failures that occurred during the testing.
- **More precision in test chamber control.** PLC automation allows adding more functionality and precision in test chamber control on top of already existing opportunities.

In Figure 21, the proposed block diagram of the draft version of the logic required in the PLC program is presented. The diagram describes the generalized logic of main measurements which should be applied as the minimum requirement for the program. If such realization of logic can not be or will not be implemented, the PLC program can not be considered a working one. Logic considers pre-established communication of test chambers and PLC and shows the order, in which processes should be completed during one series of measurements to receive all the required data from the test chamber in the required time, with the time and cycle counters synchronization.

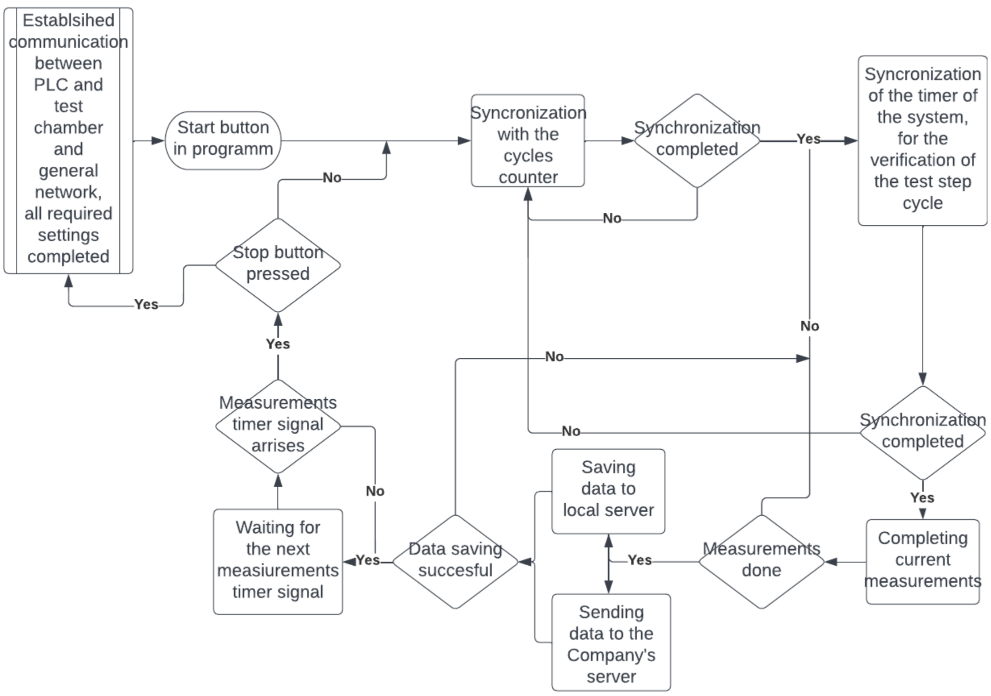

Figure 21. A draft version of the PLC program logic’s block diagram.

11.2 Correlating test and field data

The review of the process of the Electronics Company, done in frames of this thesis work, has shown that the failures observed in the field are not correlated with failures observed during the testing, in frames of the cooling functionality of the product. One of the reasons is that failed fans in the field are replaced by service engineers and are not always reaching laboratories to analyze failures. Another reason is that failures are mostly observed in older fan models, which have been used in the products during 5-10 last years and for which ALT testing has not been done as a separate part of functionality testing, meaning that it is impossible to correlate existing test data with the fans which have been replaced in the field, because of differences in fan models even in the same product line. However, this chapter proposes possible improvements to the procedure of analysis of the field data and test, based on existing workflow analysis, reaching and full implementation of which is a long-term procedure.

