Development and Analysis of Printed Circuit Board for Frost-Free Refrigerator.
At

Panasonic

A Thesis submitted in partial fulfillment of the requirement for the Award of the Degree of

Master of Engineering

In

Electronic and Communication Engineering

Submitted by

Shubham Chaudhary
Roll No: 802261002

Under the guidance of

Dr. Amit Munjal
Assistant Professor(ECED)
TIET, Patiala

Mr. Anand Singh
HOD
Panasonic Life Solutions

THAPAR INSTITUTE
OF ENGINEERING & TECHNOLOGY
(Deemed to be University)

ELECTRONICS AND COMMUNICATION ENGINEERING DEPARTMENT

THAPAR INSTITUTE OF ENGINEERING AND TECHNOLOGY
(A DEEMED TO BE UNIVERSITY), PATIALA, PUNJAB
JULY, 2024

CERTIFICATE

This is to certify that the work presented in this Seminar report entitled **"Development and Analysis of Printed Circuit Board for Frost-Free Refrigerator"** is in partial fulfillment of the requirement for the award of Degree of Master of Engineering in Electronics and Communication Engineering, submitted in the Electronics & Communication Engineering Department(ECED), Thapar Institute of Engineering and Technology, Patiala is an authentic record of my work carried out under the supervision of Dr, Amit Munjal, Assistant Professor, Electronics & Communication Engineering Department, Thapar Institute of Engineering and Technology, Patiala and Mr. Anand Singh, Head of Technology, Panasonic Life Solutions India Pvt. Ltd., Jhajjar, Haryana.

The matter embodied in this thesis has not formed the basis for the award of any other degree at this or any other university.

(Shubham Chaudhary)
Reg. No. 802261002

This is to certify that the above statement made by the student concerned is correct and true to the best of my knowledge.

24/7/24

Dr. Amit Munjal
Assistant Professor
Electronics and Communication Engg. Dept.
Thapar Institute of Engineering & Technology
Patiala 147004

Mr. Anand Singh
Head of Technology
Panasonic Life Solutions India Pvt. Ltd., Jhajjar 124103.

CERTIFICATE

Panasonic

Panasonic Life Solutions India Pvt. Ltd.
Industrial Plot No. 1,
Village Bid Dadri, Jhajjar
Haryana - 124103, India

31st May,2024

Mr. Shubham Chaudhary
Thapar Institute of Engineering & Technology
Patiala (Punjab)

<u>Certificate of Internship</u>

This is to certify that Mr. **Shubham Chaudhary**, a student of **Thapar Institute of Engineering & Technology, Patiala (Punjab)** was undergoing an Internship for **11 Months** i.e. **(3rd July'23–31st May'24)** and has successfully completed the project in **"R&D"** under the guidance of **Mr. Anand (DGM-R&D Technology).**

Mr. Shubham Chaudhary has been sincere and hardworking during the internship; we wish him the very best for all the future endeavors.

Yours Faithfully,
For Panasonic Life Solutions India Pvt. Ltd.

Tushar Verma
Sr Manager - HR

Registered Office : 12th Floor, Ambience Tower, Ambience Island, NH-8, Gurgaon-122002, Haryana.
Website : www.panasonic.in Email : contact.pi@in.panasonic.com CIN No. U31200HR1981FTC088701

ACKNOWLEDGEMENT

A noteworthy task is never crafted by only one person but the commitment of various individuals in their distinctive ways makes this achievable. A gesture of thanks to my professor Prof Kulbir Singh, Head of Department, Electronics & Communication Engineering Department(ECED), Thapar Institute of Engineering & Technology, Patiala, who has allowed me to work in this field.

It has been a matter of privilege and benefit to perform my **project in the Research and Development Refrigerator Panasonic Life Solutions India Pvt. Ltd., Jhajjar, Haryana**. I would like to extend my gratitude to my guides, Dr. Amit Munjal, Assistant Professor at Electronics & Communication Engineering Department (ECED), Thapar Institute of Engineering & Technology, Patiala, and Mrs. Anand Singh, Head of Dept. **at R&D, Technology Team, Panasonic Life Solutions India Pvt. Ltd., Jhajjar, Haryana** for their profitable supervision and also for all the mentoring throughout the project work till now. I appreciate their valuable advice and consistent encouragement throughout this journey. I think about it as an extraordinary chance to do my thesis program under their direction and be able to learn the systems of research skills.

I also express my feelings of appreciation and commitment to each one of the individuals who encouraged and helped me in the completion of this piece of work. At last, I would like to thank my family and friends for helping me survive all the stress and for not letting me give up. The incredible support and constant encouragement provided by them helped me throughout my research work.

(Shubham Chaudhary)

Reg. No. 802261002

ABSTRACT

The advancement of refrigerators and their utilization is rapidly increasing day by day. However, the reliability and availability of the components pose a critical effect on the development of new technical features and products such as PCB. PCBs are the main part of the refrigerator which is used to maintain cooling intelligently in every compartment of the refrigerator. The main focus of this project is to develop a better alternative to Printed Circuit Board than the previous one used by Panasonic. The previous PCB used in the refrigerator faced some component shortage issues in the upcoming year. So, we need to come up with a new solution that will not affect the performance of the refrigerator and also come with less cost as compared to the previous one.

Therefore, here in this study shows the finest-developed PCB for good performance and better energy consumption. For this, we compare and select the components on various factors like performance, availability, and cost of the components. After the selection of components, we perform both part-level and product-level which verify the safety of PCB usage and the performance of PCB w.r.t. the previous PCB used in the refrigerator. The results show that the new PCB produces better results, however, we go with this PCB because of its cost-effectiveness and availability of components. But in the future, as advancement in components occurs and the availability of components also meets the requirement then we further can enhance the energy efficiency of the refrigerator.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF GLOSSARY

Nomenclature

Δt	Temperature rise (°C)
R1	Cold Resistance ()
R2	Resistance after Operation ()
T1	Ambient temperature during cooling (°C)
T2	Ambient temperature after operation (°C)

Abbreviation

PCB	Printed Circuit Board
D.A.	Design Automation
DPI	Dot Per Inch
SIR	Surface Insulation Resistance
ROSE	Resistivity of Solvent extract
EMI	Electromagnetic Interference
EMC	Electromagnetic compatibility
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
SPD	surge protective devices
CFMF	Counter-electromotive Force
IGBT	Insulated Gate Bipolar Transistor
Si IGBT	Silicon Insulated Gate Bipolar Transistor
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
SIC MOSFET	Silicon Carbide Metal-Oxide-Semiconductor Field-Effect Transistor
PPF	Personal Protective Equipment

CHAPTER 1

INTRODUCTION

1 Introduction

The first working printed wire patent was introduced in 1903 by Albert Hanson, a German inventor, which was used to solve the problem of telephone exchange. But it was Paul Eisler's invention of the Printed Circuit Board (PCB) in 1936 which was a part of the radio set during the Second World War [6]. Since, PCB manufacturing and implementation has been described as the most expensive, complex, and time-consuming process [1]. The PCBs are generally used in different sectors according to their needs and the PCBs that are used single-side PCBs, Double-side PCBs, and Multi-side PCBs. However, in refrigerators, we mainly utilize single-side PCBs due to their simpler circuit design and low manufacturing cost. Refrigerators have strongly evolved since their invention with cutting-edge technology such as an increase in efficiency sustainability, size, and accessibility.

1.1 Development of PCB and selection of components

In the modern era of appliances, printed circuit boards are the key component. PCBs are essential parts that control the temperature, defrost cycles, and energy management. Dependability, enhanced performance, and user comfort are all possible by introducing development in PCBs, both as hardware and as algorithm changes for refrigerators. With some changes in technology and development, will see changes in refrigerator cooling performance and energy consumption of refrigerators.

1.1.1 Evolution of Refrigerator PCBs

Evolution in refrigerator PCBs happens due to the development of algorithms, sensor integration and semiconductor technology. In the early period function of PCB was only to control compressor operation and defrost cycle. Over some time these have evolved into complex electronic systems with temperature sensors, diagnose ability and adaptive defrost algorithms. To meet the needs of consumers, upcoming refrigerators are equipped with smart PCBs that include wireless connectivity (Wi-Fi/Bluetooth), Internet of Things (IoT) integration, and advanced energy-saving functions. PCB of frost-free Refrigerator as shown in figure 1.1.

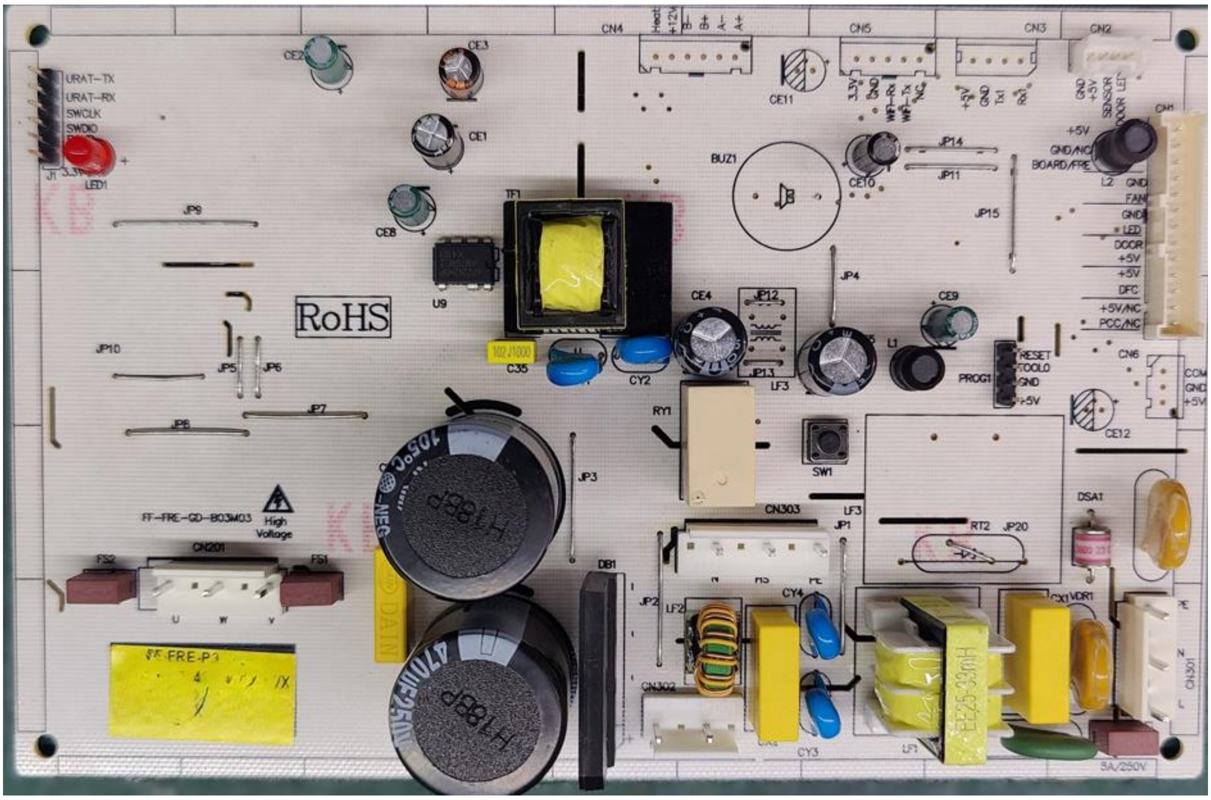


Figure 1.1 Printed Circuit Board of Frost Free Refrigerator.

1.1.2 Selection of Components

Components that are used in PCB design involve several factors like requirement, efficiency, reliability and price. Currently, in the market, there are a very large number of electronic components present which makes the selection process difficult. But when we select the components we need to carefully monitor the electrical specification, environmental condition, and manufacturer and distributor website for quantity.

Components that are used in the PCB have a direct impact on its functionality and performance in the long term. Every component used in the circuit has its contribution to operation whether it's an active component like an integrated circuit (IC), microcontroller, sensors or passive components like capacitors, resistors and inductors.

1.2 Refrigeration System and Internal Parts of Domestic Refrigerator

All household refrigerators and refrigerator-freezers mainly work on the vapour compression refrigeration system cycle. The vapour compression refrigeration system is an improved version of air compression because in it the working substance Refrigerant R600a is used. In this system condensation and evaporation occurs close to the atmospheric condition.

Now about the cycle process, the refrigerant that we used in the system does not leave but it circulates throughout for condensing and evaporation purposes. The condenser's main purpose is that give out the absorbed latent heat to its surrounding medium air or water. When the condenser works it works at high temperature and high pressure. On the other hand in an evaporator refrigerant flows at low pressure and low temperature which absorbs the latent heat and the chamber to cool which we can that in Figure 1.2. The advantage of the system is that it can achieve very low temperatures very easily and fast. The disadvantage of the system is that be aware of leakage.

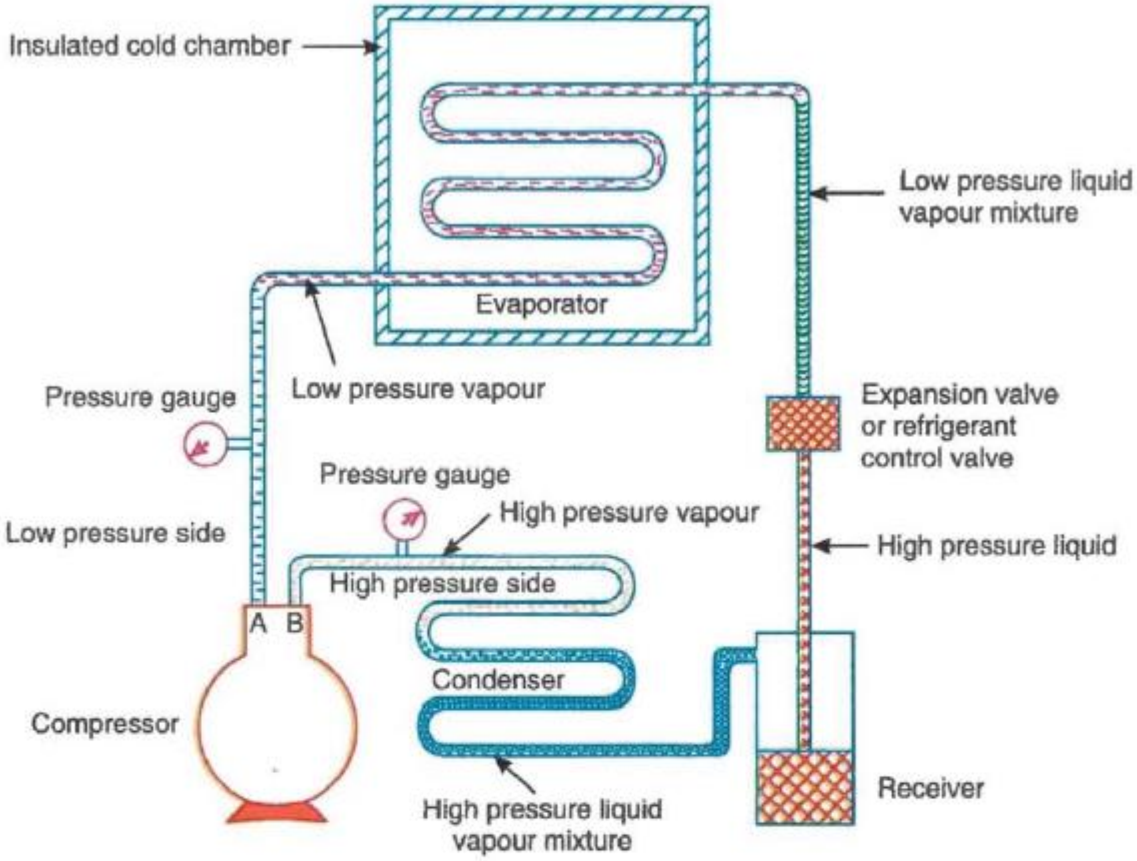


Figure 1.2 Simple vapour compression refrigeration system

1.2.1 Components of Refrigeration System

The components of the vapour compression refrigeration system are as follows and shown in Figure 1.3.

a) Compressor
b) Condenser
c) Expansion valve
d) Evaporator

a) Compressor

In the refrigeration cycle compressor plays an important role in storing the refrigerant. It compressed the refrigerant to high pressure and temperature and released it to the condenser which is shown in figure 1.3.

b) Condenser

The next important component of the refrigeration cycle is a condenser. The condenser condenses the high-pressure and high-temperature vapours into the liquid by releasing the latent heat to the surrounding medium as shown in Figure 1.3.

c) Expansion Valve

The expansion valve or dryer measures the quantity of refrigerant given to the evaporator through the capillary and lowers the pressure.

d) Evaporator

Evaporators or Eva coils used in the system is to transform the refrigerant from liquid to gas while absorbing the heat from the inside of the product as shown in Figure 1.3.

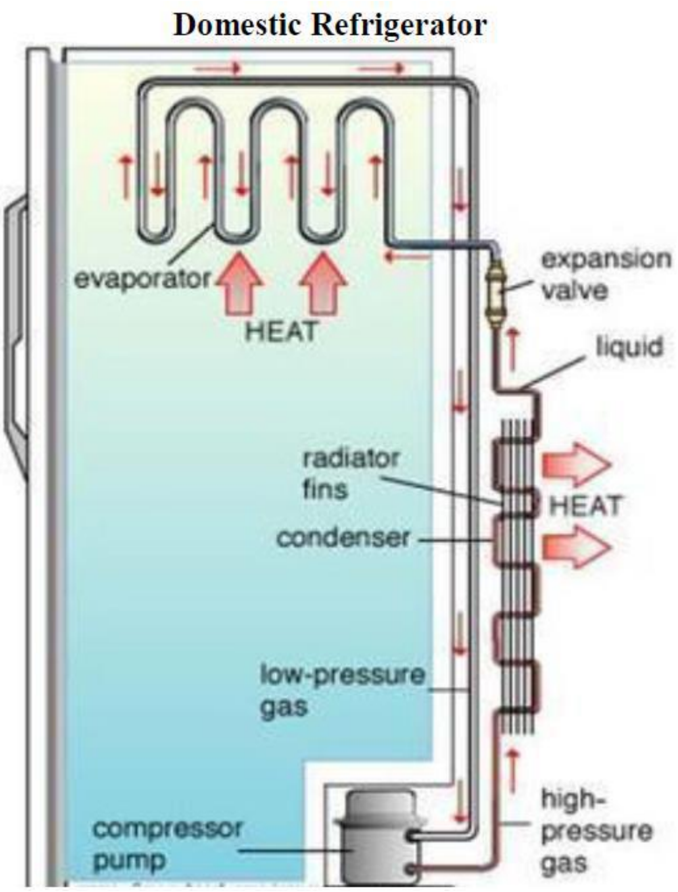


Figure 1.3 Component of refrigerator

1.2.2 Internal Parts of Domestic Refrigerator

Refrigerator parts that make the refrigerator function properly are explained as follows

1. **Refrigerant:** The refrigerant is the main and the most active component in the refrigerator. The refrigerant changes its form from vapour to liquid and goes through a phase change to move heat outside of the refrigerator. It works on both high and low pressure and temperature. By all this it able to provide a cooling effect to the evaporator.

2. **Compressor:** Refrigerant is drawn out from the evaporator through suction and then it again compresses and releases at high pressure and temperature to the condenser. The compressor is the second main high-power component of the refrigerator which is powered by an electric motor.

3. **Condenser:** The condenser is coil and pipe which is mainly made up of aluminum. The condenser takes the refrigerant from the compressor at high speed and temperature, where it loses its heat to surroundings which it takes from the evaporator. Condensers are mainly located at the back side, right side, and left side of the refrigerator.

4. **Evaporator or freezer:** The evaporator is mainly constructed as the round tube-like structure shown in Figure 1.3 and is made up of aluminum. In this, the refrigerant comes from the expansion valve which is at low pressure and temperature. It absorbs the heat from the inside of the refrigerator to refrigerant before being drawn to the compressor

5. **Temperature control devise or thermostat:** The temperature sensor is attached to the evaporator and in the refrigerator compartment dial, regulates the temperature within the refrigerator. The circular knob located within the refrigerator compartment is used to adjust the temperature. The temperature sensor also helps to stop the compressor's power supply when the refrigerator reaches its predetermined temperature and the compressor resumes again when temperature changes.

6. **Defrost system:** The refrigerator defrost feature aids in clearing the extra ice present on the evaporator during continuous running. The defrost heater and timer are part of an automated system that activates when the temperature of the evaporator reaches the cut-off point. It can be used as both manual and automatic operation.

7. **PCB:** The PCB is the main part or component of a refrigerator. Because it controls all functions of the refrigerator. It is responsible for controlling the temperature in the PC and FC compartments. PCB also controls the defrost heater to remove extra ice. PCB is also responsible for maintaining the temperature inside the refrigerator according to the room or ambient temperature.

1.3 Thesis Outline

Chapter 1 gives an introduction to the refrigerator cycle and its components. It includes the development and selection of PCB components, processes, and requirements of the present work for that is development of PCB. Chapter 2 is a literature review that I read while researching my thesis. This review presented me with a variety of key points, useful data, and important information for my current study, which has been presented in Chapter 3. This chapter gives the methodology and formulation that were used to model the development process. It describes the component change, PCB testing, change, and validation of the refrigerator cycle with energy enhancement. It describes in detail the equipment used, methods, and materials used in testing. Chapter 4 explains the findings with results with graphical and tabular data which distinguish the difference between the mass production and development of PCB. Chapter 5 presents the detailed conclusion of the current work.

CHAPTER 2

LITERATURE REVIEW

Below here is the literature review on printed circuit boards, inverters, IGBT, refrigerators, and refrigerator cycles by various scholars. According to the review's findings, there are a few things that we can adopt for development work. In the development of PCB, the crucial thing is the selection and working of components. After that, some tests are to be performed at the part level and product level.

2.1 ANALYSIS OF PRINTED CIRCUIT BOARD

Ken Gilleo and Jerry Murray (1999) researched and reviewed the history of printed circuit boards. Alexander Graham Bell demonstrated the need and importance of communication for the modern world. So, telephones and radios were invented, but complex circuits and hand wiring made it impossible to make circuits error-free. In 1903, **Albert Hamson** of Berlin filed the first patent on a printed circuit for solving the problem of handwriting. **Thomas Edison** and **Frank Sprague** found the adhesive to separate printed circuit patterns from conductivity on board and the adhesive was polymer glue, patterning dielectric with silver nitrate solution. Finally, it was **Paul Eisler's** invention of the Printed Circuit Board (PCB) in 1936 which was a part of the radio set during the Second World War. So, this is how the Printed circuit board emerged with time [1].

Harvel Maekrevel (1978) their study show the types of PCBs and the cost-effective solutions. The product design process of designing a PCB was mentioned as the most expensive and time-consuming process. So, there are different approaches when choosing an approach broad categorization is something that needs to be focused on. PCB is divided into four types. Analog boards were largely made up of discrete components and digital boards were mainly based upon logic devices. In some PCBs, analog and digital components were mixed. Some boards have special mechanical requirements for those we had to define the distinct types of components for the design automation system (D.A.). For digital designs, we had to consider various factors which include the number of design approaches, number of components, component density, particular circuit requirements, and whether the design was compatible with the existing D.A. system [2].

Jerry Branson and John Naber (2000) demonstrate the simplistic way of the printed circuit board fabrication process. Therefore the disclosed PCB manufacturing methodology offers a variety of benefits over the standard approach. These methods reduce the capital and manufacturing expenses, faster changeover time, and reduce dependency on wet processes. These approaches come upon a mix of both quality and financial states, which deliver cutting-edge trace widths and spacing as thin as 4 mils using a 300 DPI laser printer. This yields around 1.2 printed dots per 4 mil line. 1200 DPI laser printer is thought to be capable of duplicable printing lines as thin as 1 mil. This process can only be expanded to two-sided boards with additional attention to mask alignment before iron transfer. Mask alignment is critical for good results. Therefore the above concept has been used successively by certain teams to develop two-sided, through-hole designs with much lower footprints [3].

Daren Slee, Jeremiah Stepan, Wei Wei, and Jan Swart (2009) their study investigated the low-rate failure modes in printed circuit boards, which results in circuit failure and burning faults. The failures result in a wide range of PCB-related faults and flaws which can be common and rare. This study stresses the faults in low-rate failure modes in the context of PCB reliability and performance. The reasons for faults and failures sequence are resistive heating, interconnection, overheating, contamination, component failures, design margin, etc. Sneaky pathways were the result of manufacturing faults and physical harm. Some of the faults can be solved during the design time by providing accurate path size which reduces heating and making use of material or coating that is contamination-free for use [4].

Xiaofei He et al. (2012) studied and came up with a solution for insulation resistance and surface contamination of PCB. The IPC-B-52 design was able to produce good test results and determine the importance of cleanliness. Different testing was used in this study to assess the process, and downside and develop ranking criteria the methods were surface insulation resistance (SIR), resistivity of solvent extract (ROSE), IC testing, and optical inspection. Therefore, the sustainable connection between these tests results only for the most polluted boards which demonstrates the effectiveness of these approaches. For less contaminated boards results were less consistent to get the desired results, we need fluxing systems connected with proper cleaning techniques [5].

2.2 PRINTED CIRCUIT BOARD TESTING PROCESS AND CRITERIA

The literature evaluation below employs a variety of testing procedures to determine whether PCB is suitable for usage in the product.

Montrose, Mark I (1996) explains the PCB design techniques for electromagnetic compatibility (EMC) compliance which helps to reduce the generation of electromagnetic interference (EMI) between the components. EMC was able to produce an environment to operate in its specified electromagnetic region without any damage, functional degeneration, or danger. EMI is linked with radio frequency transmission in which the transfer of electromagnetic radiation from one electronic equipment to another via a conducted path may hamper. Different IEC standards were used to design PCBs to ignore EMI. It only happens with optimum printed circuit board design while retaining all system operations [6]. **Byong-Su Seol et al.** (2008) research shows an electrostatic discharge (ESD) model for a simple and effective circuit model. This model helps the circuit designers quickly check the ESD properties of their PCB design and the software used is a simulation program with an integrated circuit emphasis (SPICE) – compatible circuit simulator. With such techniques, PCB designers were able to produce improved electrical performance PCBs from the base stage of the design and the incurring cost is very low [7].

Ronatd B. Standler (1993) this paper analyses the different factors that influence the design and installation of surge protectors and checks the protector's performance. As of 1993, there was no standard for surge suppression approved by the IEC, ANIS, or IEEE. Due to this, the author underwent for creating the performance standard, notable through IEC 37A. The main focus of the standard was on voltage protection level, potential fire, isolating failing varistor due to surge current, failure indicator, and excessive current leakage [8]. **A. M. Ariffen et al.** (2011) study explains the effect of using surge protection devices (SPD) in the circuit. Study shows that using filters as an isolating element between stages of SPD increases the performance. With additional filters, there was 38% of let-through voltage than those without filters resulting in an experimental activity. This modification results in a more dependable and protective approach for SPD [9].

J. CHATZAKIS et al. (2007) their study shows how a spike protection system was built, designed, and tested for electrical testing. This system successfully creates similar spikes as we can see in electrical power networks. This system identified the vulnerability in the appliance and with this system, we were able to deploy more strong protection measures against electrical fluctuation. The circuitry of the spike protection system was designed in a way that reduced the occurrence of defects which was crucial for testing. At last, the properties or values of the spike were regulated by the Personal computer or device [10]. **Peiravi, Ali** (2009) explains the test techniques for PCB used for high-reliability consumer electronics. These tests were conducted because of the faults in the PCB which were related to delamination, failure mechanism, and plated-through hole (PTH) failure. Design changes were made to solve these faults, which was followed by accelerated life testing on 10 to 20 PCB samples. The tests we perform to check the reliability of PCB are temperature cycle, vibration cycle, and mixed cycling. When the testing was completed the outcome was product had a high dependability rating when compared to locally-made electronic consumer items [11].

Arabi, Faical, et al. (2018) in this work PCB went under examination for mechanical testing. Here, the main focus was on the vibration testing and simulation of the printed circuit board. PCBs are of two different frequencies in nature one is isotropic and another one is anisotropic. PCB has a different nature and works on different frequency values, PCBs measuring the vibration were completely based upon the frequency change in the program of PCB [12]. **Lahokallio, et al.** (2013) their study was based on endurance testing of extreme environmental conditions. Tests were performed under high humidity and high-temperature environments. Polyimide (PI) showed outstanding results under severe environments. During the test despite water absorption, PI’s thermal, chemical structure, and working characteristics remained unchanged with time making it the best choice for challenging conditions. However, water absorption creates some issues of delamination within some period [13].

2.3 INVERTER CIRCUIT AND IGBT

E. L. Owen (1996) David Prince begins his research of past work by looking into the operation of a single-phase full-wave center-tap rectifier circuit. The rectifier circuit produces the DC output which contains both passive resistance and reactance. Prince's figures depict ideal waveforms for a variety of circuit variables, such as potential and current at the AC and DC terminals. The first diagram of the rectifier circuit is structurally similar to Today’s diagram, but the only difference is the vacuum tube symbol (diode). But then advancement in grid-gate control of the rectifier and use of counter-electromotive force (CFMF) source instead of load resistor [14]

Noriyuki Iwamuro et al. (2017) Insulated gate bipolar transistor (IGBT) plays an important role in this project and this research shows the IGBT history after more than three decades how silicon insulated bipolar transistor (Si IGBT) technology. The advancement is far from done, ongoing efforts were put into improving power density and efficiency. Although a significant improvement, the financial gap between Si-based systems and those employing wide bandgap transistors in terms of "costs/power" is expected to narrow, both devices had their own distinct merits and demerits. However, the wide bandgap and Si power devices would last for more than two decades. Both power devices continue to serve for varied applications [15].

M.E. Lahlaci et al. (2024) study explains the electromagnetic compatibility of conducted electromagnetic interference from IGBT in the power supply. The main difference that separates IGBT from MOSFET is its ability to provide smoother switching, lower harmonics, and electromagnetic interference during switching time. The feature is important for electromagnetic compatibility because smoother current transmission lowers the possibility of EMI emission. MOSFETs are more suited for fast switching and low-frequency applications, but IGBTs better work with Low-frequency and high-frequency situations. The behavioral difference between MOSFET and IGBT is switching time, MOSFET has shorter switching time and IGBT has longer switching delays. Therefore IGBTs are better for inverter circuit usage [16]. **A. Albanna et al.** (2016) work shows the saber model of the currently low-scale use 1200V 300A SIC MOSFET module and compares it with the Si IGBT model with the same rating. The results show that 1200V SiC MOSFET has a quicker switching speed and much lower loss than industrially available Si IGBT. Although Si IGBT exhibits a higher rise in switching loss at higher operating temperatures, the SiC MOSFET maintains constant switching loss throughout temperature ranges; this last aspect will be elaborated in the research's final version [17].

Chang, Wen Ruey, et al (2004) this study represents a significant advancement in household appliances with the arrival of inverter-controlled refrigerators. Refrigerators provide good features/operation, energy conservation, excellent temperature control, fast cooling, freshness prevention, and quiet operation. Variable frequency control helps modify the speed of the compressor which improves the performance of the refrigerator. By adjusting compressor speed and coordinating other parts in response to changing factors, variable frequency control enhances refrigerator performance. However, managing the appropriate control techniques and integrating all the parts were required to get maximum performance with shifting frequency, and the control sequence of the six-step inverter as shown in Figure 2.1 In appliance development, intellectual control is the most common trend overall. Software integration into appliances is becoming increasingly feasible thanks to the accessibility of inexpensive electrical and electronic components. Compared to prior systems, digitally controlled inverter-controlled refrigerators offer more precise temperature control [18].

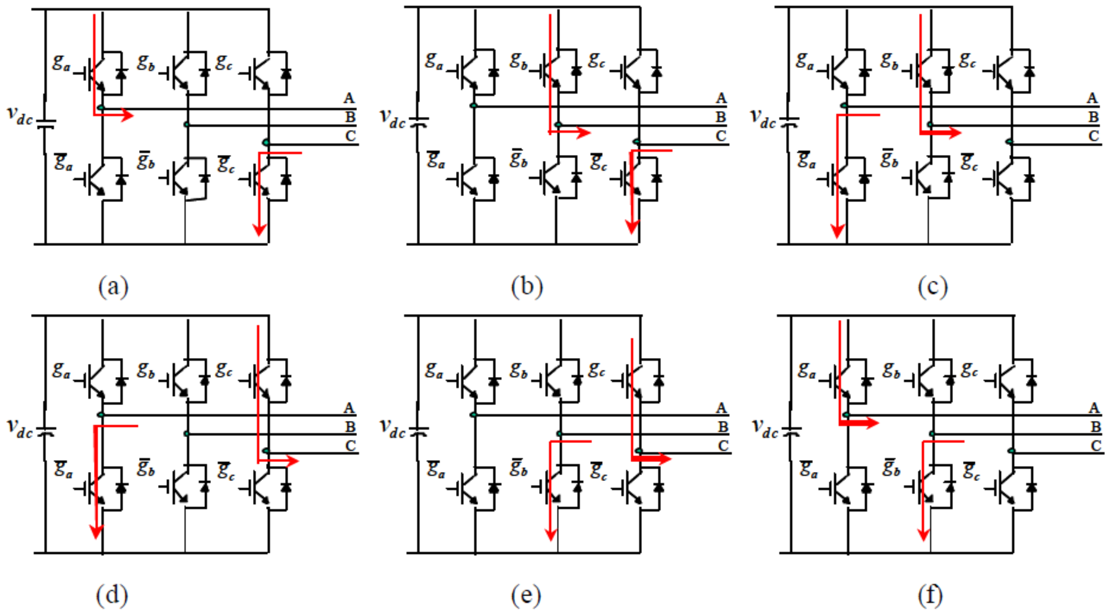


Figure 2.1 (a)-(f) Control sequence diagram for six-step driving inverter [18].

J. Li, M. Zhou, Y. Sha, W. Jiang and L. Wang (2024) This study builds a multi-physics field coupling model of an IGBT module, including its mechanical, thermal, and electrical components, using ansys. It looks at how temperature and humidity in the surrounding air affect the internal stress that IGBT modules experience during power cycle operations, the profile of the IGBT module is shown in Figure 2.2. Heat is transferred from the IGBT chips to the solder layers and bonding wires below throughout the power cycle.

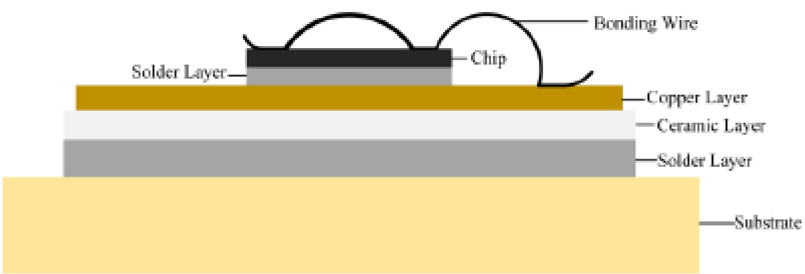


Figure 2.2 Profile of the IGBT module [19]

The stress in every IGBT module component grows with ambient temperature, speeding up the aging of the solder layers and the breaking of the bonding wires. Every IGBT module component experiences a little reduction in stress when the surrounding humidity rises. For the

IGBT module, there are more disadvantages than advantages to the overall increase in humidity [19]. **A.H. Sabry and P. J. Ker** (2020) in this study experiments were performed on variable speed compressor refrigerators to check the performance of refrigerators with solar power voltage sources. By using this system refrigerator performs very well and helps save energy [20].

2.4 REFRIGERATOR CYCLE AND ITS TESTING METHODS

G Venkatarathnam, Badr, et al. (1990) several studies were combined in this work which explain how several refrigerators had appeared and disappeared in the last 150 years. The one that lasted for a long time was chlorofluorocarbons (CFCs) and it disappeared because of ozone depletion. After this hydrofluorocarbons (HFCs) were the replacement for CFCs, but later detected that they had high global warming potential (GWP) and phased out. So, natural refrigerants like ammonia, carbon dioxide, and hydrocarbons were used until future breakthroughs [21].

Akintunde et al. (2011) in the refrigerator the positions of the main components, compressor, condenser, expansion valve, and evaporator operating characteristics such as mass flow rate, the temperature had a direct impact on its performance. In this study, the rig is used to test different settings with similar pattern, rig image is shown in Figure 2.3.

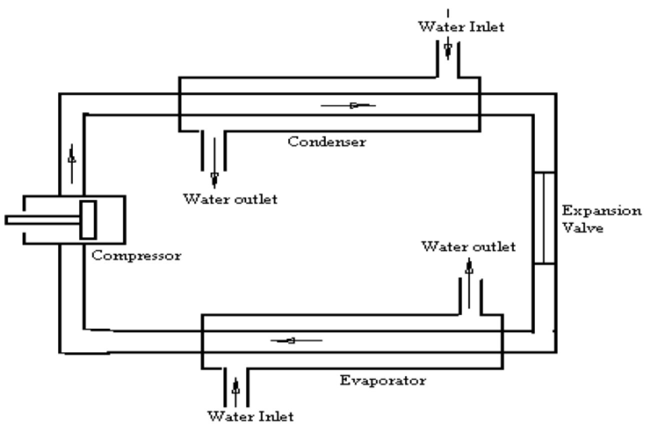


Figure 2.3 schematic representation of the test rig [22].

Change in coefficient of performance (COP) between the original model and experimental rig follows the same pattern. Data recorded in Excel format and calculation reveal that the value of COP under sub-cooling and sub-heating conditions were 80.7% and 88%, respectively. Then after this, there is a comparison between COPs settings were 88% and 99.9%, respectively [22]

Ding, Guo-liang (2007) this study shows the coupling of boundary parameters components with simulation techniques for designing vapour compression refrigeration system. It provides stability, speed, and precision, various simulations on various models were performed for unique results and coupling of boundaries among components as shown in Figure 2.4. The main concern with this simulation technique and models was noise. It is critical to consider the noise created by the refrigerator and its components.

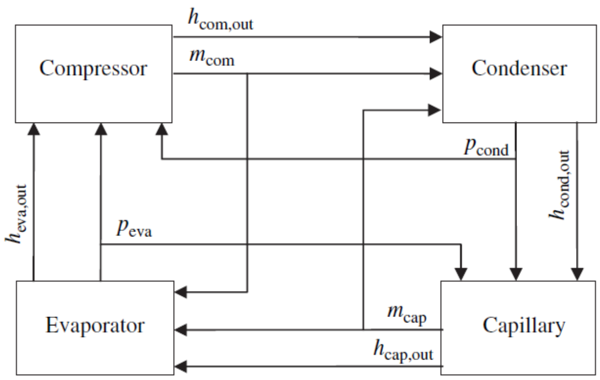


Figure 2.4 Coupling of boundary parameters among components [23].

Simulation tools primarily address fluid noise, therefore more thorough designing approaches were required to measure refrigerant flow noise, vibration noise, and other sources of noise in the refrigeration process [23].

All household refrigerator appliances have to follow Indian standards for manufacturing, buying, and sales. Refrigerators both direct cooling and frost-free must follow IS 17550:2021. Meeting different requirements we had to follow the whole standard which was divided into three parts. First, check the energy consumption and volume requirement in part 3. For performance checking, part 2 is responsible and all tests were in it. Part 1 had all the measurements and dimensions of the refrigerators below figure 2.5 shows the 5-star rating.

Star rating band	Annual Energy Consumption (kWh/year)
1 Star *	(0.157* Vtot+243) ≤ AEC < (0.180* Vtot+279)
2 Star **	(0.136*V_{tot}+211) ≤ AEC < (0.157* Vtot+243)
3 Star ***	(0.118*Vtot+184) ≤ AEC < (0.136* Vtot+211)
4 Star ****	(0.103* Vtot +160) ≤ AEC < (0.118*Vtot +184)
5 Star *****	AEC < (0.103*Vtot+160)

Figure 2.5 BEE rating Frost Free Refrigerator (Valid from 1st January 2023 to 31st December 2024) [24].

However, it should be noted that this notice does not include refrigerating equipment other than single and double-door models [24]. **IS 17550** IS 17550 is further broken into three parts that discuss the various forms of product-level testing [25, 26, 27, and 28].

2.5 FUTURE COMMENTS FROM THE LITERATURE REVIEW

The analysis of the above-mentioned research papers led to the following conclusions regarding improving the switching speed off IGBT and improving the power consumption/ energy efficiency of frost-free refrigerators.

- Improvement of on/off timing is also going to impact the power consumption. We use the Japanese product specification for the software/algorithm implementation.
- Developing the PCB is one of the great challenges. While in the developing phase, we have to check or take every step carefully. The main focus is on the testing and validation of products.
- Cost reduction is the major point in the application of industry.

2.6 OBJECTIVE OF THE PROJECT

- ❖ Performance and Evaluation of New Inverter Circuit Components
- ❖ Verification of PCB Functionality through Part-Level Testing to Confirm Specifications of Standards.
- ❖ Validate Newly Developed PCB with Old PCB through Product-Level Testing for Checking Refrigerator Performance.
- ❖ Analysis of Energy consumption and performance enhancement compared with the old model.

CHAPTER 3

METHODOLOGY

This section deals with the methodology that we followed to achieve the goal. The basics of the inverter, IGBT, and refrigeration cycles are also discussed in this section. It can be well defined through the following flow chart shown in Figure 3.1.

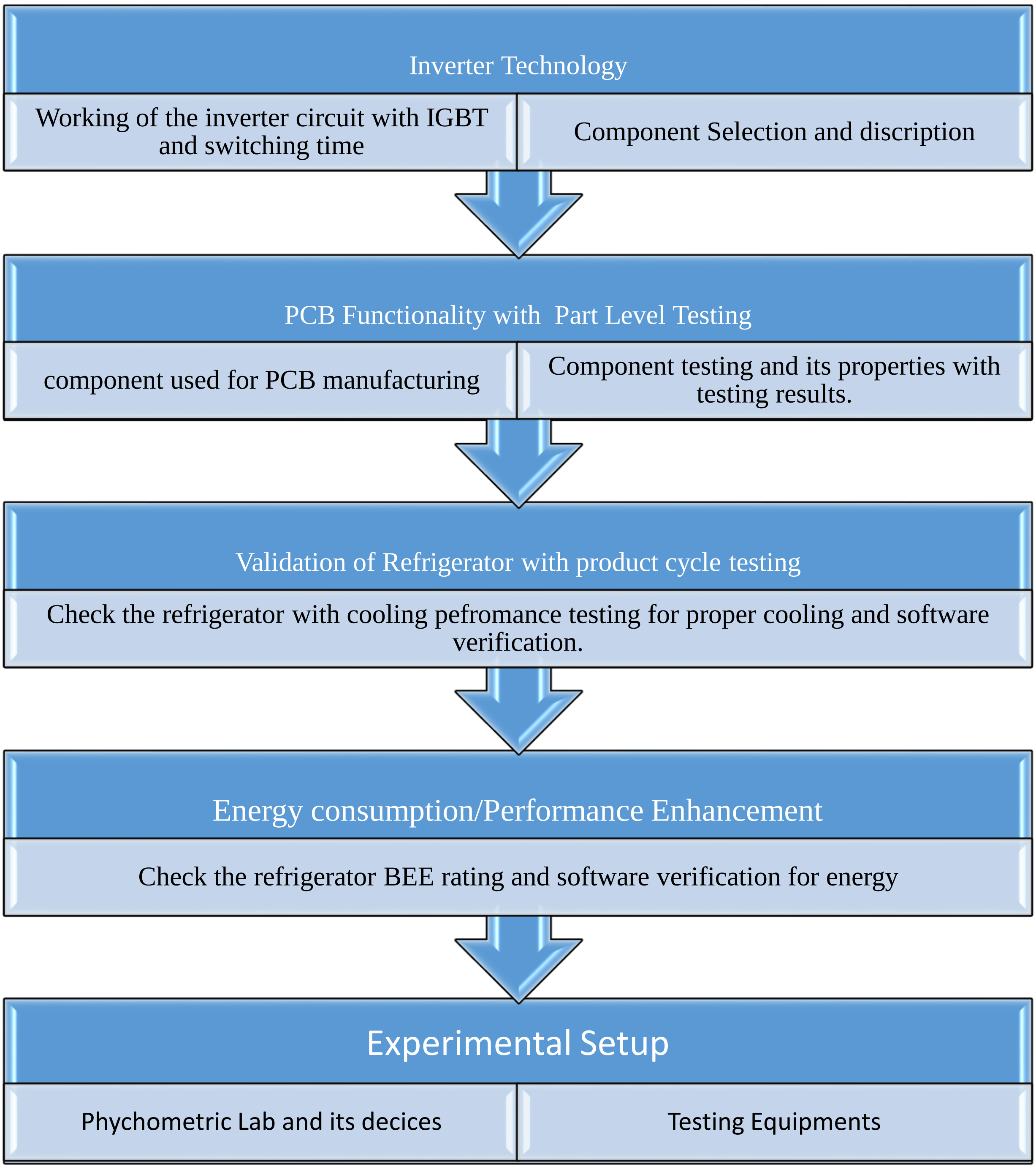


Figure 3.1 Flow Chart of Methodology Followed.

3.1 INVERTER TECHNOLOGY

Electronic parts called MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors) or IGBTs (Insulated Gate Bipolar Transistors) are used in inverter technology to transform direct current (DC) into alternating current (AC). This technical term is widely used in many different industries, including electric cars, renewable energy systems, uninterruptible power supplies (UPS), and home appliances like refrigerators and air conditioners. Inverter technology makes it easier to control the speed of the compressor motor in refrigerators. This allows for variable-speed operation, which improves energy efficiency over fixed-speed compressors.

3.1.1 INVERTER CIRCUIT

The compressor motor speed is controlled by the inverter circuit in a refrigerator. Refrigerators using inverter technology have variable-speed compressors, as opposed to traditional refrigerators, which have fixed-speed compressors that run at a constant pace regardless of cooling demand. Variable speed compressor enables speed in response to cooling requirements, improving temperature control and energy efficiency. Given below is the basic overview of how the inverter circuit works in a refrigerator.

i. The inverter circuit makes it easier for rectification circuits to convert incoming electrical power from the mains into DC electricity.

ii. The DC electricity is then reintroduced and converted to AC power at the inverter step, which comes next. Power electronic components like MOSFETs or IGBTs are typically used at this level.

iii. Control logic for adjusting the frequency and amplitude of the AC output waveform is included in the inverter circuit. To determine the optimal compressor speed, the control logic monitors several characteristics, such as refrigerator temperature, door opening frequency, and user preferences.

iv. The AC output of the inverter circuit is directed toward powering a variable-speed compressor motor. The inverter controls the speed of the compressor motor by modulating the voltage and frequency of the AC power supplied to it. The compressor can increase speed for rising cooling needs and reduce speed to drop in cooling requirements. Below figure 3.2 shows the flowchart on the inverter circuit working and Figure 3.3 shows the inverter circuit schematic.