11.2.1 Failure and aging mechanisms analysis of fans used in the field

As has been mentioned previously, replaced fans from the field are not always reaching the laboratories for analysis. Fans, failures which have been noticed before the estimated lifetime end and before the standard service replacement time has been reached and failures that are highly repetitive or causing greater product functionality problems, are reaching laboratories for analysis and a better understanding of the fan model problems and verification of root-causes of failures. Such results are stored in documentation format and can be easily revised in case of need and for the possible comparison with test results or to initiate testing of one or another fan model which is already actively used in the field not only fans, which will be used in projects which are under development.

However, a large number of fans, that were replaced by service engineers after the standard fan replacement time for the product on the customers' side, are staying unanalyzed after usage and are disposed of as the waste after replacement. Analysis of such used fans can potentially give an understanding of how the fans are serving for the stated lifetime in different operating environments and what are fans' components levels of aging, compared to nominal new fans, how the aging of components depends on the environment in the real application. Such understanding potentially can show the weak and strong points of various fan models. Possible improvements to newly developed fan models for the same product lines based on lessons learned. And lastly, such understanding can give room for reviewing service periods and possibly increasing standard time for a fan replacement, for specific fan models or product lines where the application environment potentially is not accelerating the aging of fans' components as fast as in other applications. For the implementation of such an analysis procedure, further investigation of fans and products where fans are used, with the comparison of profile or typical application of the product in the field should be done. In the frames of this thesis work, a roadmap for the preparation of such analysis is proposed for review.

- **Fans models matrix.** The first step should be the creation of the matrix, which will describe which fan model is used in all product lines, starting with product lines, which are the most popular in the industry. Such matrix has already been partially developed in another department of the Electronics Company and can potentially be used and upgraded by the Reliability Team.
- **Verification of the frequency of ordering of new fans for products in the field.** This information will show how frequently one or another model of the fan is ordered for replacement in the product in the field, not considering fans, replaced after standard service time. Such verification can be done with the help of the service department. The verification will show the number of fans replaced because of failure that happened before the estimated lifetime end and statistically show how many fans are not analyzed in case of failure in the field. And finally, it will be possible to request such a fan for analysis with every new order.
- **Requesting fans replaced in frames of standard service time procedure.** According to the created matrix of product lines and fan models used there, starting with the most popular in industry products, initiate requests to receive fans for analysis after they have been replaced in the field after standard service time. Analysis can be conducted with the help of fans' vendors and their component vendors, in case of such need.
- **Keeping track of fans that have been tested.** Another important point is to keep the fan models which have been tested and verify that they are not failing in the field or case of failure verify what kind of failure mechanisms have not been considered during the testing process.

11.2.2 Reviewing possibilities of improvements in test specification

To conclude the roadmap proposed in the previous chapter, it is needed to state how such analysis will generally influence the testing specification, methods, and procedure in future development.

Understanding of results of the analysis, proposed in the previous chapter potentially can influence stress factors applied in the testing. A deeper understanding of the customer application of the product can result in the derivation of new factors which are influencing fans aging in the field and which should be reviewed as stress factors in testing projects. Understanding of failure modes of the fans, met in the field, will show the potential weakness of the testing, which is not able to identify these modes. Additionally to that, testing conditions can be adjusted specifically for particular fan models based on their application portfolio.

The last point is the knowledge development of the team members in the components level testing, which will be positively reflected in team performance in other testing projects.

12 Summary

This thesis work has been completed based on the needs and interest of the testing improvements for the electronics cooling fans ALT testing, done in one Electronics Company located in Estonia. Fans that have been and are tested in frames of this components level testing are used for the cooling of electronics components inside the final product manufactured by Electronics Company, which is the electrical drive.

As the basement of the thesis work, the general need for ALT testing has been reviewed and explained. The next step taken in the thesis work has been the review of the standards which are defining what is electronics cooling fan, defining applications of such fans, and requirements set for manufacturers of fans. The IPC-9591 standard has been defined as the most applicable standard for such appliances. The mentioned standard has been reviewed and deeply analyzed, with the derivation of the main requirements stated in the standard to fan manufacturers, which considered fans' design, manufacturing, storage and transportation, testing, and reliability assessment requirements. For a deeper understanding of the testing methods, it has been needed to review the electrical fan's construction and its components. After completing a review of the fan's construction and components, the analysis of the failure modes and effects has been completed.