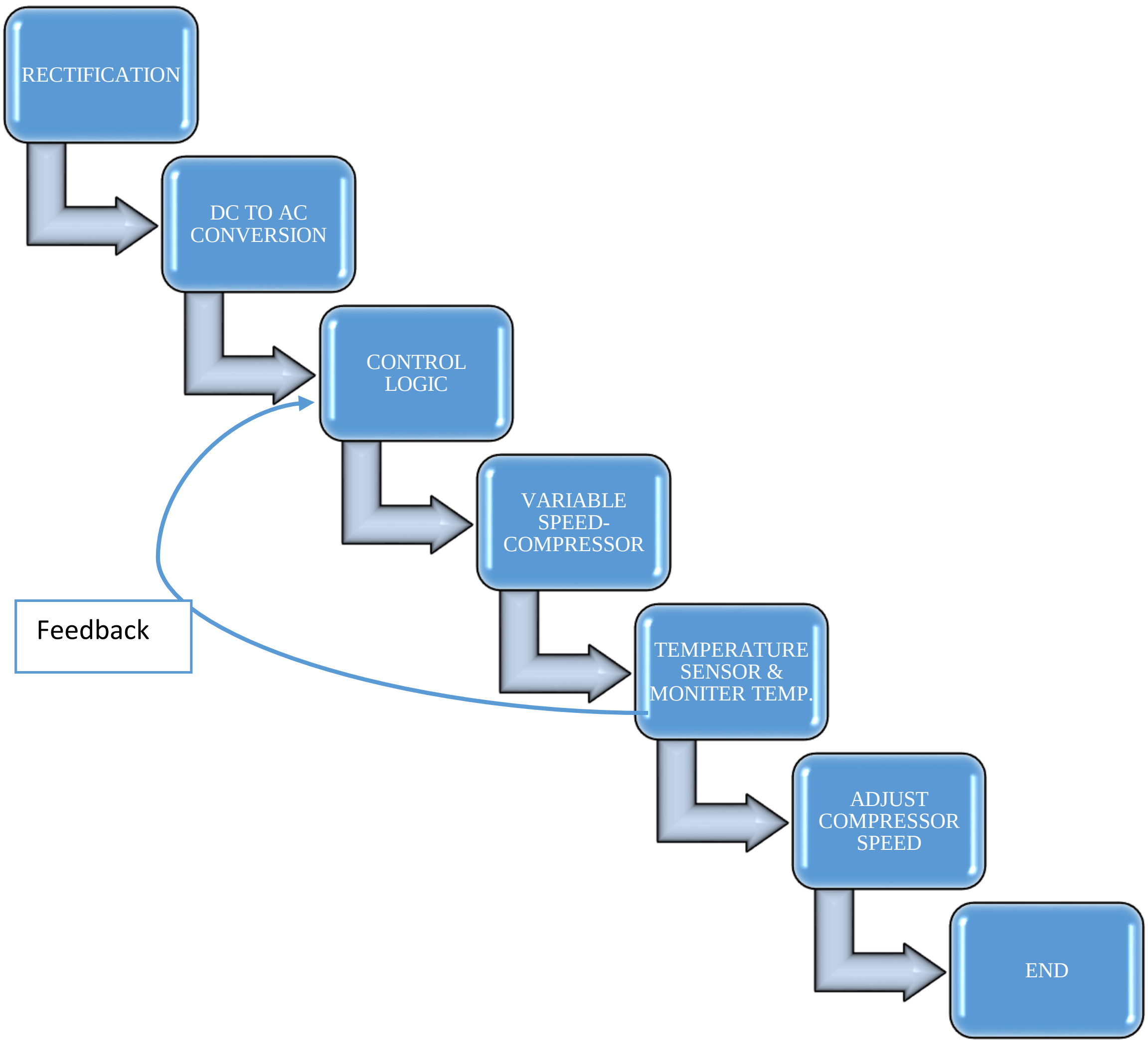


Figure 3.2 Flow chart on inverter circuit work process

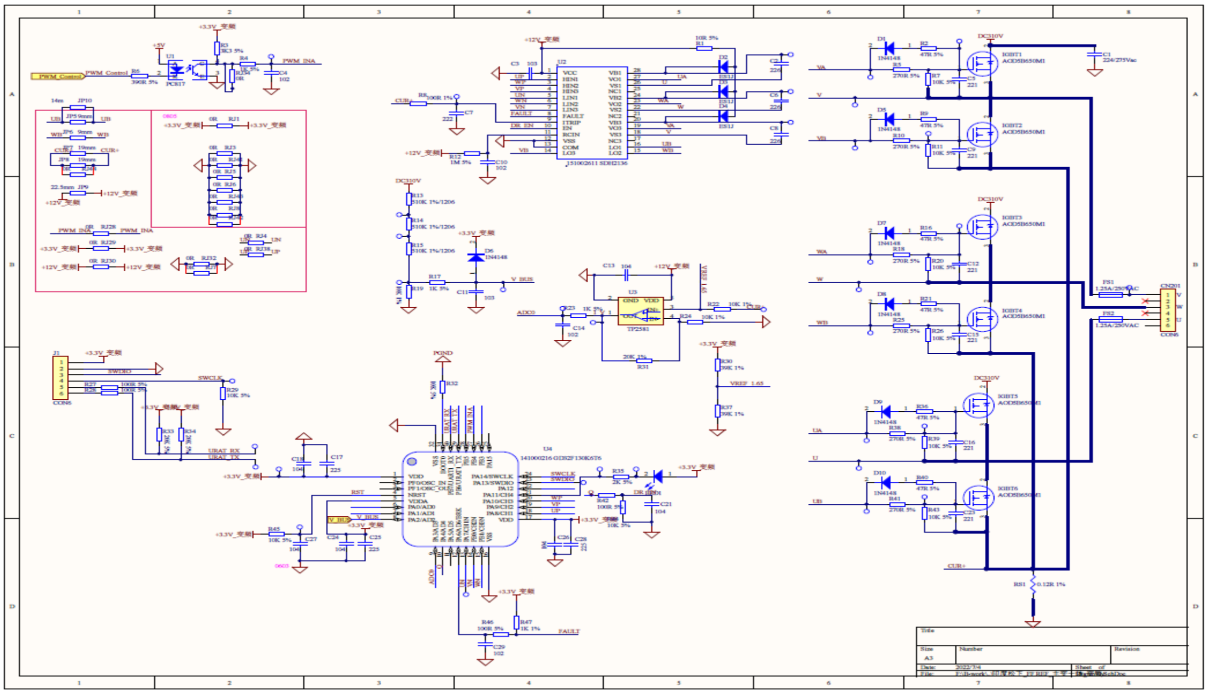


Figure 3.3 Inverter Circuit Schematic

3.1.2 Analysis of IGBT Functionality, Applications, and Advantages of IGBTs over MOSFETs in Power Electronics.

A Gate with Insulation the Bipolar Transistor (IGBT) is a semiconductor device that is the combination of the low on-state power loss of a Bipolar Junction Transistor (BJT) with the high input impedance and quick switching of a Metal Oxide Semiconductor Field-Effect Transistor (MOSFET). The emitter, gate, and collector are its three primary layers. The current flow between the collector and emitter is controlled by the gate terminal.

i. **Structure:** An n+ layer (emitter), a p-type layer (body), an n-type layer (drift), and a p+ layer (collector) make up the layered structure of IGBTs.
ii. **Operation:** Current can go from the collector to the emitter when a positive voltage is provided to the gate to the emitter. This causes electrons to be pulled to the gate and forms an inversion layer.
iii. **Switching:** Like MOSFETs, IGBTs are turned on and off by applying a voltage to the gate. However, they are appropriate for high-voltage and high-current applications since their switching includes both electron and hole conduction.

Applications of IGBT

Because of its versatility and ability to effectively manage high voltages and currents, IGBTs are frequently utilized in power electronics. Important uses consist of:

i. **Motor drives:** Used to regulate motor speed and torque in household appliances, electric vehicle (EV) motors, and industrial motor drives.
ii. **Inverters:** Used in renewable energy systems to convert DC electricity to AC power, such as solar and wind power inverters.

Advantages of IGBT over MOSFET

Power electronics uses both IGBTs and MOSFETs, although IGBTs have many benefits over MOSFETs, especially in high-voltage and high-power applications:

I. **Enhanced Voltage Handling:** Unlike MOSFETs, which are often restricted to 500V, IGBTs can withstand voltages of up to 1200V. As a result, IGBTs are better suited for high-voltage applications.
II. **Lower Conduction Losses:** Because of its low on-state voltage drop, which is similar to that of a BJT, IGBTs have lower conduction losses at high currents.
III. **Thermal Performance:** IGBTs are more reliable in challenging situations because they can run at greater junction temperatures and have superior thermal stability.

IV. **Switching Characteristics:** IGBTs have sufficient switching speeds for many high-power applications and offer an excellent balance between switching losses.

V. **Cost-Effectiveness:** Because of their efficiency and capacity to manage greater power levels without requiring a considerable amount of heat dissipation, IGBTs are more cost-effective than other devices. A comparison between IGBT and MOSFET is shown in Table 3.1.

Table 3.1 Difference between IGBT and MOSFET

Features	IGBT	MOSFET
Voltage Range	Up to 1200V and beyond	Typically up to 500
Current Handling	High-current capability	Lower current compared to IGBT
Conduction Loss	Lower at high current	Higher at high current
Switching Speed	Moderate	Faster than IGBT
Thermal Performance	Better thermal stability	Adequate but less robust
Cost	More cost-effective at high-voltage	More expensive for high-voltage

Here, the IGBT is crucial to the inverter circuit's development during PCB development. However, because of the worldwide semiconductor scarcity and the development of new alternative sources. Therefore, we had to carefully choose the component based on our needs for long-term usage.

3.1.3 Component Selection and Description for IGBT

Many important considerations need to be made when choosing components for an IGBT-based power electronics system, including switching speed, thermal management, voltage and current ratings, and overall system requirements.

IGBT Selection key parameters:

I. **Voltage Rating (Vces):** To guarantee safe operation, select an IGBT whose voltage rating is at least 20–30% greater than the highest voltage allowed in your application. For example, choose an IGBT rated at 800V or above for a 600V application.

II. **Current Rating (Ic):** Make sure the IGBT's current rating is sufficient for the highest current your application can manage in addition to a safety margin, which is usually between 20 and 30 percent.

III. **Switching Speed:** High-frequency applications require fast-switching IGBTs notwithstanding the possibility of larger switching losses.

IV. **Thermal Resistance (Rth):** To enhance heat dissipation and dependability, use IGBTs with low thermal resistance.

As a result, we have chosen **IGBT: JT05N065RED** and **IGBT: IXYP20N65C3D1M** as an alternative source after thoroughly examining the **IGBT: RGT16TM65DGC9** that we presently utilize in the MP PCB. Below in Table 3.2 are measured values of the IGBT performance that we currently using in the mass production of PCB.

Table 3.2 IGBT performance confirmation

IGBT：RGT16TM65DGC9		Specification Value	Recommended measurement value	Test Condition	Measured value
Voltage	VGES VCES	±30V 650V	＞10V.＜24V ＜520V	Voltage：230V, temperature: 20℃-70℃, (Output with compressor load), Rotating speed: 22RPS,44RPS,58RPS	min：11.01V max：12.5V max：385V
Electric Content	IC	6A	IC＜4A		MAX:5A
Short Current	ISG	-	＜32A, t＜4us		19.7A
IGBT C/E pole	TON	-	t＜800ns		max：350ns
IGBT C/E pole	TOFF	-	t＜800ns		max：200ns
IGBT C/E pole	TDE	-	＞1us		min：5us

But when we select the IGBT for the development of PCB we choose **IGBT: JT05N065RED** instead of **IGBT: IXYP20N65C3D1M** because of its easy availability in quantity and cost is also less.

Driving IC/ Gate Driver/ IC Driver:

Appropriate gate drivers are needed to effectively turn on and off IGBTs. The current and voltage needs of the IGBT's gate should be met by gate drivers.

Important variables:

I. **Output power:** Usually between 15 and 20 volts, the gate driver must supply enough power to completely activate the IGBT.

II. **Current Capacity:** To ensure rapid switching, the driver must provide enough current to charge and drain the gate capacitance rapidly.

III. **Isolation:** To shield the control circuitry from high voltages, isolated gate drivers are recommended for high-power applications.

Three separate driving ICs are used in MP PCBs. **L6391DTR (ST)** drives a three-phase IGBT, which drives a three-phase compressor. However, as an alternative, we are currently using the **SDH2136UTR (Silan)** single-driving integrated circuit to drive a three-phase IGBT compressor. Below in table 3.3 shows the driver IC performance, figure 3.4 shows the mass production PCB with driver IC and IGBT circuit diagram, and Figure 3.5 shows the new PCB driver IC and IGBT circuit diagram.

Table 3.3 Driver IC Performance Confirmation

Drive IC-2136		Specification Value	Recommended measurement value	Test Condition	Measured value
Output voltage of upper bridge/IC output voltage	VCC	20V	10-16V	Voltage ：230V, temperature: 20℃-70℃, (Output with compressor load), Rotating speed: 22RPS,44RPS,58RPS	min：11.01V max：12.5V
Logic input voltage	HIN/LIN	VSS-VSS+5			min：3.2V max：3.3V
HIGH Bridge gate output voltage	VHO	VS1,2,3-VB1,2,3			min：11.01V max：12.5V
LOW Bridge gate output voltage	VLO	COM-VCC			min：11V max：12.5V
Startup time delay	TON	550ns	425	Voltage：230V, (Output with compressor load) Rotating speed：44RPS	405ns
Cut-off time delay	TOFF	550ns	400		415ns
On time	Trise	120ns	60ns		62ns
Off time	Tfall	90ns	40ns		40ns
Dead time	DT	200ns-380ns	290ns		290ns

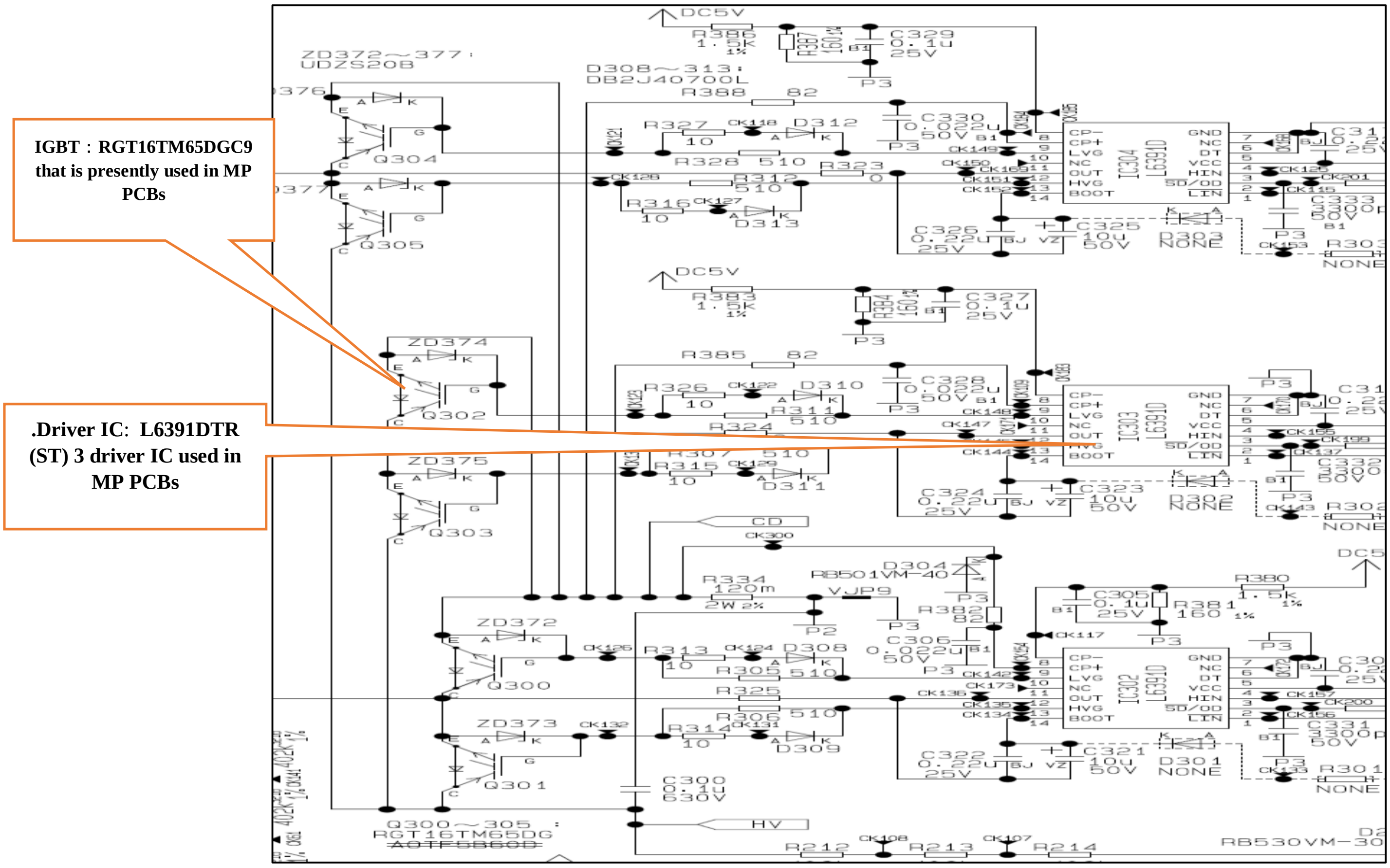


Figure 3.4 MP PCB driver IC and IGBT Circuit diagram

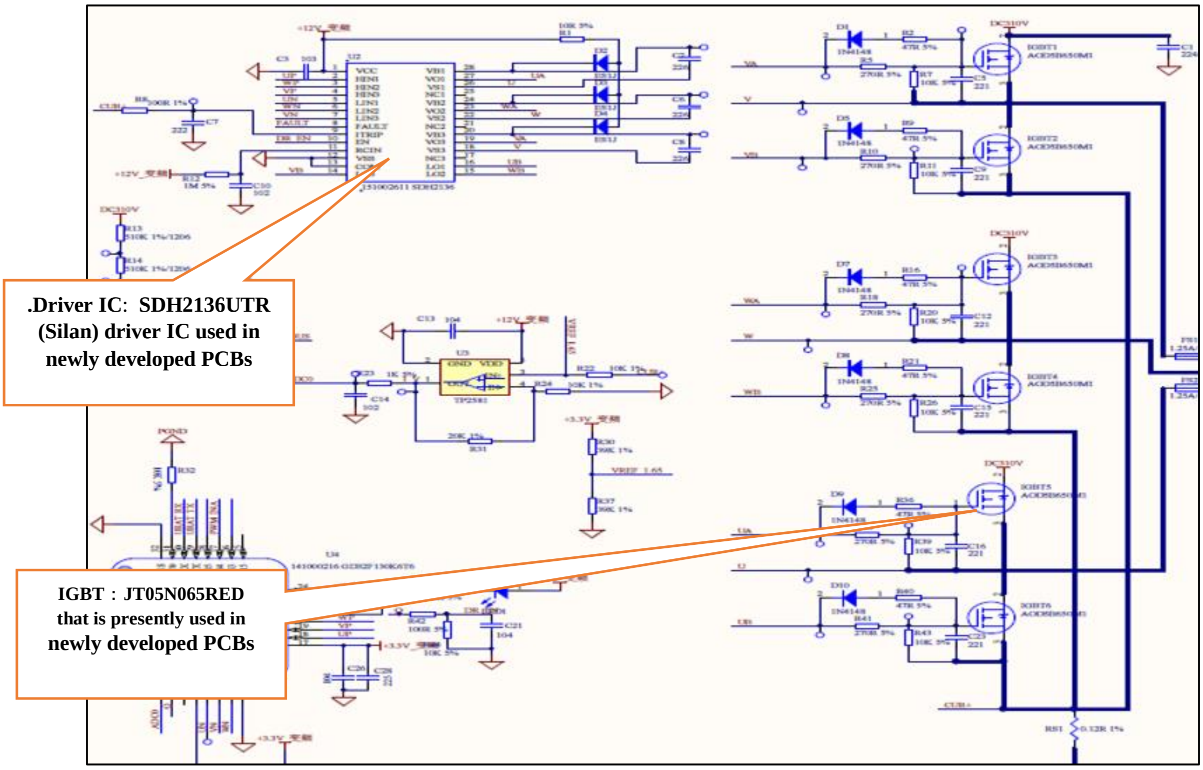


Figure 3.5 New PCB driver IC and IGBT Circuit diagram

3.2 PCB Functionality with Part-Level Testing

In printed circuit boards (PCBs), part-level testing confirms that individual parts are functioning properly to the components being combined into the finished PCB. By ensuring that every component functions as it should, this method reduces the possibility of errors and harmful events. An outline of the role that part-level testing plays in PCB functionality is provided below:

3.2.1 Excellence Checking: IC Examination uses diagnostics and test programs to ensure integrated circuits are operating as intended. Oscilloscopes are used to generate signals and utilizing signal behaviour analysis, test analog components. While performing testing on the component, we compare and check its waveform to verify that it is a valid choice for new PCB development. We check the switching of IGBT and driver IC working with fully intact PCB. Other testing like insulation resistance, leakage current, withstand voltage test, etc. performed with PCB.

3.2.2 Thermal testing: Examines how long components will last in different temperatures. In this test, we also check the PCB components and how their temperature varies when we change the voltage.

I. Prepare the PCB for the temperature-rise test.

II. Prepare the PCB with thermocouples for testing with the specified locator for testing according to the standard in Figure 3.6 shows the location of the thermocouple.

III. For testing, use the cooling lab at 43 °C according to Japanese standards.

IV. Specify the voltage for the test: low voltage (216V) and high voltage (243.8V).

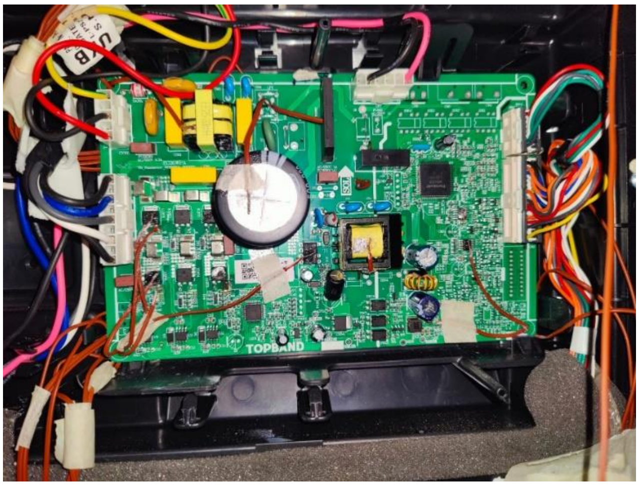


Figure 3.6 Thermocouples attached to PCB for temperature rise

3.2.2 Insulation Resistance:

Insulation Resistance: Insulation resistance test is an essential step in guaranteeing the dependability and electrical integrity of printed circuit boards (PCBs). To make sure that the conductive components on a PCB are appropriately isolated from one another, it entails measuring the resistance between them. Below are the steps to perform the insulation resistance test and Figure 3.7 shows the setup.

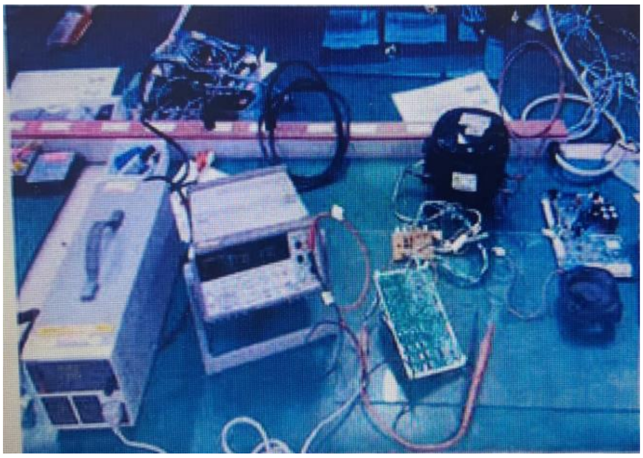


Figure 3.7 Insulation Resistance Setup

I. **Preparation:** First, make sure the printed circuit board is unplugged. Clean the PCB to get rid of any impurities or residues that might affect the test findings.

II. **Test Tools:** Acquire the Electrical Safety Multi-analyzer TOS9303LC insulation resistance tester, which can measure high resistance levels and apply the required test.

III. **Test Voltage Selection:** Using the PCB's operational voltage as a guide, choose the proper test voltage. Depending on the needs, most test voltages might be used anywhere from 100V to 500V or greater.

IV. **Connection:** Attach the positive lead of the Multi-analyzer TOS9303LC to a conducting element (such as a component lead, trace, or pad) and the negative lead to another conductive element where the insulation is being examined.

V. **Apply Voltage:** Activate the Multi-analyzer TOS9303LC to apply the test voltage across the leads.

VI. **Measure Resistance:** Look at the Multi-analyzer TOS9303LC reading for insulation resistance. Make that the value is within allowable bounds; depending on the requirements, this is usually in the range of mega ohms (MΩ) to gig ohms (GΩ).

VII. After that check the measured resistance that lies under the specification provided. Record the data of the test and then discharge the PCB safely and inspect the PCB for any sign of damage. Lastly, compile the result and generate the report.

3.2.3 Leakage current: On a printed circuit board (PCB), a leakage current test is necessary to make sure that accidental currents between conductive parts stay within bounds. Leakage current can result in many problems, such as component damage, and safety risks. Below are the steps to perform the Leakage current test in Figure 3.8 leakage test setup.

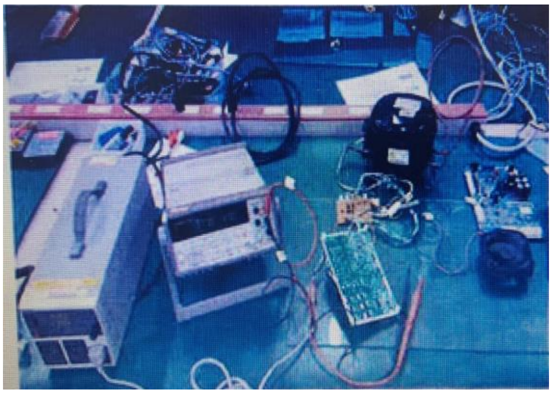


Figure 3.8 Leakage Current Test Setup

I. **Preparation:** Make sure the printed circuit board is unplugged. Clean the PCB to get rid of any impurities or residues that might affect the test findings. Accurately measure low currents with Electrical Safety Multi-analyzer TOS9303LC that is suitable or a leakage current tester.

II. **Test Voltage:** Depending on the PCB's working circumstances, ascertain the proper test voltage. To prevent harming the PCB, the voltage should be strong enough to replicate working circumstances while yet being within acceptable bounds.

III. **Connection:** Attach the leakage current analyzer to the PCB and power supply in series. In particular, attach the positive lead to the positive terminal of the power supply and the negative lead to the ground or return channel of the PCB.

IV. **Apply Voltage:** Switch on the test apparatus and provide the PCB with the test voltage within the specified range.

V. **Permitted Limits:** Verify that the measured leakage current is within the PCB's permissible threshold. Generally, depending on the application and design of the PCB, leakage current ought to be in the microampere (μA) range or less.

VI. **Removal:** After testing, safely remove any remaining voltage from the PCB.

VII. Physically examine the PCB to look for any indications of damage or irregularities.

3.2.4 Withstand Voltage or High Voltage Test: A withstand voltage or high voltage test (also known as a dielectric withstand test or a high potential test) on a printed circuit board (PCB) is used to confirm that the insulation between various conductive paths can endure high voltage without failing and check that its tracks were able to handle that voltage or not. This test is critical for ensuring the safety and dependability of the PCB, especially in applications.

I. **Precautions:** Ensure that all safety measures are in place. High voltage testing may be dangerous, therefore it's critical to employ the right personal protective equipment (PPE) and keep the test environment safe.

II. **Test equipment:** Get a high voltage tester (hipot tester) Multi-analyzer TOS9303LC that can apply the required test voltage and detect leakage current.

III. **PCB Preparation:** Clean the PCB to eliminate any pollutants that may interfere with the test results. Before beginning the test, ensure that the PCB is correctly placed and linked.

IV. Calculate the appropriate test voltage based on the operational voltage and insulation. A typical test voltage is 10-20 times the operational voltage + 1000 volts. Refer to IS15750 (2006) or UL 61010-1 for specific requirements [9]. We also do this test at 1500 volts as per Japanese standards.

V. **Duration:** Average durations range from one to sixty seconds, based on the standard and needs.

VI. Now connect the PCB or product with the tester and perform the test according to the procedure.

VII. The Result is shown as PASS/FAIL on the screen.

VIII. Check the PCB visually that if there is any burning or damaged area.

3.2.5 Earth Continuity/ Ground Bond Testing: By testing a PCB's earth continuity, you can be confident that its grounding connections are solid and that it has a dependable, low-resistance path to the ground.

i. PCB should be plugged out and removed from any power source.

ii. For this test, we also use Multi-analyzer TOS9303LC.

iii. Make sure the PCB is clear and clear of any impurities that might disturb the test.

iv. Connect the PCB or refrigerator with the tester and the testing points one is the tester to the ground and another probe with the ground pin of a connector or designated ground point on the machine.

v. Switch On the tester and the tester display shows that PCB is PASS/FAIL.

vi. After completion of the test check the PCB that no damage occurred during the test. And Fail then check the reason for its failure.

3.3 Validation of Refrigerator with product cycle testing

During the product cycle and testing, I learned various types of tests and parameters. While performing the test, I also learned the location of the thermocouples to be placed in the machine. The location of thermocouples varies from test to test. Here, shown were the tests that were conducted during the validation process.

3.3.1 Evaluation of Notch or Double Cut Test.

3.3.2 Reducing Cycle Time for Notch or Double Cut Test.

3.3.3 Continuous Performance Testing

3.3.4 Temperature Rise test of the whole machine.

3.3.5 Vibration Testing.

3.3.6 Noise Testing.

3.3.1 Evaluation of Notch or Double Cut test: Double Cut or notch test is performed to check the cycle size, on and off time, and duration of defrost time to occur during the cycle. Mainly, notch testing helps us to know how the refrigerator is going to perform during normal work at home or any other location. While performing the test we have to evaluate the machine at different ambient temperatures (16℃, 32℃, 43℃) and the setting of the refrigerator also changes during the test. At every ambient temperature setting of the machine change and settings are MED, MIN, MAX. So, according to the above explanation I had to perform this test 9 times at different temperatures and settings. The average time taken to perform one test is 2 days which includes performance and soaking.

Figure 3.94 Thermocouples placement in the frost-free refrigerator for notch and continuous testing

The location of thermocouples for the notch test is shown in Figure 3.9. Steps to put the machine in notch mode:

I. After placing the thermocouples check the machine for leakage area.
II. Power On the refrigerator.
III. Within the first, 30 seconds press the door switch 6 times, LED light starts blinking.
IV. After 30 sec press the door switch another 6 times, LED stop blinking.

Precaution: Start the system for recording the data and data should be recorded at a 30-second sampling rate.

3.3.2 Reducing Cycle Time for Notch or Double Cut test: In this test, I studied the standards from which I learned that we can reduce the time of defrost to defrost from 13 hours to 12 hours. For the notch test, I can reduce time from 1 hour to 2 hours or 3 also. But we can only do 1-hour reason that it didn’t impact the cycle data and the machine was able to reach the temperature as of the 13-hour cycle. The main reason is that we can save power with that 1 hour time reduction in the cycle during testing.

3.3.3 Continuous Performance Testing: Continuous cooling test is also known as the maximum cooling the maximum cooling done by the refrigerator. In the continuous operation test, after the refrigerator is run continuously with the temperature control device short-circuited at the ambient temperature of 30±2 °C specified in "Standard" and reaches a stable state, the temperature in the refrigerator compartment and freezing compartment must be measured. When we perform the continuous test we must put the refrigerator setting in MED condition. This mainly focuses on the cooling capacity of the refrigerator maximum the cooling capacity of the refrigerator is better than refrigerators perform in the worst environment. This test is either performed for 22 hours or 99 hours to check maximum cooling in the refrigerator. In this test, we cannot change the speed of the compressor from R6 because it's the maximum frequency or speed at which the compressor can run. R1, R2, R3, R4, R5, and R6 are the different speed settings for the compressor. These settings were set to run the compressor at different speeds according to the ambient condition. Figure 3.9 shows the placement of thermocouples for continuous testing.

Steps to put the machine in continuous mode:

I. After placing the thermocouples check the machine for leakage area.
II. Before starting temperature control device should be short-circuited.
III. Power On the refrigerator.

Precaution: Start the system for recording the data and data should be recorded at a 30-second sampling rate.

3.3.4 Temperature Rise test of the whole machine:

When the electric refrigerator is run continuously at the ambient temperature of 30±2℃ specified in "Standard" with the temperature control device (including the thermistor) short-circuited and the temperature of each part becomes nearly constant, the temperature at each point specified in the product specification must be measured using the thermoelectric thermometer (thermocouples) method or the resistance method. Also, ensure that the overload-protecting mechanism is not activated and that no anomalous heat is created in the remaining areas. The device that regulates the circulation of cold air must be adjusted so that it cools to the lowest feasible temperature in line with the product specifications. Figure 3.10 shows the thermocouple location for the temperature rise test.

Figure 3.10 Thermocouples placement in frost-free refrigerator for Temperature rise testing.

$$\Delta t = \frac{R2 - R1}{R1}(234.5 + t1) - (t2 - t1)$$

Δt: Temperature rise (℃)

R1: Cold Resistance ()

R2: Resistance after Operation ()

T1: Ambient temperature during cooling (℃)

T2: Ambient temperature after operation (℃)

Precaution: Start the system for recording the data and data should be recorded at a 30-second sampling rate. While the testing is started, make the temperature of the winding equal to the ambient temperature. Tapping and putty on the thermocouples must be fixed and in small amounts.

3.3.5 Vibration Testing: In the vibration test, the refrigerator must be put on a flat sturdy platform and run continuously at the rated voltage and frequency. Vibration (peak-to-peak amplitude) must be monitored at places and it must be confirmed that vibrating noises are not produced by the components ordinarily placed in the refrigerator. The vibration gouge must be an amplitude meter. The Location of placing the sensor on the refrigerator is explained below.

I. Cabinet side face (near the center of the refrigerator compartment's side face).

II. Uppermost piece of the door (back-and-forth, side-by-side, and vertical directions with the door opened at 90 degrees).

III. Compressor

Reciprocating types include back-and-forth, side-by-side, and vertical directions. Rotary type: Vertical (center of the body).

IV. Compressor base (back-and-forth direction, up and down to the house's connecting point).

V. Dryer (back-and-forth and vertical directions (side-by-side for vertically mounted types)].

VI. Plate water evaporator (center and plate sections of the input and outflow pipes).

VII. Piping in the machine room [back-and-forth and vertical directions (side-by-side for vertical piping).

VIII. Fixing Pipe Points 20 mm distant from the front of the entry, near the cabinet, clumping pipes, and the entrance of the fin-tube (Back-and-forth, left-and-right, and vertical directions)

To measure amplitude at a specific point, use a stroboscope to identify areas with high amplitudes. If the compressor is a power supply frequency model (induction), adjust the frequency from 20 to 75 Hz to ensure the peak is within the rated frequency range of ± 2 Hz. Figure 3.11 shows the placement of the sensors according to the above points.

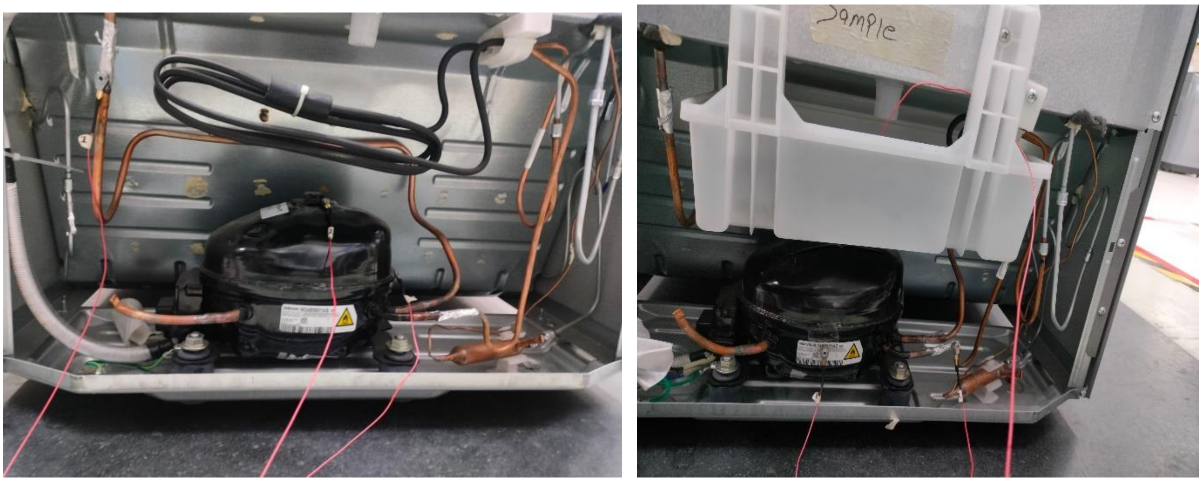


Figure 3.11 Images show the sensor placement in the machine room of the refrigerator

3.3.6 Noise Testing: To conduct the noise test, set an ambient temperature of 30±5°C and put a refrigerator in the measurement room. The noise measuring room must be anechoic (the difference between the dark noise and measured value must be 10 dB or greater; otherwise, the estimated value must be corrected using the correction value specified in JIS Z 8731

(Description and measurement of environmental noise)], and the distance between the microphone and the wall surface must be large enough to ignore the effect of wall-reflected sounds. The microphone must be a condenser microphone. For recording the noise we need to achieve a steady condition, the refrigerator must be run continuously while the temperature control mechanism is short-circuited to determine the noise level. The below points explain the location of the microphone for testing.

I. Point 10 cm away from the front panel of the electric refrigerator and one meter above the floor.
II. Point 10 cm away from the rear of the compressor.
III. Point 10 cm away from the front panel of the electric refrigerator and 10 cm up from the floor.
IV. Point 10 cm from the rear of the internal fan motor.
V. Point 1 meter away from the front panel of the electric refrigerator and one meter above the floor.
VI. Point 10 cm from the back of the accumulator.

3.4 Energy Consumption/Performance Enhancement

Here, this is the most crucial phase of the testing that will determine the star rating of the refrigerator and registration of the refrigerator.

Star rating band	Annual Energy Consumption (kWh/year)
1 Star *	(0.157* Vtot+243) ≤ AEC < (0.180* Vtot+279)
2 Star **	(0.136*V_{tot}+211) ≤ AEC < (0.157* Vtot+243)
3 Star ***	(0.118*Vtot+184) ≤ AEC < (0.136* Vtot+211)
4 Star ****	(0.103* Vtot +160) ≤ AEC < (0.118*Vtot +184)
5 Star *****	AEC < (0.103*Vtot+160)

Figure 3.12 BEE rating Frost Free Refrigerator (Valid from 1st January 2023 to 31st December 2024) [24].

To determine the characteristics of a household refrigerator that meet the requirements of this standard, temperature, and energy consumption measurements must be taken during a representative period of steady-state operation that satisfies the appropriate criteria (i.e., compartment temperatures at or below their energy consumption target). To achieve the optimum (optimal) energy use result, numerous test points may need to be done at varied temperature control settings.

When a product includes automated defrost features that affect its power consumption (a defrost control cycle), the excess energy required during defrost and recovery. For the energy test to be performed we need to follow the process. Firstly, we need to understand what interpolation, Interpolation is used to estimate energy consumption or performance measures when circumstances are not explicitly evaluated during testing. This method is critical because it allows for the prediction of refrigerator performance under different operating situations without the need to test each scenario individually. Below are the steps that need to be considered for energy testing in the refrigerator. Figure 3.13 and figure 3.14 shows the location of thermocouples for energy location.

I. The test must performed in the Psychometric Lab.

II. Ambient of the lab should be 32 °C and 55% humidity (40-70%).

III. Installation of thermocouples should be accurate according to IS-17550(part 3) [28].

IV. And temperature needs to be maintained in the FC and PC compartments. FC= -18±2°C, PC=4±2°C.

V. Temperature specification for hot and cold energy that needs to be maintained

VI. For Cold energy= FC -18°C to -20°C, PC= 2°C to 4°C.

VII. For Warm energy= FC is -16°C to -18°C, PC= 4°C to 6°C.

VIII. These temperatures are achieved by the stabling machine with its temperature dial noble during its stabilizing period.

IX. The whole process for the energy consumption test took around 8 to 10 days.

Figure 3.13 FC compartment with thermocouples.

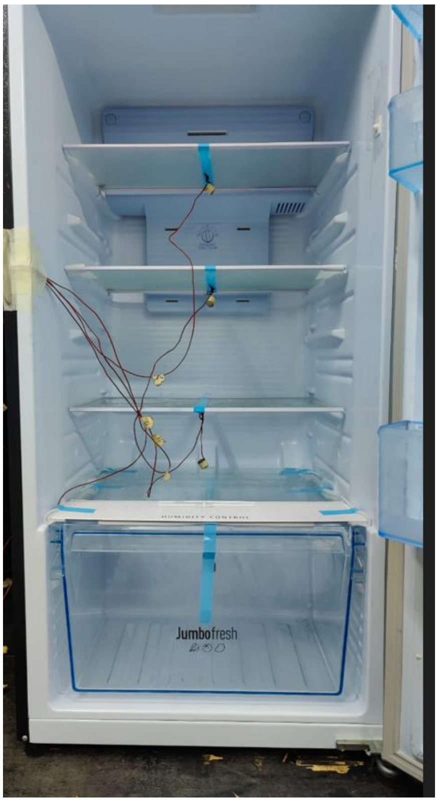


Figure 3.14 Thermocouples location for PC compartment

Precaution: Start the system for recording the data and data should be recorded at a 30-second sampling rate. Check temperature regularly while stabilizing the machine for temperature. Maintain the ambient temperature of the lab.

3.5 Experimental Setup and Equipment

Experiments and testing are performed at Panasonic Life solution premises at different locations. The equipment that is used during the experimental process is as follows:

3.5.1 Multi-analyzer TOS9303LC
3.5.2 Oscilloscopes DOS-X 4024A
3.5.3 Psychometric Lab
3.5.4 Temperature and Humidity Sensor
3.5.5 Temperature and Humidity Panel
3.5.6 Thermocouple
3.5.7 System
3.5.8 Variac Meter
3.5.9 Electric panel

3.5.1 Multi-analyzer TOS9303LC: The TOS9300 series is a high-performance electrical safety analyzer that meets the needs of different testing setups. Hipot, insulation resistance, ground bond, leakage current, and partial discharge may all be checked. Figure 3.15 shows the device image used for testing.

I. AC hipot testing has a maximum output voltage of 5kV/100mA (500 VA).
II. Maximum output voltage for DC hipot testing: 5kV/20mA, 7.2kV/13.9mA (100W).
III. Insulation resistance testing ranges from 0.001MΩ to 100.0GΩ (DC-25V to -1000V, DC+50V to +7200V).
IV. Ground bond testing has a measurement range of 0.001Ω to 0.600Ω (3.0A-42.0A).
V. Leakage current testing has a measurement range of 1μA to 100mA (RMS).
VI. Electrical failure inspection setting is offered.

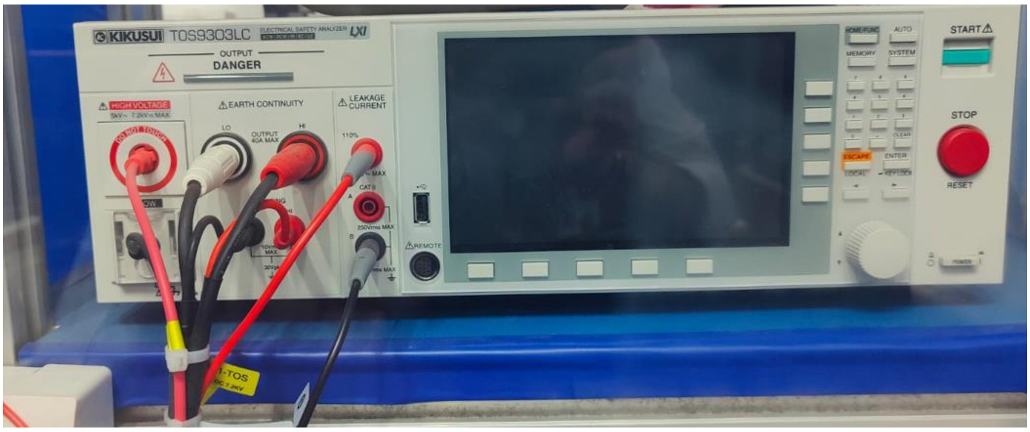


Figure 3.15 Multi-analyzer for PCB testing

3.5.2 Oscilloscopes DOS-X 4024A: An oscilloscope is an electrical testing tool that allows you to see continually changing signal voltages, often as a two-dimensional representation of one or more signals over time. The fundamental function of an oscilloscope is to show and study the waveforms of electrical signals.

Figure 3.16 Oscilloscope used for switching single testing for IGBT

This device is mainly used to analyze the circuit for the switching speed, starting time delay, cut-off time Output dead time, etc. We use a **DSOX4024A Oscilloscope, 4-channel, 200 MHz** for testing PCB shown in figure 3.16.

3.5.3 Psychometric Lab: A refrigerator lab for testing is a specialized facility that assesses the performance, efficiency, and safety of refrigerators and other cooling equipment. These labs are critical for manufacturers, regulatory authorities, and researchers to guarantee that refrigeration goods fulfill strict criteria and customer expectations.

Figure 3.17 Refrigerator Lab for testing

3.5.4 Temperature and humidity sensor: Temperature and humidity sensors play vital roles in a variety of applications, including environmental monitoring, heating and cooling systems. They measure the ambient temperature and humidity level, giving data for system control, safety, and ideal conditions. Figure 3.18 shows the temperature and humidity sensor.

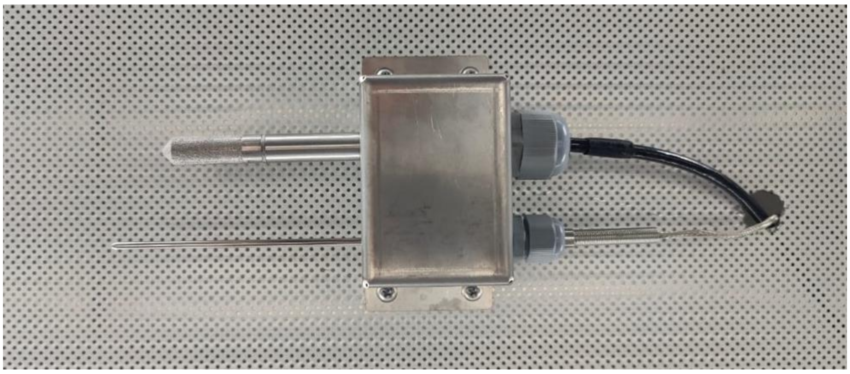


Figure 3.18 Temperature and humidity sensor used in Lab

3.5.5 Temperature and Humidity panel: A temperature and humidity panel is a customized interface that monitors and controls the environmental conditions of a given region or system. These panels are extensively used in cooling and heating systems, industrial operations, labs, and other environments that require precise temperature and humidity control.