At the practical stage of preparation of this thesis work, the review of the existing test setup and procedure together with all the earlier completed updates have been reviewed, aiming to define possible improvement points in the testing project. After weak or missing points have been defined, the implementation of the improvement has been completed and described. What is more, several improvement points have been defined and proposed for the review in the Company, aiming to be considered in the future, long term development of the project. Some of the proposed ideas have entered the active discussions stage and possibly might be implemented in the nearest future when the priority level of tasks will be defined. Worth mentioning is the review of the fan failures observed and analyzed during the testing in frames of this thesis work, which confirms the importance of testing for the company and the importance of continuous improvements in the testing procedure. Verification with the testing standards compliance in this testing project has been an additional outcome of the thesis work and which is beneficial for achieving high testing standards for the Reliability Team of Electronics Company, for which this thesis has been completed. The updated test procedure has been presented in the format of the checklist, which has already been taken into use for preparation and running fan ALT testing rounds, on regular basis. All the testing preparation results, testing results, and after testing results, and required information should be noted in the Test tracking table and Test summary table documents.

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Appendix 2 – Electrical requirements specified by the fan manufacturing company to the customer [14]

Appendix C
Electrical Requirements

All the tests of Appendix C are performed at free air and room temperature unless otherwise specified. All results are nominal (not worst case) unless otherwise specified.

	Section 1: Current and Voltage Start-Up	Specification	Units	Notes
1.1	Nominal input voltage for fan operation		V	
1.2	Tachometer output starting voltage		V	
1.3	Minimum motor starting voltage		V	
1.4	Worst-case maximum peak startup current draw, including start-up, speed change, and in-rush		A	
1.5	Tach output leakage current (sink to supply voltage rail or source from supply voltage rail)		µA	
1.6	Reverse polarity protection included?			[ ] Yes [ ] No
	Section 2: Spin Up Time	**Specification**	**Units**	**Notes**
2.1	Maximum time to reach 100% RPM during power up to nominal voltage with PWM at 100% duty cycle		s	
2.2	Minimum time to reach start up operational speed		s	
	Section 3: Operational Current and Voltage	**Specification**	**Units**	**Notes**
3.1	Maximum operational voltage		V	
3.2	Minimum operational voltage		V	
3.3	Continuous power dissipation		mW	
	(All specifications for Section 3.3 of IPC-9591 are in reference to the source voltage rail at all valid temperatures)			
	Section 4: PWM Control Input Signal	**Specification**	**Units**	**Notes**
4.1	Minimum start Pulse Width Modulated (PWM) duty cycle		%	
4.2	Maximum PWM frequency		KHz	Without causing erratic speed performance
4.3	Minimum PWM frequency		KHz	Without causing erratic speed performance
4.4	PWM high range		V	
4.5	PWM low range		V	
4.6	Operational duty cycle if PWM signal is not present		%	
4.7	Maximum pull up voltage on PWM signal		V	
	Section 5: PWM Modulated Power Rail Control	**Specification**	**Units**	**Notes**
5.1	PWM frequency		Hz	
5.2	Voltage high range		V	
5.3	Voltage low range		V	
	Section 6: Locked/Rocked Rotor Signal (Fan Failure Characteristics)	**Specification**	**Units**	**Notes**
6.1	Maximum locked rotor current		A	
6.2	Maximum current sink capability		A	
	Section 7: Tachometer Output Signal	**Specification**	**Units**	**Notes**
7.1	Number of pulses per revolution		N/A	
7.2	Maximum output low voltage		V	
7.3	Maximum output high voltage		V	
7.4	Max input voltage for tachometer signal without damaging the fan		V	
7.5	Pull up voltage supplied by the system		V	