Figure 3.19 Temperature and humidity controller of lab

We use Yokogawa UT55A which is a seven-segment display LCD panel. This is a mid-level temperature and humidity control device shown in Figure 3.19.

3.5.6 Thermocouples: The temperature is monitored using thermocouples with the sensitive components positioned in the middle of a 25-gram tinned copper cylinder with a minimum exterior diameter of 15.2 mm. Figure 3.20 shows the type three thermocouples.

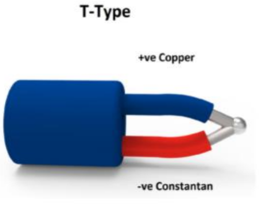


Figure 3.20 T type of Thermocouples

Type T thermocouples, also known as Copper-Constantan, are widely used in laboratories to detect temperatures ranging from -250°C to 400°C. They are particularly appropriate for detecting low temperatures because of their stability, making them perfect for cryogenics and ultra-low freezers that operate at extremely low temperatures. Pros and Cons T-type thermocouples are explained below.

Pros:

I. Can be utilized in both oxidizing and reducing environments.
II. Suitable for cryogenic and low temperatures.

Cons:

I. Not appropriate for temperatures beyond 370°C.

T-type thermocouples have the following applications:

Used to measure cryogenic and low temperatures. Used in testing labs, etc. Used in areas with low temperatures.

3.5.7 System: Temperature and humidity control systems are crucial in laboratories to ensure accurate environmental conditions. These systems guarantee that experimental, testing, and storage settings are consistent and trustworthy. Figure 3.21 shows the setup of the system used for recording data.

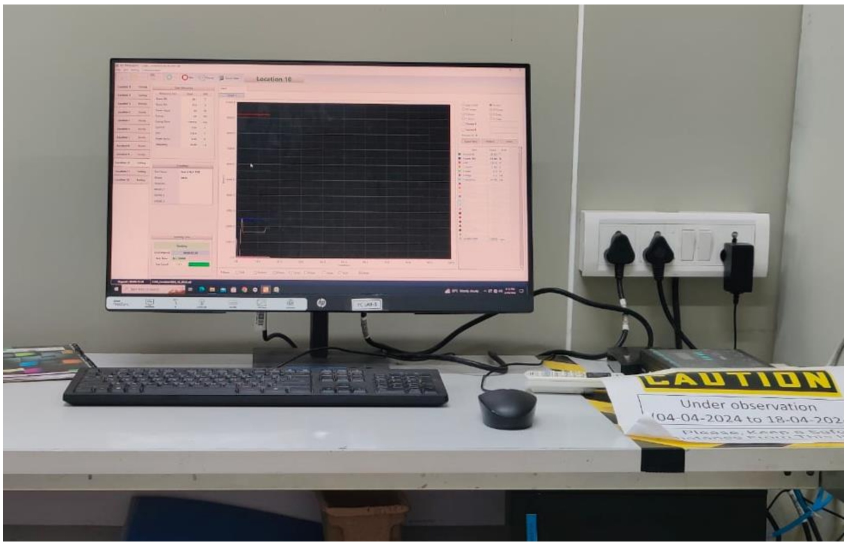


Figure 3.21 System used for recording data

3.5.8 Variac Meter: A Variac meter is an electrical instrument used to control and measure the voltage output of a variable autotransformer, also known as a Variac. Variacs are used in different applications to demand precise control of the AC voltage. A Variac is made up of a single winding coiled around a magnetic core, with a moveable brush that controls the output voltage. Which allows the user to change the location of the brush, hence adjusting the output voltage. Displays the output voltage. Analog meters employ a needle and scale, but digital meters use an LCD or LED display to provide more accurate readings. Figure 3.22 shows the Variac meter image.

Figure 3.22 Variac mater used to adjust the voltage for testing.

3.5.9 Electric panel: An electric panel, also known as a distribution board or breaker panel, is an important part of an electrical system since it serves as a central hub for managing and distributing energy throughout the lab. It holds circuit breakers, fuses, and other safety devices that guarantee the electrical system operates safely and efficiently. On the electric panel, the humidity and temperature devices are connected to and digital power meter. Instruments that measure the power used by electrical equipment to help ensure the highest levels of energy efficiency and conservation. This instrument, which combines accurate and reliable power measurement over a wide power range with flexibility, ease of use, and a variety of communication interfaces, will assist electrical equipment developers, engineers, and manufacturers in ensuring that their products comply with emerging IEC and EN standards, as well as increasingly complex and stringent energy efficiency specifications. Figure 3.23 shows the electric panel used in labs

Figure 3.23 Electric Panel for performance handling and measurement

CHAPTER 4

RESULT AND DISCUSSION

The detailed research and complete testing of components have been thoroughly examined, and the resulting findings have been carefully discussed.

4.1 Performance and Evaluation of New Inverter Circuit Components.

We had to improve and develop an alternate source of components for cost reduction and from a shortage point of view. So, firstly with the help of my mentor, we started searching for the components that meet our requirements without increasing any cost. After selecting the components according to the need we also had to check its values with waveforms for on-time, off-time, dead time, etc. We had to match the specifications of the old PCB. We worked on the mass-production PCB and got the results of IGBT as shown in figure 4.1 explains output characteristics and in figure 4.2 is forward bias operating timing.

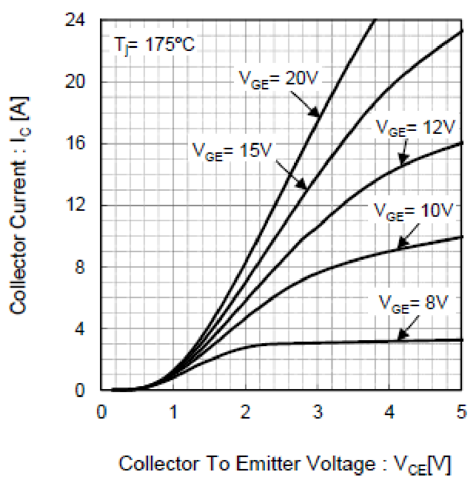


Figure 4.1 Typical Output Characteristics

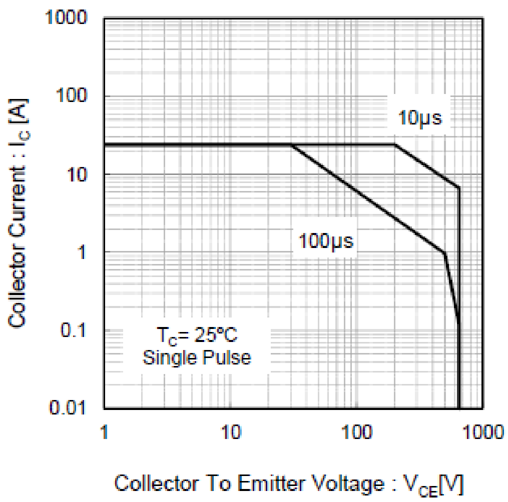


Figure 4.2 Forward Bais operating timing

With the help of an oscilloscope to analyse the IGBT performance for verifying the recommended measured values and the measured values of IGBT JT05N065RED as shown in table 4.1. Measured the IGBT value with 230V and temperature 20℃-70℃, output with compressor load Rotating speed: 22RPS, 44RPS, and 58RPS. Waveform results of driving voltage, on time, off time, and dead time as shown in figure 4.3, figure 4.4, figure 4.5, and figure 4.6 values are shown below figures. The waveform drive of the U item is as follows (CH2 (green) is the driver of the upper bridge, and CH3 (blue) is the driver of the lower bridge.

Table 4.1 IGBT JT05N065RED performance confirmation

IGBT : JT05N065RED		Specification Value	Recommended measurement value	Test Condition	Measured value
Voltage	VGES VCES	±30V 650V	＞10V.＜24V ＜520V	Voltage：230V, temperature: 20℃-70℃,	min：11.01V max：12.5V max：385V
Electric Content	IC	6A	IC＜4A	(Output with compressor load),	MAX:5A
Short Current	ISG	40A.t＜5us	＜32A, t＜4us	Rotating speed: 22RPS,44RPS,58RPS	19.7A
IGBT C/E pole	TON	-	t＜800ns		max：330ns
IGBT C/E pole	TOFF	-	t＜800ns		max：170ns
IGBT C/E pole	TDE	-	＞1us		min：1.2us

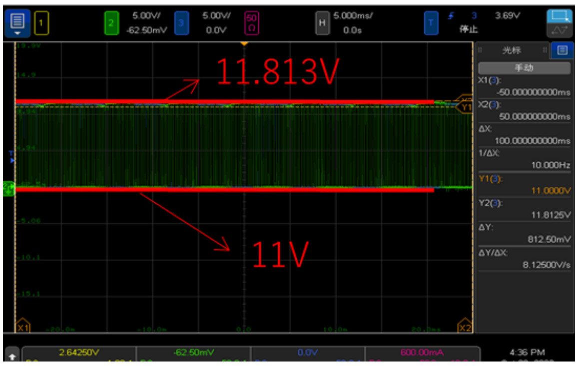


Figure 4.3 G/E pole driving voltage: upper 11.8125V/lower 11.0V standard: >10V

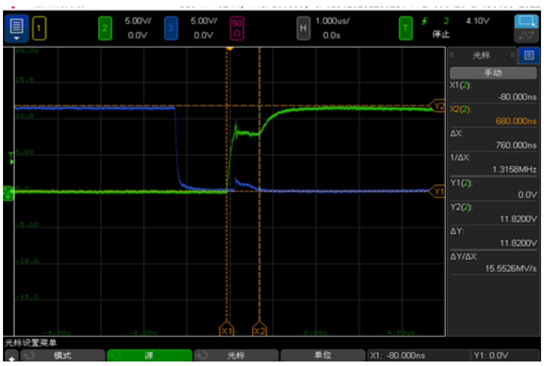


Figure 4.4 G/E upper bridge turn-on time: 760ns Standard: <800ns

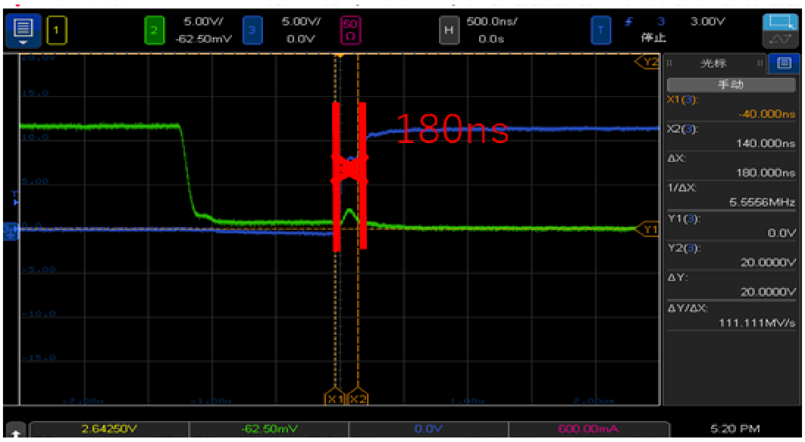


Figure 4.5 G/E lower bridge turn-on time: 140ns Standard: <800ns

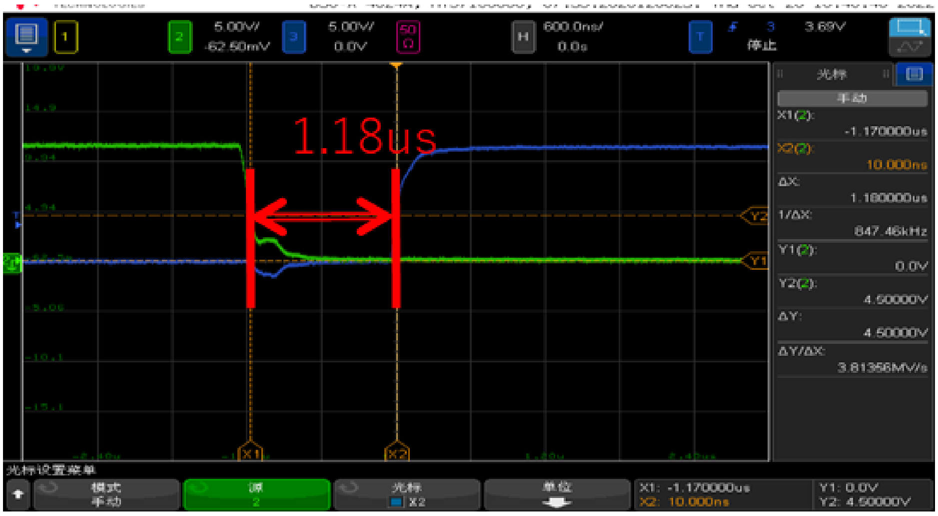


Figure 4.6 G/E pole dead time: 1.18us Standard: >1us

From the above work, we can say that the test performed showed better results. But we have to consider assembly, arrangement of components, and cost. So, we have to check with the procurement department for its availability.

After successfully testing the IGBT we also had to test the driver IC used with it. Below is the test result of driver IC performance that we are going to use with IGBT JT05N065RED. While testing the driver IC with the IGBT got a satisfactory result that matched the recommended measured values and performance confirmation values as shown in Table 4.2.

Table 4.2 Driver IC: SDH2136UTR performance confirmation

Drive IC-SDH2136UTR		Specification Value	Recommended measurement value	Test Condition	Measured value
Output voltage of upper bridge/IC output voltage	VCC	20V	10-16V	Voltage ：230V, temperature: 20℃-70℃ , (Output with compressor load), Rotating speed: 22RPS,44RPS,58RPS	min：11.01V max：12.5V
Logic input voltage	HIN/LIN	VSS-VSS+5			min：3.2V max：3.35V
HIGH Bridge gate output voltage	VHO	VS1,2,3-VB1,2,3			min：11.01V max：12.5V
LOW Bridge gate output voltage	VLO	COM-VCC			min：11V max：12.56V
Startup time delay	TON	550ns	425	Voltage：230V, (Output with compressor load) Rotating speed：44RPS	380ns
Cut-off time delay	TOFF	550ns	400		400ns
On time	Trise	120ns	60ns		59ns
Off time	Tfall	90ns	40ns		30ns
Dead time	DT	200ns-380ns	290ns		280ns

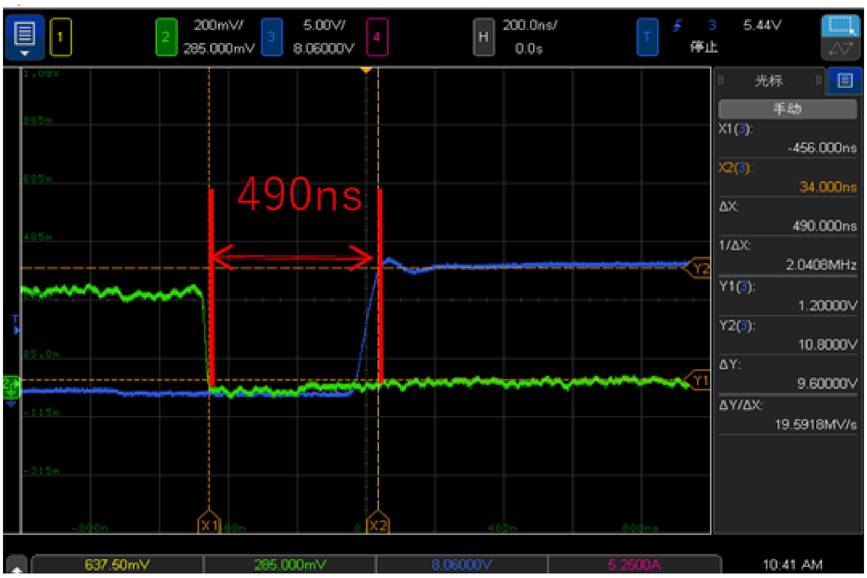


Figure 4.7 Start-up time delay Ton：490ns, Standard value：Ton<800ns

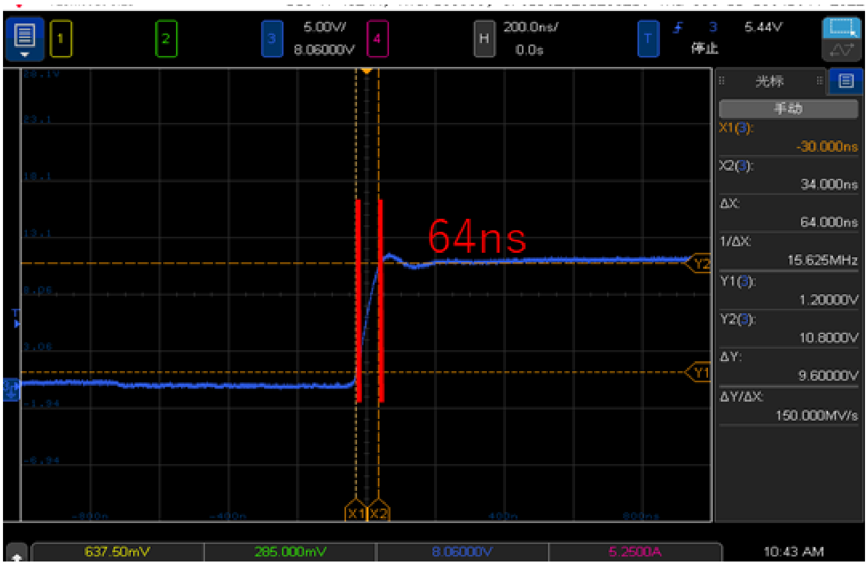


Figure 4.8 Turn-on rise time Tr: 64ns, Standard value: Tr<170n

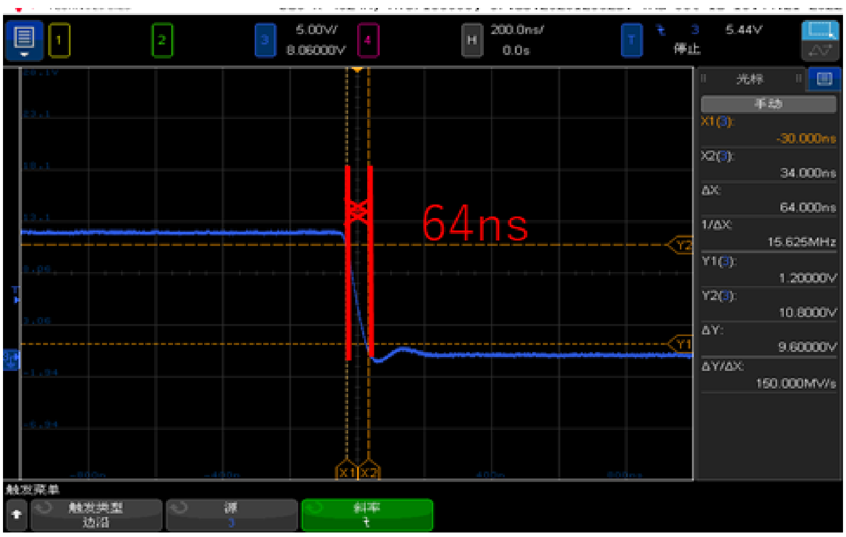


Figure 4.9 Opening and closing drop time Tf: 64ns, Standard value: Tf < 90ns

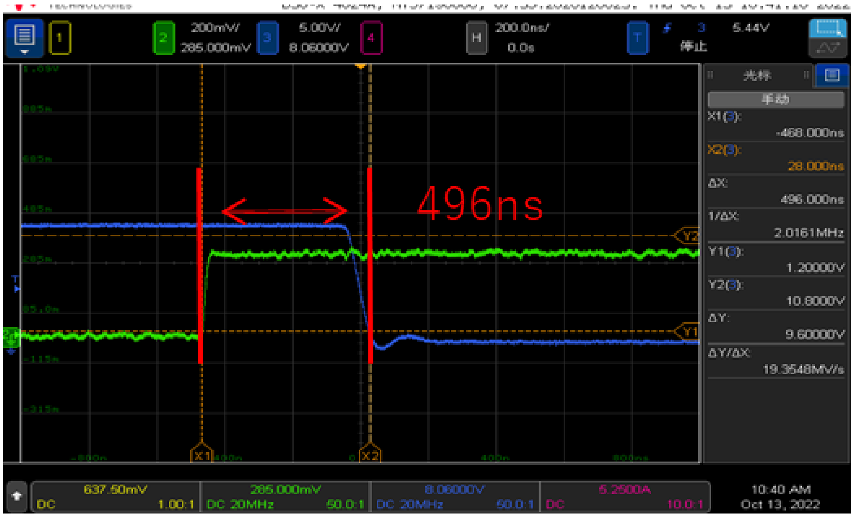


Figure 4.10 Cut-off time delay Toff: 496ns, Standard value: Ton<800ns

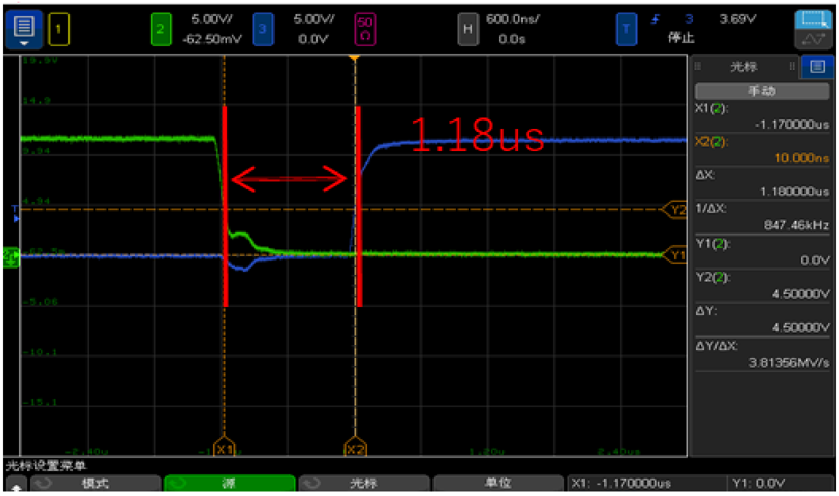


Figure 4.11 Output dead time 1.2us standard value > 1us

Therefore, Figure 4.7 shows the startup time delay, Figure 4.8 turn on-rise time figure 4.9 operating and close time, figure 4.10 shows cut-off time delay, and Figure 4.11 output dead time. From the above results of the driver IC **SDH2136UTR** performance, we checked the compatibility of the driver IC with IGBT for compressor run at a different speed.

4.2 Verification of PCB Functionality through Part-Level Testing to Confirm Specifications of Standards.

While we are improving or developing the new PCB for frost-free refrigerators we have to do PCB testing to check and make sure that we are using the standard components that perform well under severe circumstances. We have to follow the safety standards for testing the refrigerator for its usage at home so that it does not harm anybody. First, we are going to see the result of the Thermal Testing of the refrigerator. In this, we use the standard procedure to do the testing of the components with the refrigerator under the Lab at 43℃ temperature. Here, below is the temperature rise test result of the new PCB under different voltages 198V and 264V at 43 ℃. Therefore figure 4.12 shows a temperature rise at 198V while Figure 4.13 refrigerator compartment temperature at 198V, figure 4.14 shows a temperature rise at 264V, and Figure 4.15 refrigerator compartment temperature at 264V.

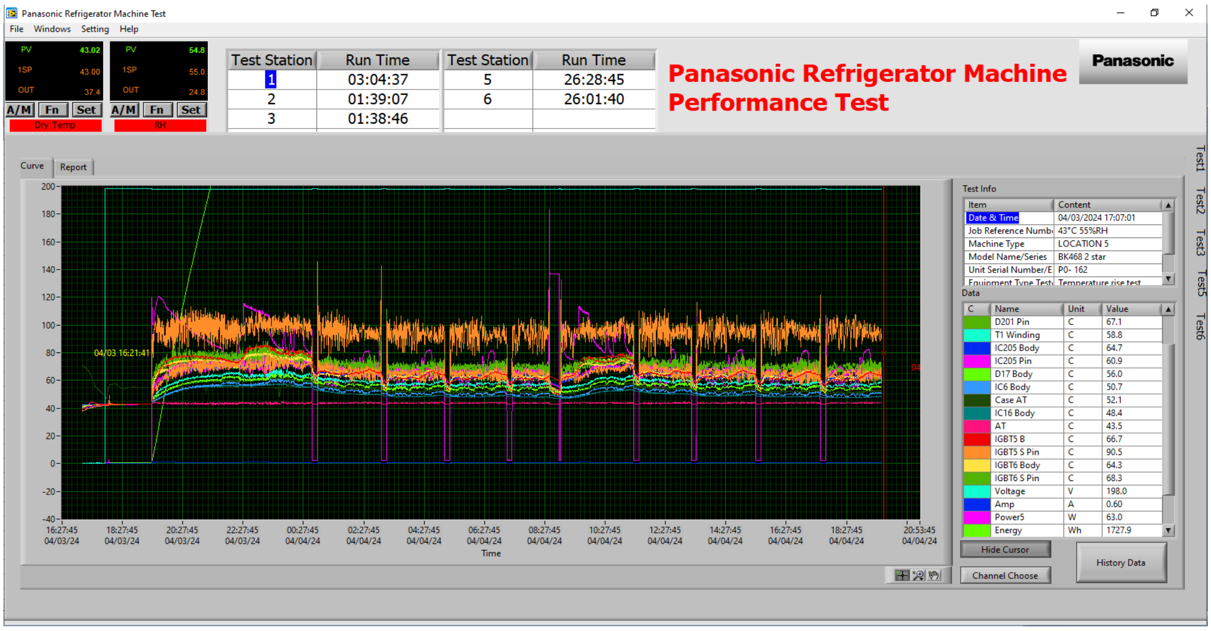


Figure 4.12 Data of temperature rise of PCB at 198V

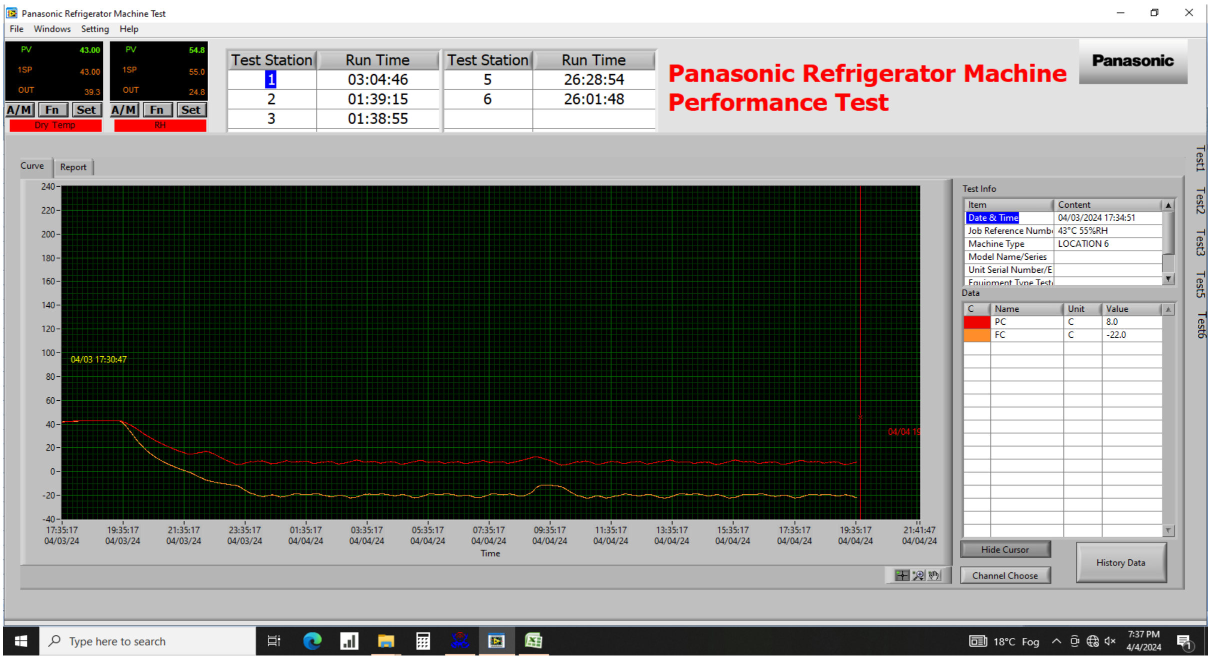


Figure 4.13 Refrigerator compartment temperature at 198V

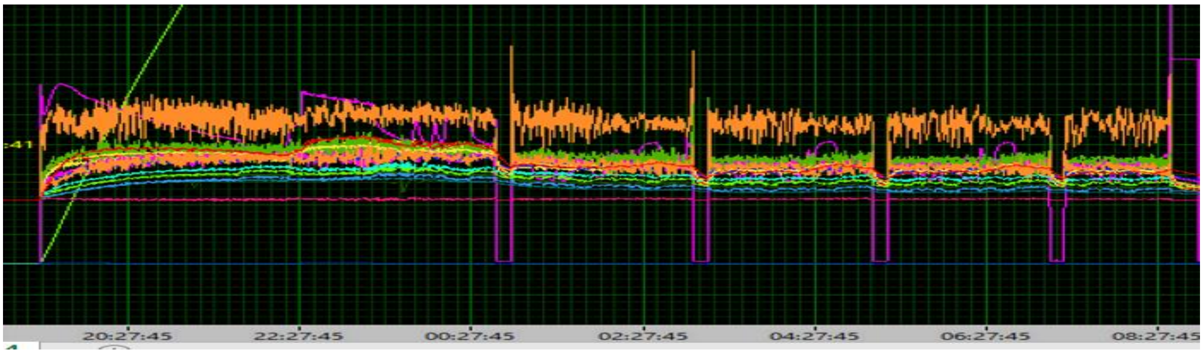


Figure 4.14 Data of temperature rise of PCB at 264V

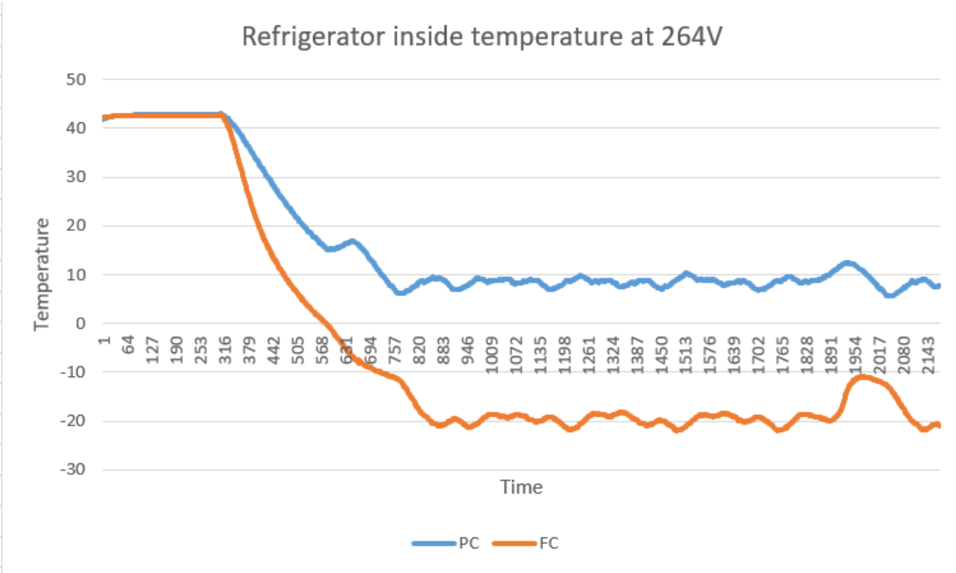


Figure 4.15 Refrigerator compartment temperature at 264V

Table 4.3 Temperature rise test detail

Operating Temperature			43℃	43℃
Voltage			264	198
Temperature measurement point	Target	Panasonic standard	Max	Max
IC302 Body	120℃	120℃	78.8℃	77.9℃
IC302 pin22 (solder)	95℃	100℃	64.4℃	63.5℃

DB201 Body	145℃	145℃	72.5℃	71℃
DB201 solder	95℃	100℃	65℃	64.2℃
IC205 Body	100℃	100℃	63.7℃	62.8℃
IC205 Pin1 (solder)	900℃	100℃	68.2℃	67.6℃
PCB box AT	-	-	55.4℃	54.8℃
L301 (winding surface)	100℃	100℃	70.4℃	69.5℃
C201 (top surface)	95℃	95℃	59℃	58.8℃
T1 (Winding surface)	100℃	100℃	63.8℃	62.8℃
D202 Body	95℃	100℃	67℃	66.6℃
IC16 Body	95℃	100℃	78.2℃	77.9℃
CT301 (Winding surface)	100℃	100℃	64.3℃	63℃
IC5 (body)	95℃	100℃	77.3℃	77℃

Above, as I showed the results it cannot explain the temperature rise result. So, table 4.3 is a detailed comparison of the target value, Panasonic standard with voltage values. Therefore, the result comparison of the values PCB can withstand severe test conditions.

Insulation resistance, leakage current, withstand voltage/high voltage test, earth continuity/ground bond testing. These tests are individually performed on the development PCB. These tests were based on the standards so the comparison between the old PCB and the developed PCB was not needed. If PCB lies under the criteria, that means we can use it for further testing purposes. Firstly, here we show the Insulation resistance test in Figure 4.16 where two tests were conducted at 500V.

Model	NR-TG323
Rated	Not operate
Condition	Normal Temperature
Compressor	GMCC_DZ90V1W

1185MΩ

1- Insulation resistance test result

Figure 4.16 Insulation resistance test result

After the insulation resistance test below we show the leakage current test results in Figure 4.17 where the PCB test at 230V and approx. 0.5A. Here, we got two test results and both passed the standard criteria.

Model	NR-TG323
Rated	230V,50Hz
Condition	AT32
Dial Notch	N/N
Compressor	GMCC_DZ90V1W

0.324 mA

2-Leakage Current test result (R1)

Figure 4.17 Leakage Current test result

Below are the two main tests shown in Figure 4.18 and Figure 4.19 which are the high voltage test and earth continuity tests. High voltage test performed at 1500V and earth continuity test performed around 20A to 30A both these tests pass the criteria and we use this PCB for further testing.

Model	NR-TG323
Rated	Not operate
Condition	Normal Temperature
Compressor	GMCC_DZ90V1W

1500V , 1min OK.

3-Withstand Voltage test result

Figure 4.18 High voltage test results

Model	NR-TG323
Rated	Not operate
Condition	Normal Temperature
Compressor	GMCC_DZ90V1W

4- Earth Continuity test result

Figure 4.19 Earth Continuity test result

4.3 Validate Newly Developed PCB with Old PCB through Product-Level Testing for Checking Refrigerator Performance.

After completely testing the PCB individually for its inverter circuit (IGBT and Driver IC) and its durability, and also the safety test for its use with the refrigerator for performance testing. In this part, we are going to see the results of performance testing and improvements from the previous PCB.

4.3.1 Notch/ Double Cut test: In this test, we test MP PCB with the newly developed PCB and validate the software for its proper working. In this, we are going to see the result of the notch test and compare the results for getting temperature as a product specification for FC1, FC2, PC1, PC2, PC3, PC4, VC, AT, and power consumption.

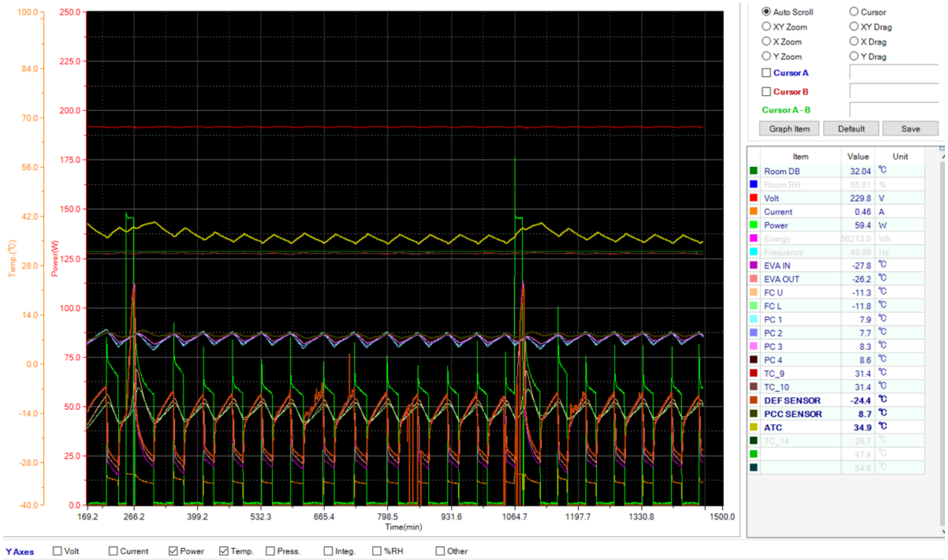


Figure 4.20 Min notch at 32℃ With MP refrigerator

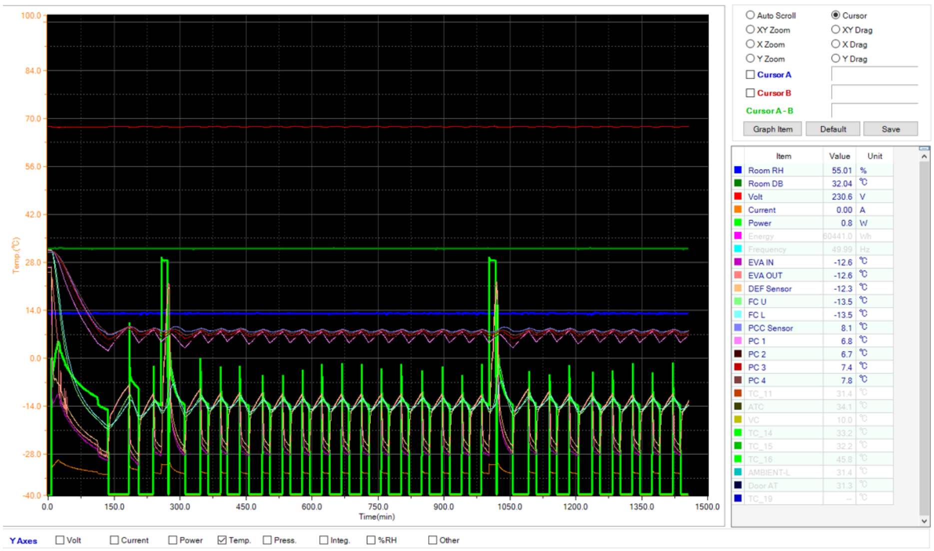


Figure 4.21 Min notch at 32℃ with newly developed PCB

Figure 4.20 and Figure 4.21 above show the graph of the min notch test at 32℃ Temperature comparison of the min notch at 32℃ shown below in Table 4.4.

Table 4.4 Result of Min notch at 32℃

Notch test > AT32		**Lab-01**	**Lab-01**
Model:	Spec	NR-TG323 3Star	NR-TG323 3Star
Comp :		GMCC_DZ90V1W_	GMCC_DZ90V1W_
Location:		LOC-4	LOC-5
Sample No:-		APIN-R&D-REF-2023-24-214	APIN-R&D-REF-2023-24-213
Gas Qty:		65gm	65gm
		New PCB	MP
Eva in		-19.3	-20.3
Eva out		-18.1	-19.3
FC Upper		-13.8	-15.0
FC Lower	**-16.0±2.5**	**-14.3**	**-15.5**
PC 1		4.2	4.4
PC 2		5.1	5.4
PC 3		4.6	5.5
PC 4	**7.0±2.5**	**5.7**	**6.1**
VC		7.4	8.4
FC Door U		-13.3	-14.5
FC Door L		-13.5	-14.9
PC Door U Shelf		4.7	5.3
PC Door L Shelf		6.0	6.8
Egg Tray		5.7	5.5
AMB	**32**±1	**31.9**	**32.1**
On Time		33.0	30.8
Off Time		63.0	34.3
Run %	**40**±15	**34.4**	**47.3**
Cycle/Hour		0.6	0.9
Voltage		230.1	230.1
Amp		0.2	0.2
Power		21.2	24.5
-		-	-
Results		**OK**	**OK**
Change Point	*Development PCB		

Here, the above result shows that the new PCB performs very well as we compare it with mass production PCB.

After that now we are going to compare the med notch result of 32℃. Figure 4.22 shows mass production PCB med notch results and figure 4.23 shows newly developed PCB med notch test results.

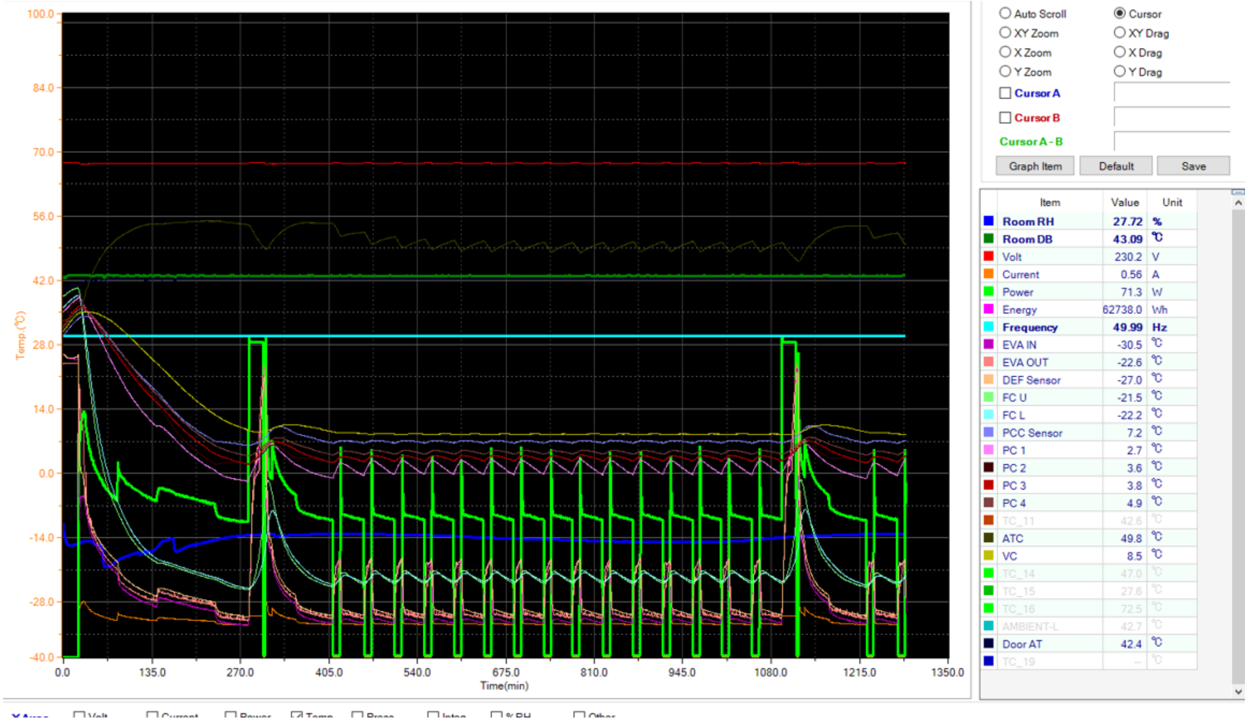


Figure 4.22 MP refrigerator med notch results at 32℃

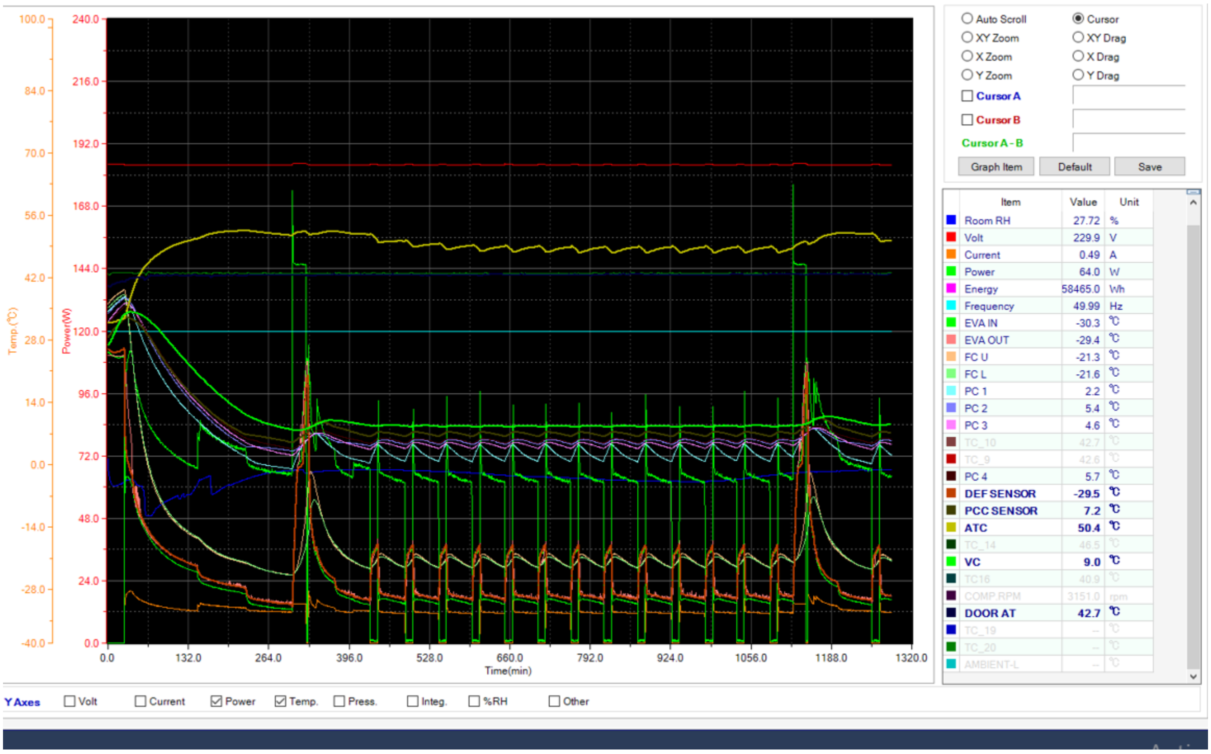


Figure 4.23 Min notch at 32℃ with newly developed PCB

Below is the temperature comparison of the med notch at 32℃ with respect to the above graph data.

Table 4.5 Result of Med notch at 32℃

Notch test > AT32		**Lab-01**	**Lab-01**
Model:	Spec	NR-TG323 3Star	NR-TG323 3Star
Comp :		GMCC_DZ90V1W_	GMCC_DZ90V1W_
Location:		LOC-4	LOC-5
Sample No:-		APIN-R&D-REF-2023-24-214	APIN-R&D-REF-2023-24-213
Gas Qty:		65gm	65gm
		New PCB	MP
Eva in		-27.1	-25.7
Eva out		-26.4	-23.5
FC Upper		-19.5	-19.0
FC Lower	-19.5±2.5	**-20.3**	**-19.4**
PC 1		2.3	1.2
PC 2		3.0	2.4
PC 3		2.2	1.3
PC 4	4.0±2.5	**3.3**	**2.7**
VC	6.0±2.5	**5.5**	**4.7**
FC Door U		**-19.0**	**-18.6**
FC Door L		**-19.5**	**-18.6**
PC Door U Shelf	5.0±2.5	**5.3**	**3.4**
PC Door L Shelf	5.0±2.5	**4.3**	**3.2**
Egg Tray		**5.2**	**3.7**
AMB	32±1	31.7	31.8
On Time		43.0	38.5
Off Time		38.7	30.0
Run %	45±15	**52.7**	**56.2**
Cycle/Hour		0.7	0.9
Voltage		230.1	230.1
Amp		0.3	0.3
Power		26.5	28.3
-		-	-
Results		**OK**	**OK**
Change Point	*Development PCB		

Table 4.5 is the comparison between the mass-production PCB and the newly developed PCB. After that now we are going to compare the max notch result of 32℃. Figure 4.24 shows the

mass-production PCB max notch result and figure 4.25 shows the newly developed PCB max notch result.

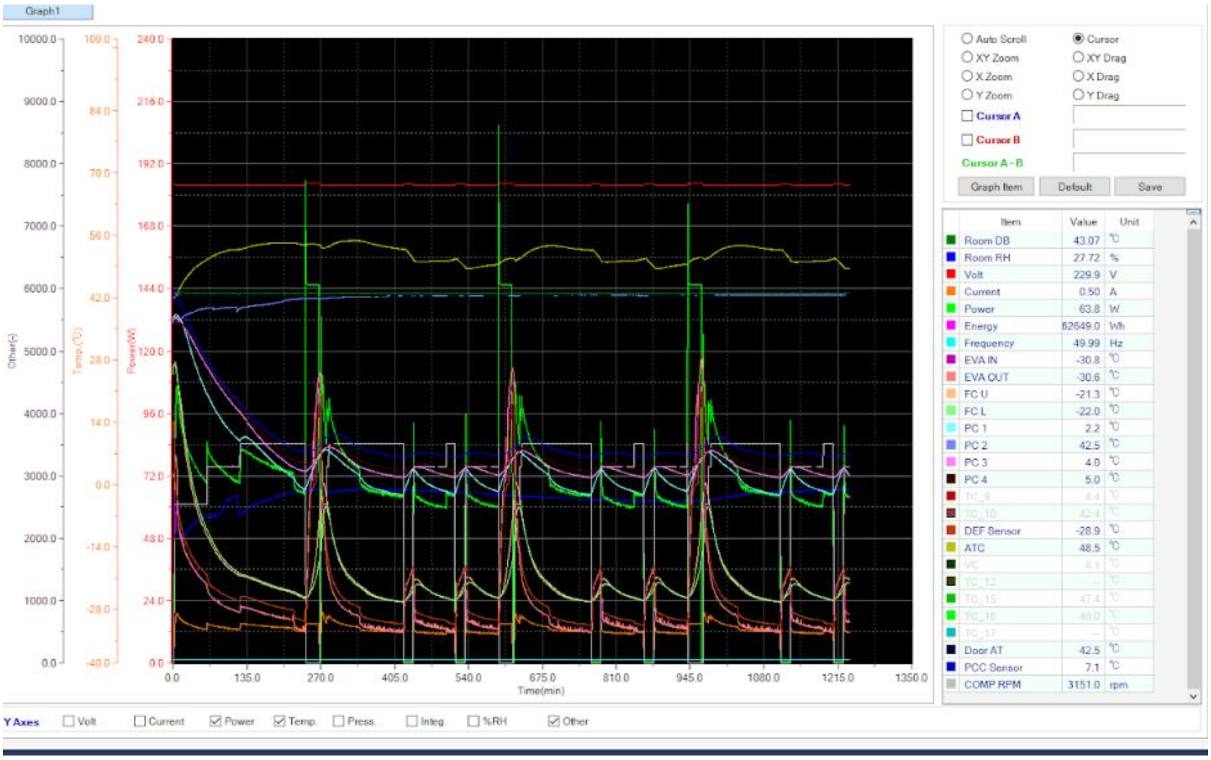


Figure 4.24 MP refrigerator max notch results at 32℃

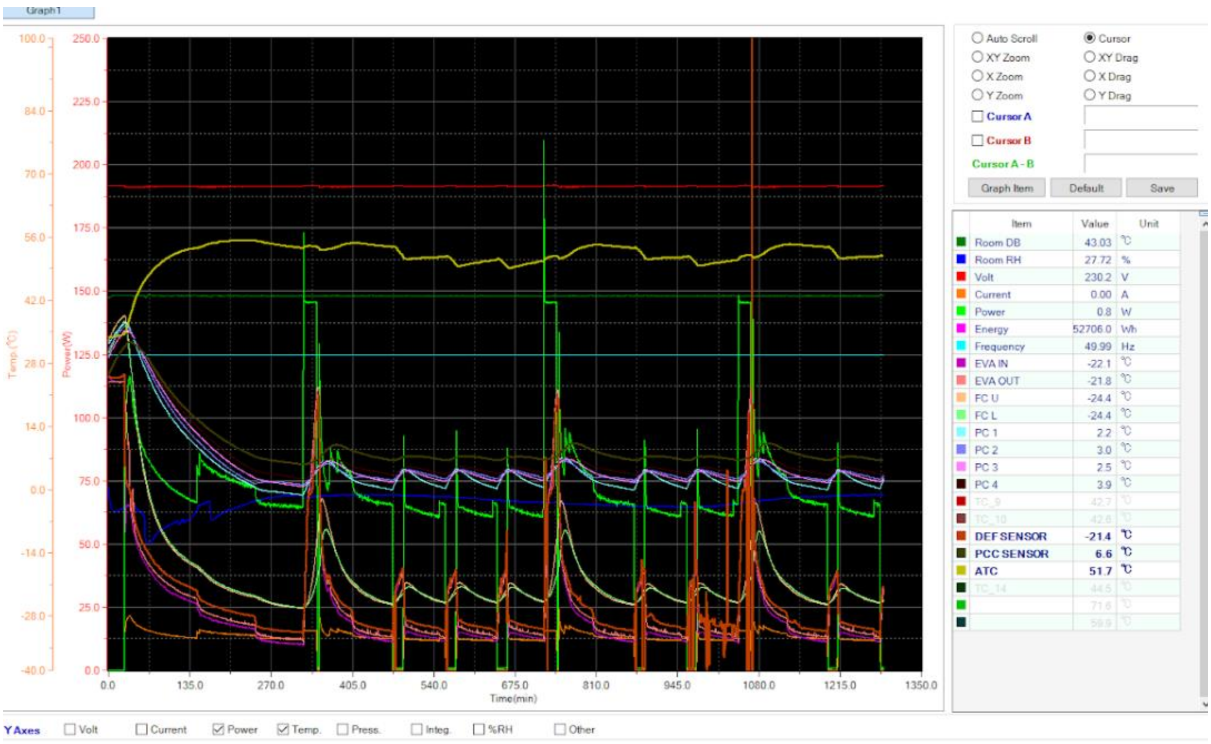


Figure 4.25 Max notch at 32℃ with newly developed PCB

Table 4.6 is the comparison between the mass-production PCB and the newly developed PCB max notch at 32℃ with respect to the above graph data.

Table 4.6 Result of Max notch at 32℃

Notch test at 32		**LAB-1**	**LAB-1**
Model:	Spec	NR-TG323 3Star	NR-TG323 3Star
Comp :		GMCC_DZ90V1W_	GMCC_DZ90V1W_
Location:		LOC-4	LOC-5
Sample No:-		APIN-R&D-REF-2023-24-214	APIN-R&D-REF-2023-24-213
Gas Qty:		65gm	65gm
		New PCB	MP
Eva in		-30.3	-31.8
Eva out		-29.6	-31.1
FC Upper		-24.8	-25.4
FC Lower	**-24.0±2.5**	**-25.2**	**-25.7**
PC 1		-2.5	-3.4
PC 2		2.0	1.6
PC 3		1.1	1.0
PC 4	**1.5±2.5**	**1.7**	**2.0**
VC		4.6	5.5
FC door upper		-24.8	-24.6
FC door Bottom		-24.8	-24.9
PC door upper		4.5	4.3
PC door Bottom		2.6	2.7
Egg tray		3.8	3.4
AMB	**32±1**	**32.0**	**31.9**
On Time		50.0	41.5
Off Time		17.5	16.5
Run %	**60±15**	**74.1**	**71.6**
Cycle/Hour		0.9	1.0
Voltage		230.2	230.0
Amp		0.3	0.3
Power		34.1	36.2
-		-	-
Results		**OK**	**OK**
Change Point	*Development PCB		

From all the graphs and comparison tables we got the result about the performance of the refrigerator with the newly developed PCB. By performing a notch/double-cut test we got similar results and improved results from the newly developed PCB. The main improvement is that the power consumption is decreased by approximately 2 to 4 watts.

4.3.2 Cycle Time change for Notch or Double Cut test: In this, the cycle time between two defrost cycles is about 13 hours but I reduced the cycle time to 12 hrs.

Benefits and graphical representation are as follows:

I. By reducing time does not impact the results of notch testing.
II. By reducing 1 hour we save approximately 1 cycle time for results.
III. We save 1 hour of energy while testing.

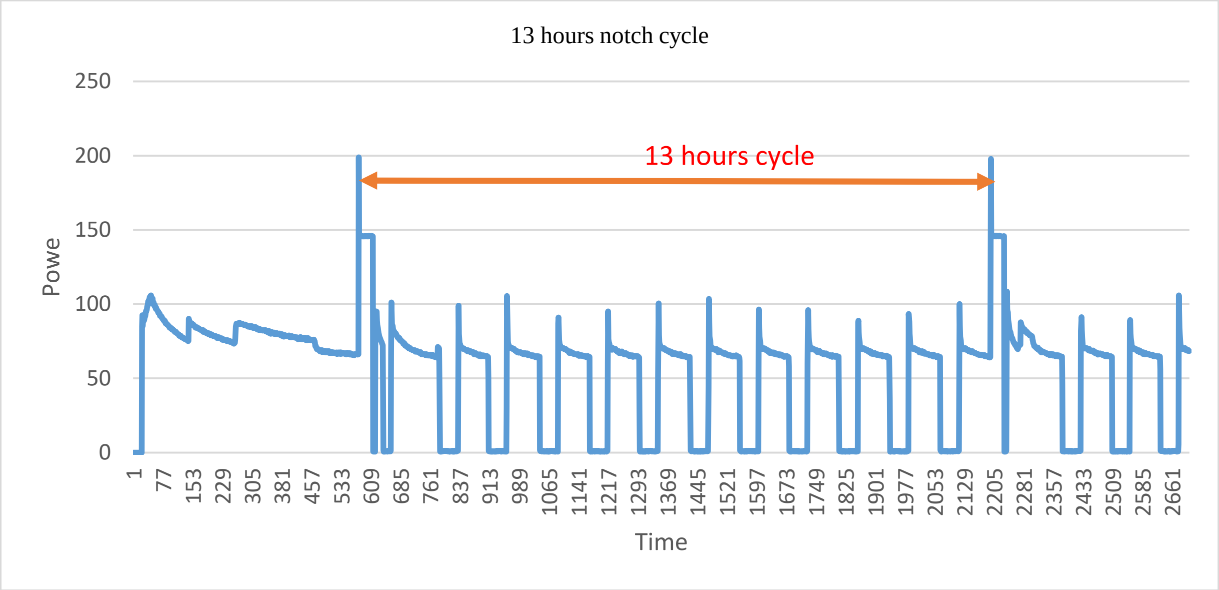


Figure 4.26 13-hour cycle graph of notch cycle

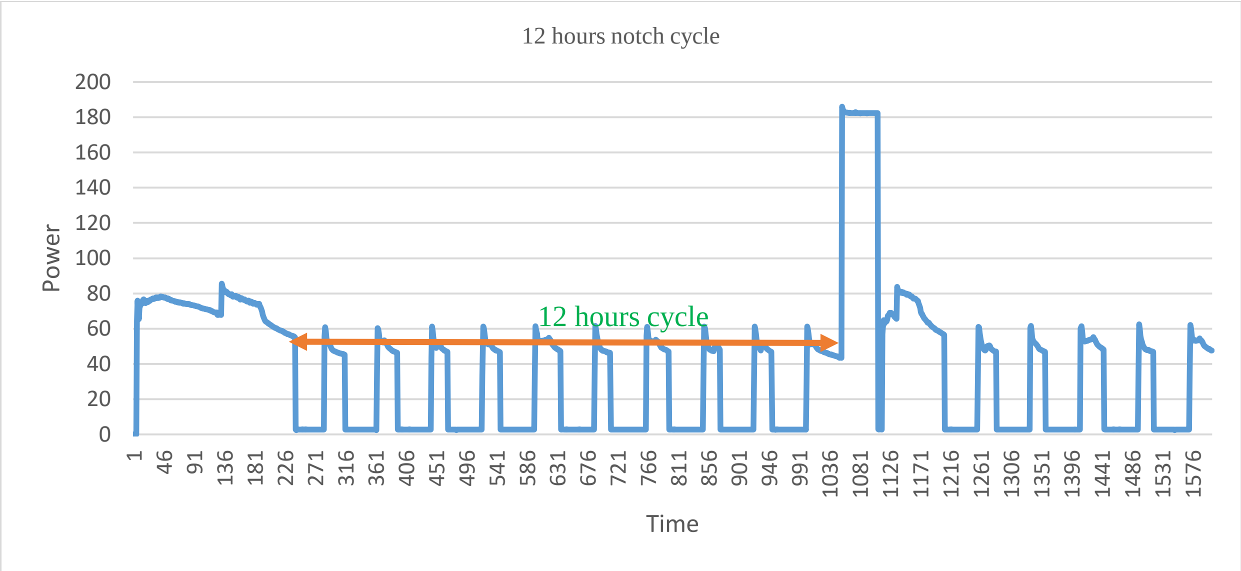


Figure 4.27 12-hour cycle graph of notch cycle

As you can see reducing 1 hour did not impact the cycle and performance of the refrigerator but instead, it saved 1 hour of energy and time as we can see in Figure 4.26 and Figure 4.27.

4.3.3 Maximum Cooling: In this test, we run the machine with both new and MP PCB by short-circuiting their temperature control settings to run the compressor at high frequency for 99 hours to achieve maximum cooling. Here below is the comparison between the maximum cooling done by which PCB.

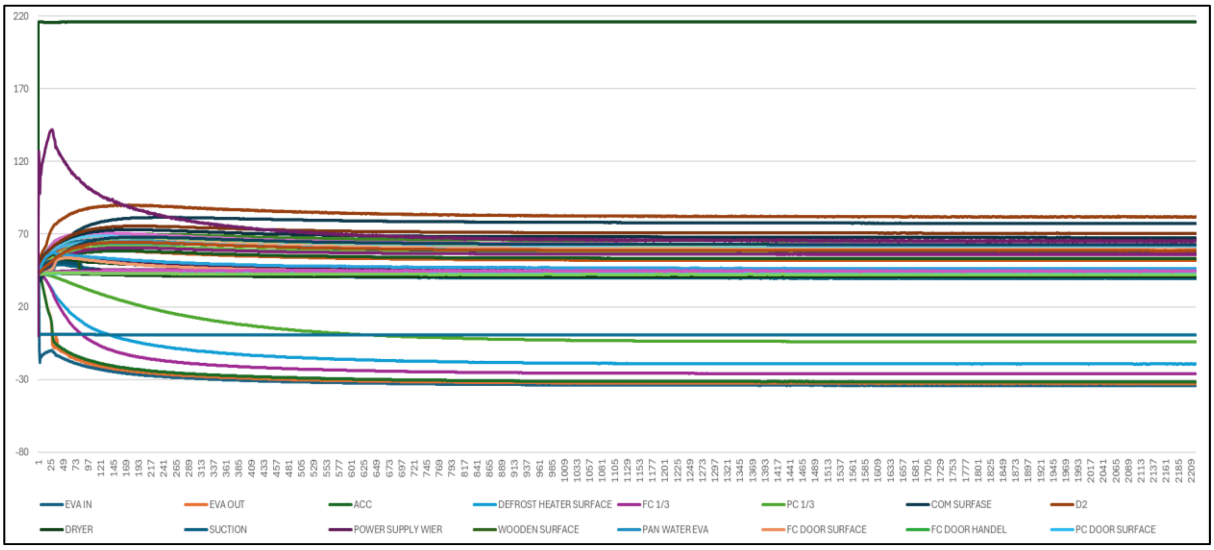


Figure 4.28 Maximum cooling results of mass production PCB

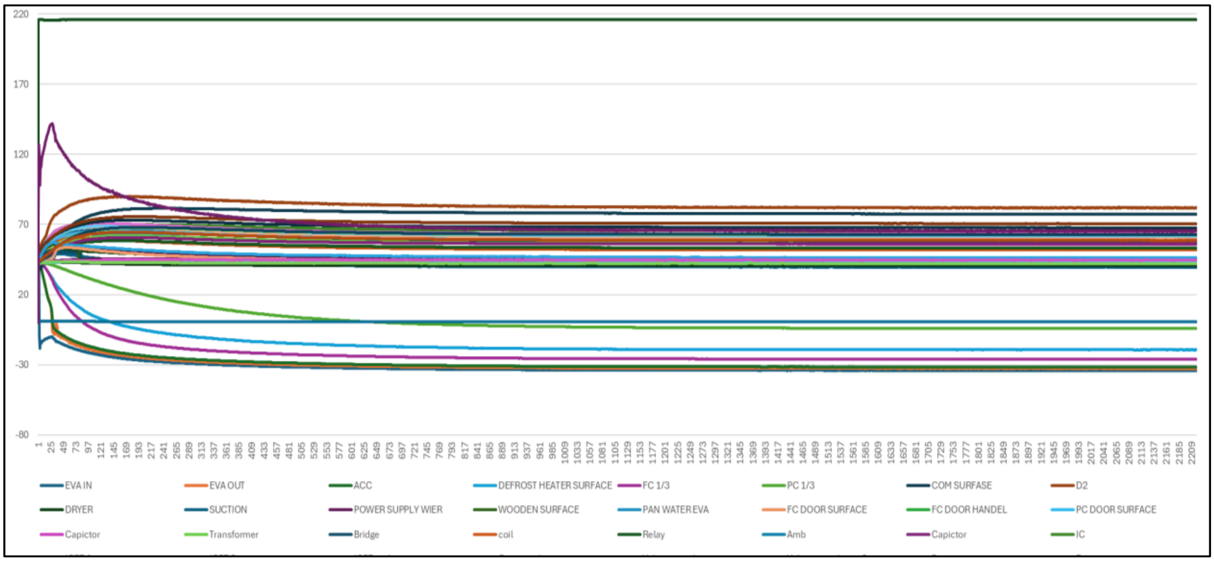


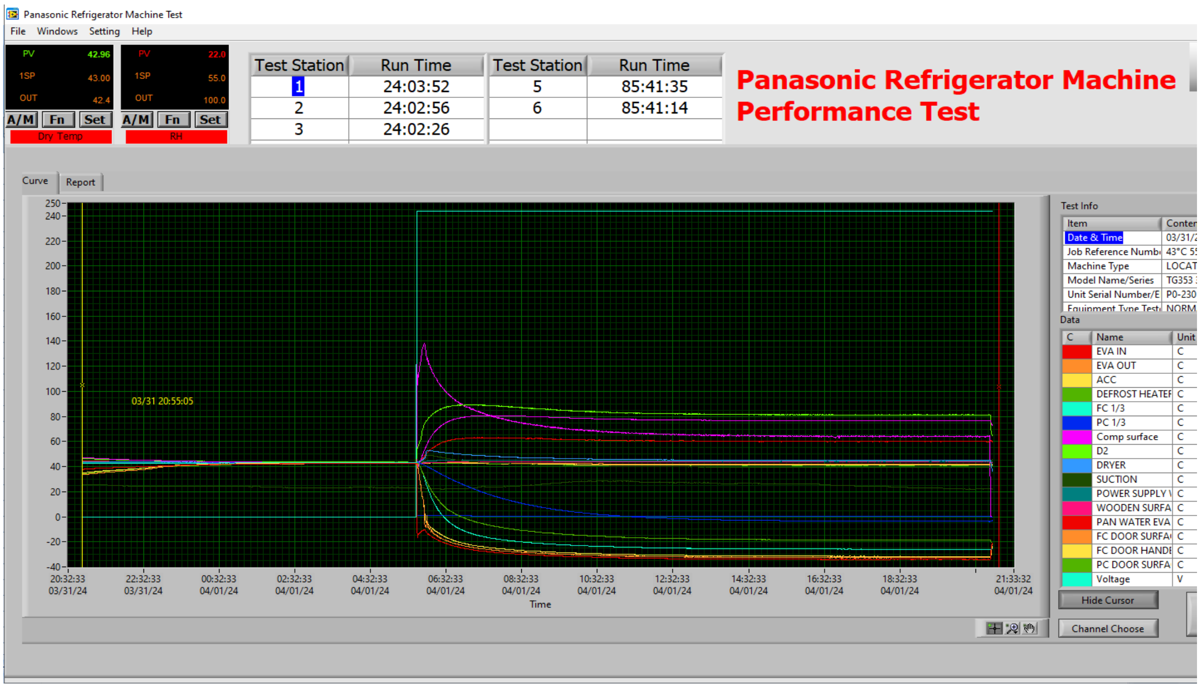
Figure 4.29 Maximum cooling results of Development PCB

Figure 4.28 and Figure 4.29 show the maximum cooling results of both mass-production PCB and newly developed PCB. We all can see how the continuous cycle works that cycle works continuously for 99 hours. The above image graphs show that there is no change in the graphs because in continuous cooling machine works at its maximum capacity so that is why they look identical. But the main change is that we change the rpm of the compressor to increase the cooling in the refrigerator. We move R3 and R4 to 42rps which provide the maximum cooling. The comparison of both mass-production PCB and newly developed PCB is shown in table 4.7.

Table 4.7 Maximum cooling comparison test between new and MP PCB

Continuous running test >@32		**LAB-2**	**LAB-2**
Model:	Spec	NR-TG35 3Star	NR-TG35 3Star
Comp		GMCC_DZ90V1W	GMCC_DZ90V1W
Location:		LOC-3	LOC-5
Sample No:-		APIN-RND-RF-2023-24-195	APIN-RND-RF-2023-24-196
Gas Qty.		65gm	65gm
		New PCB	MP
Eva in		37.7	-35.0
Eva out		-36.5	--34.4
FC Upper		-30.2	-29.9
FC Lower	**('-31.0±2.5°C)**	**-30.0**	**-29.6**
PC 1		-17.5	-16.9
PC 2		-17.3	-16.5
PC 3		-15.9	-14.9
PC 4	**('-15.0±2.5°C)**	**-14.3**	**-13.8**
VC		-9.8	-9.7
AMB	**(32.0±1)**	**32.0**	**32.3**
Dryer	(REFERENCE)	32.2	34.5
Hotline		35.7	35.6
Suction	(REFERENCE)	**27.9**	**30.1**
Comp		63.2	65.9
Discharge		65.4	66.0
Voltage		229.9	229.7
Amp		0.5	0.5
Power		56.2	54.7
-		-	-
Results		**OK**	**OK**
Change Point	*Development PCB	**base**	**base**

4.3.4 Temperature Rise test of the whole machine: With this test, we check the temperature of the machine at different voltages and extreme conditions. The results of this test are shown in Figure 4.30. This is the standard base test so we don't need to compare the PCB for this.



Test Station	Run Time	Test Station	Run Time
1	24:03:52	5	85:41:35
2	24:02:56	6	85:41:14
3	24:02:26		

Figure 4.30 Temperature rise graph of newly developed PCB

Figure 4.3 shows the standard conditions the temperature rise test at 216V.

(Model name)		NR-TG353 3Star		
No. (Refrigerator No.)		APIN-R&D-REF-2024-25-230		
(Comments)		CU winding (234.5)		
(Ambient temperature)		AT43℃		
(Voltage)		216V （230*0.94）		
(Frequency)		50Hz		
(Installation conditions)		4 sides enclose（50mm left and right, 100mm back,		
(Dial)		(Continuous operation)		
(Measurement point)		V-W間	V-U間	W-U間
(Ambient temperature during primary resistance measurement)		AT43℃	AT43℃	AT43℃
(Original Resistance)		**15.8**	**15.7**	**15.8**
(Winding resistance during operation)		**18.3**	**18.2**	**18.3**
(Winding temperature during operation)	120℃ or below	86.9℃	87.2℃	86.9℃
remarks				

Figure 4.31 Test condition for temperature rise at 216V

AT43℃_216V measurement					
Parameters	STANDARD VALUE	Stable Data	Max Data	Min Data	Avg Data
EVA IN		-34.1	42.5	-34.3	-31.9
EVA OUT		-32.8	42.5	-32.9	-30.0
Accumlator		-31.6	42.7	-31.6	-28.8
DEFROST HEATER SURFACE		-19.4	42.4	-19.5	-15.0
FC 1/3		-26.1	43.0	-26.1	-22.2
PC 1/3		-4.2	43.0	-4.2	2.0
Comp Surface	150℃ or below	77.4	81.6	37.9	77.7
D2		82.0	90.1	43.0	83.2
DRYER		45.1	52.7	43.1	45.9
SUCTION		39.6	49.1	39.5	40.6
POWER SUPPLY Wire		44.4	45.5	43.4	44.6
WOODEN SURFACE		43.6	43.8	42.6	43.6
PAN WATER EVA		60.6	63.6	42.5	61.0
FC DOOR SURFACE		42.1	43.2	42.0	42.2
FC DOOR HANDEL		41.3	44.1	41.2	41.6
PC DOOR SURFACE		41.2	43.1	41.0	41.4
CE4 - Capacitor	95℃ or below	55.8	61.4	43.0	56.7
Transformer		56.7	61.9	43.1	57.5
DB1 Bridge		58.4	66.1	43.0	59.7
LF1 Coil		51.7	60.8	43.0	53.1
RY1 Relay	100℃ or below	53.1	58.4	43.0	54.0
PCB Surface		60.4	66.2	43.2	61.3
CE6 Capacitor	95℃ or below	56.3	60.6	43.1	56.8
U9 IC	113℃ or below	65.2	70.2	43.1	66.1
IGBT 1	145℃ or below	60.1	65.1	43.1	60.9
IGBT 2	145℃ or below	60.6	68.4	43.0	62.0
IGBT pad 1	145℃ or below	62.7	70.5	43.1	64.0
IGBT pad 2	145℃ or below	58.6	64.5	43.3	59.5
U1 Octo coupler		61.8	69.2	43.1	63.1
U6 Voltage regulator 1		62.9	70.8	43.1	64.3
U5 Voltage regulator 2		62.5	67.4	43.1	63.2
Fan IC	113℃ or below	67.5	73.0	43.1	68.5
U2 Driver IC	113℃ or below	70.6	75.5	43.2	71.2
D12 Diode		62.7	68.0	43.2	63.4
PC DOOR HANDEL		40.8	42.9	40.7	41.0
CABINET TOP CENTER		43.1	51.9	42.8	43.4
CABINET LEFT CENTER		45.8	56.7	43.0	46.8
CABINET RIGHT CENTER		42.9	55.9	42.8	43.3
BACK PANEL SURFACE		46.4	57.4	43.0	47.7
CROSS RAIL CENTER		43.7	53.6	42.8	44.8
BACK PILOT		43.2	43.4	42.9	43.3
RIGHT SIDE PILOT		43.4	43.9	42.4	43.5
LEFT SIDE PILOT		44.6	45.5	43.2	44.6
AT		42.1	43.2	41.9	42.2
Voltage		216.1	216.1	0.0	215.9
Amp		0.6	1.1	0.0	0.6
Power2		65.6	141.8	0.0	71.2

Figure 4.32 Measured values of temperature rise at 216V

Figure 4.32 shows the test result of temperature rise at 216V and it passes the standard condition of temperature rise. Now below Figure 4.33 shows the measured value of the temperature rise at 243.8V.

AT43℃_243.8V measurement				
Parameters	Stable Data	Max Data	Min Data	Avg Data
EVA IN	-34.1	42.6	-34.1	-31.4
EVA OUT	-32.7	42.5	-32.8	-29.4
Accumlator	-31.5	42.9	-31.6	-28.1
DEFROST HEATER SURFACE	-18.6	42.7	-18.8	-13.5
FC 1/3	-26.0	43.0	-26.0	-21.2
PC 1/3	-3.8	43.0	-3.8	3.6
Comp Surface	76.4	80.7	39.0	76.7
D2	81.3	89.4	43.5	82.7
DRYER	45.1	52.8	43.4	46.1
SUCTION	39.5	49.2	39.4	40.8
POWER SUPPLY Wire	44.2	45.5	43.4	44.4
WOODEN SURFACE	43.6	44.0	42.8	43.7
PAN WATER EVA	60.0	63.2	42.9	60.4
FC DOOR SURFACE	42.1	43.2	41.0	42.3
FC DOOR HANDEL	41.4	43.1	41.1	41.6
PC DOOR SURFACE	41.2	43.1	40.9	41.4
CE4 - Capacitor	54.1	59.5	43.3	55.1
Transformer	55.4	60.4	43.3	56.3
DB1 Bridge	56.4	63.6	43.2	57.9
LF1 Coil	50.2	55.9	43.2	51.4
RY1 Relay	51.9	57.1	43.2	52.9
PCB Surface	58.0	63.8	43.4	59.1
CE6 Capacitor	55.1	60.0	43.4	55.9
U9 IC	64.4	69.2	43.3	65.2
IGBT 1	57.0	63.3	43.3	58.2
IGBT 2	57.2	64.7	43.3	58.7
IGBT pad 1	58.7	66.6	43.4	60.3
IGBT pad 2	57.4	63.1	43.5	58.4
U1 Octo coupler	58.7	65.7	43.3	60.0
U6 Voltage regulator 1	58.7	66.5	43.3	60.3
U5 Voltage regulator 2	61.7	66.3	43.4	62.4
Fan IC	66.5	71.4	43.4	67.3
U2 Driver IC	70.1	74.6	43.4	70.6
D12 Diode	61.8	66.9	43.5	62.5
PC DOOR HANDEL	40.8	42.9	40.6	41.0
CABINET TOP CENTER	43.9	51.4	43.6	44.8
CABINET LEFT CENTER	45.7	56.6	43.0	47.0
CABINET RIGHT CENTER	45.2	55.7	42.5	46.3
BACK PANEL SURFACE	46.1	57.4	43.0	47.8
CROSS RAIL CENTER	43.6	53.6	42.9	45.0
BACK PILOT	43.2	43.7	43.1	43.3
RIGHT SIDE PILOT	44.8	45.7	42.8	44.3
LEFT SIDE PILOT	43.1	44.4	42.9	43.3
AT	42.1	43.2	41.9	42.2
Voltage	243.7	243.8	0.0	243.4
Amp	0.5	1.0	0.0	0.6
Power2	64.0	138.7	0.0	70.7

Figure 4.33 Measured values of temperature rise at 243.8V

(Model name)	NR-TG353 3Star		
No. (Refrigerator No.)	APIN-R&D-REF-2024-25-230		
(Comments)	CU winding (234.5)		
(Ambient temperature)	AT43℃		
(Voltage)	243.8V （230*1.06）		
(Frequency)	50Hz		
(Installation conditions)	4 sides enclose（50mm left and right, 100mm back,		
(Dial)	(Continuous operation)		
(Measurement point)	V-W間	V-U間	W-U間
(Ambient temperature during primary resistance measurement)	AT43℃	AT43℃	AT43℃
(Original Resistance)	**15.8**	**15.7**	**15.8**
(Winding resistance during operation)	**18.5**	**18.4**	**18.5**
(Winding temperature during operation)	90.4℃	90.7℃	90.4℃

Figure 4.34 Test condition for temperature rise at 243.8V

Figure 4.34 shows the test condition of temperature rise at 243.8V and above results share max, min, standard, and average values, and the resulting values lie under the standard criteria for both voltages.

4.3.5 Vibration Testing: I performed the test according to the Japanese standards and the vibration readings of the refrigerators were discussed in Figure 4.35.

measuremer		Compressor								
direction		上下（Upper and Lower）			前後（Before and After）			左右（Left and Right）		
Standard		－			－			－		
target		200			200			200		
Ref		No.1	No.2	No.3	No.1	No.2	No.3	No.1	No.2	No.3
運転周波数（Rotation Speed）	20	50	30	40	70	60	110	50	50	60
	21	50	30	40	70	70	10	40	50	50
	22	40	20	30	40	50	50	30	40	40
	23	30	20	30	50	50	40	30	40	50
	24	30	20	30	50	40	40	20	60	40
	25	30	20	30	40	40	30	20	70	20
	26	20	20	30	30	40	20	20	70	30
	27	20	20	20	30	50	20	20	60	20
	28	20	20	20	20	40	10	10	60	10
	29	20	20	20	20	30	10	10	50	10
	30	20	10	30	20	30	10	10	50	10
	31	20	20	30	20	30	10	10	40	10
	32	20	20	30	30	20	10	10	30	10
	33	20	20	40	20	20	10	10	30	10
	34	20	20	40	20	20	10	10	30	10
	35	20	20	40	20	20	10	10	20	10
	36	20	20	40	20	20	10	10	20	10
	37	20	30	40	20	20	10	10	20	10
	38	20	30	30	20	20	10	10	20	10
	39	20	30	30	20	20	10	10	10	10
	40	20	30	20	10	20	10	10	10	10
	41	20	30	20	10	20	10	10	10	10
	42	20	30	20	10	20	10	10	10	10
	43	20	20	20	10	20	10	10	10	10
	44	20	20	20	10	20	10	10	10	10
	45	20	20	20	10	20	10	10	10	10
	46	10	10	10	10	10	10	10	10	10
	47	10	10	10	10	10	10	10	10	10
	48	20	10	10	10	10	10	10	10	10
	49	20	20	10	10	10	10	10	10	10
	50	20	10	20	10	10	10	10	10	10
	51	10	10	20	10	10	10	10	10	10
	52	10	10	20	10	10	10	10	10	10
	53	10	10	20	10	20	10	10	10	10
	54	10	10	10	10	10	10	10	10	10
	55	20	10	20	10	10	10	10	10	10
	56	10	10	30	20	10	10	10	10	10
	57	10	20	30	10	10	10	10	10	10
	58	10	20	30	10	10	20	10	10	10
	59	10	20	30	10	10	20	10	10	10
	60	10	20	30	10	10	10	10	10	10
	61	10	10	20	10	10	10	10	10	10
	62	10	30	20	10	10	10	10	10	10
	63	10	20	20	10	10	10	10	10	10
	64	10	10	20	20	10	10	10	10	10
	65	10	10	20	20	10	10	10	10	10
	66	20	10	20	10	10	10	10	10	10
	67	20	20	20	20	10	10	10	10	10
	68	10	10	20	10	10	10	10	10	10
	69	10	20	30	10	10	10	10	10	10
	70	10	20	30	20	10	10	10	10	20
	71	10	30	20	10	10	10	10	10	10
	72	10	30	20	10	10	10	10	10	10
	73	10	10	20	10	10	10	10	10	10
	74	20	10	20	10	20	10	10	10	20
	75	10	20	20	10	10	10	10	10	10
MAX		50	30	40	70	70	110	50	70	60

Figure 4.32 Vibration readings of the refrigerator in micrometer.

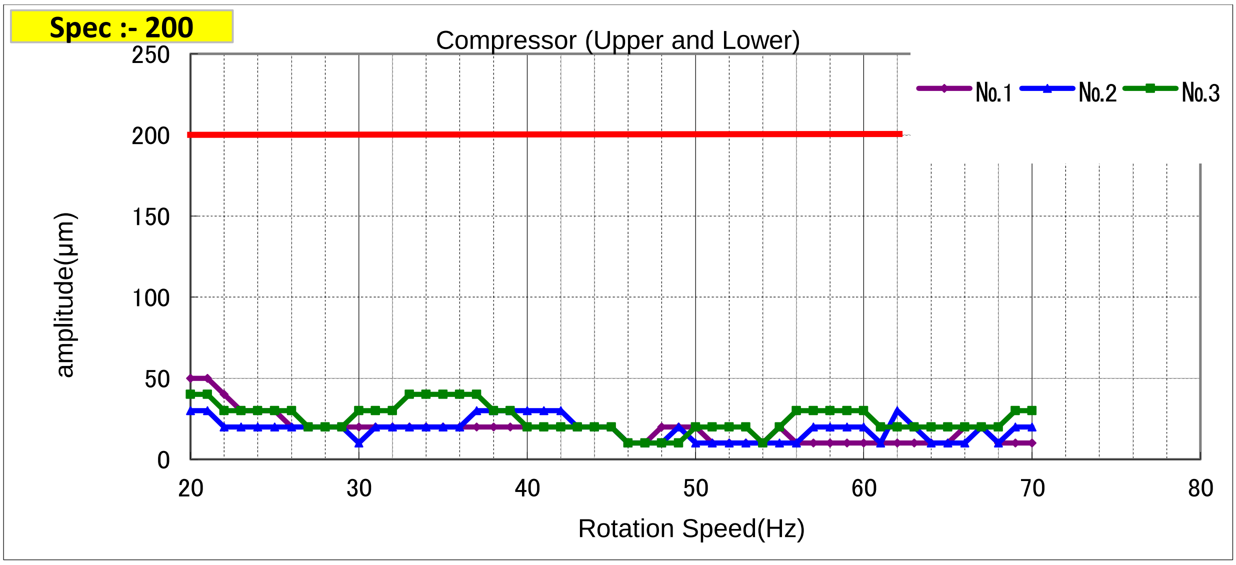


Figure 4.36 Compressor upper and lower vibration result

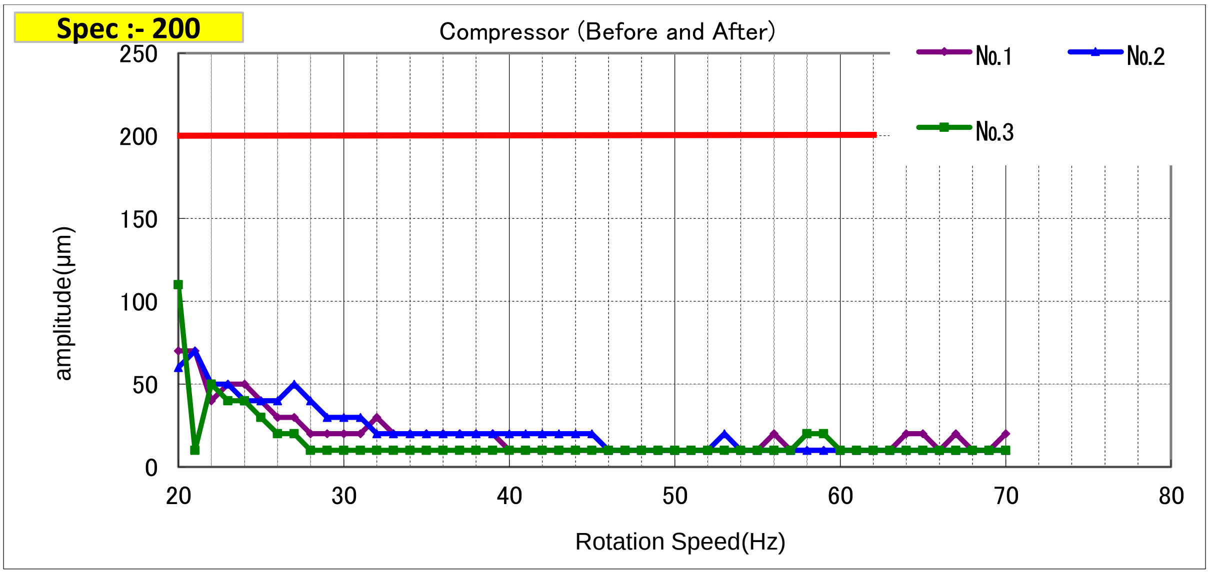


Figure 4.37 Compressor before and after vibration result

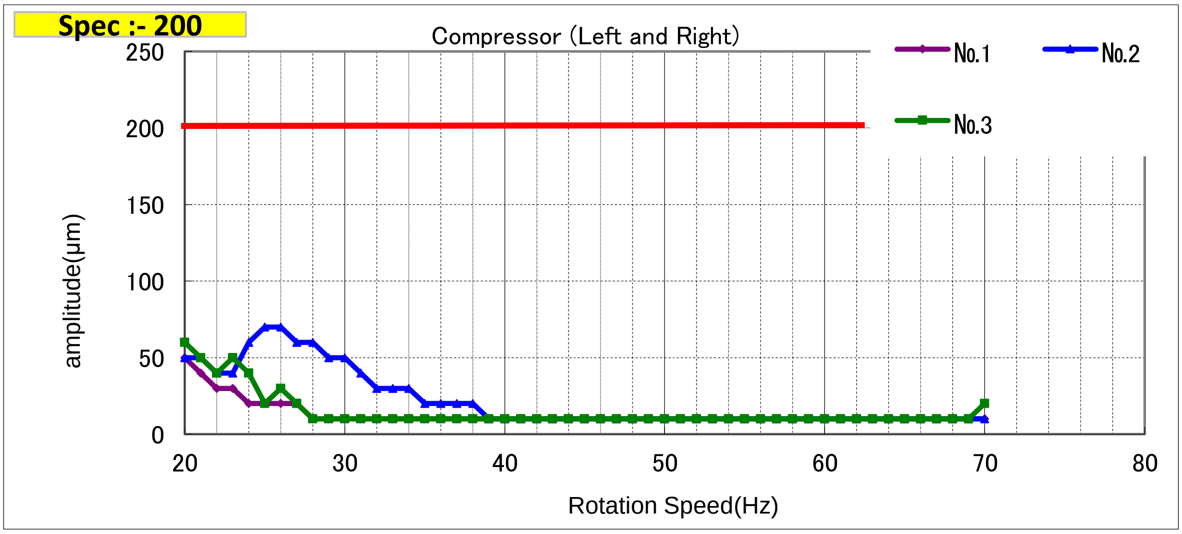


Figure 4.38 Compressor left and right vibration result

Above we discussed the result of the vibration test in Figures 4.36, figure 4.37, and figure 4.38 showing the vibration result in graphical form with spec value. This test is only performed on development PCB because it is a standard-based test and there is no need for comparison. And with the newly developed PCB, it passed all the criteria for the vibration test.

4.3.6: I performed the noise test according to the Japanese standards and the results of the test are discussed below in Table 4.8

Table 4.8 Sample test with new development PCB at different frequencies before PCB case location.

	R1/27			R2/36			R3/40			R4/54			R562			R6/70		
Standard Value	40			40			40			41			42			42		
Sr. No.	Sample1	Sample2	Sample3	Sample1	Sample2	Sample3	Sample1	Sample2	Sample3	Sample1	Sample2	Sample3	Sample1	Sample2	Sample3	Sample1	Sample2	Sample3
1	35.8	22.8	30	34.4	36.7	31.1	34.9	34.3	29.7	34.4	33.9	30.6	31.2	32.2	30.8	34.5	31.9	28.7
2	34.2	33.6	30.2	35.1	36.4	32.2	34.8	33	29.6	35.1	33.4	30.9	33.4	32.1	30.7	34.1	32.6	29.8
3	35.3	34	29.7	34.6	36.7	31.6	34.7	33.5	30.2	36.4	33.7	30.9	32.2	35	30.9	34.8	33.9	29.7
4	33.6	34.4	29.9	35.2	36.3	31.4	34.4	35.6	30.8	35.8	33.3	30.8	32.5	32.4	31	33.8	33.1	27.6
5	33.8	33.9	29.3	34.1	36.7	30.6	35.7	35.2	30.3	35.9	33.5	31.2	32.6	32.9	31.2	33.9	33.4	27.8
6	34.1	33.8	30	33.7	37	31.3	34.4	36.2	30.5	36.4	33.7	30.7	32.7	33.3	31.7	35	33	28.5
7	34.3	34.8	29.7	33.9	38.9	31.5	34.3	33.6	30.7	35.7	33.6	30.5	31.7	34.7	30.9	34.3	33.5	27.9
8	34	34.3	30.1	35.6	37.5	32	35.2	33.5	33.2	35.1	33.4	29.7	32.2	34.2	31.1	34.9	35.9	28.3
9	35.2	33.8	29.6	34.9	37	31.6	36.7	34.5	31	36.7	35.6	31.9	33.1	32.9	32.3	34	33.8	30.6
10	33.4	33.7	31.1	35	37.3	31.2	34.9	33.8	30.2	35	34.9	31.4	33.2	32.5	31.1	34.9	33.4	31.6
11	33.2	33.5	29.3	34.8	36.8	31.7	35	34.7	30.1	34.9	34.6	30.4	30.9	33.2	31.3	34.2	32.5	27.9
12	33.3	34.1	30.5	34.5	37	31.9	35.3	33.5	30.5	35.8	34.8	30.3	32.8	34.7	31.4	32.7	32.4	27.8
13	32.6	34.8	28.7	35.3	37.9	30.6	34.7	33.5	29.3	35.1	33.9	31	33.6	32.7	31.6	34.2	32.3	27.6
14	32.5	34	30.4	34.2	36.4	31.6	35.5	33.4	30.1	35.9	33.8	30.4	32.8	35	31.1	34.1	32.6	28
15	34	34.7	32.5	34.7	35.9	32	35.8	34.1	32	34.7	33.7	30.5	31.6	33.7	31.7	35	34.3	28.9
16	33.6	33.4	30.5	34.3	36.9	31.5	35.7	35.2	32.6	35.6	33.4	30.1	31.8	34.1	30.6	33.6	32.8	28.8
17	33.3	35.1	20	34.4	37.1	30.9	35.1	35.3	30.5	34.8	33.4	30.9	31.6	34.1	31.3	34.6	33.2	29.2
18	33.1	34.2	29.8	34.8	37.7	32.8	34.9	33.4	30.6	36.7	33.5	30.2	33.1	32.6	32	33.6	32.5	27.6
19	33.6	34.4	29.9	34.2	36.9	31.6	35.5	33.7	30.2	35.8	33.6	30	30.2	33.3	31.4	34.8	32.8	30
20	34.1	33.8	30.5	34.5	36.5	31.8	35	33.6	32.3	35.9	34.6	30.6	29.9	33.8	31.5	34.3	32.8	30.3
21	33.2	33.9	29.5	34.2	36.4	30.6	35.5	33.7	30.2	34.5	33.2	30.5	31	32.8	31.6	34.5	32.7	28.4
22	33.5	33.3	30.9	33.8	37.3	30.9	35.4	33.8	30.6	34.4	32.8	30	32	32.7	31.3	35.9	34.2	29.7
23	33.9	34	28.9	34.1	36.3	32.4	34.4	33.7	31.3	35.1	33.4	30.8	32.9	34.3	31.8	34.8	34.8	27.8
24	33.7	34.8	29.9	35	37.4	31	35.7	34.3	30.9	35.6	33.5	30.7	30.4	32.5	30.6	33.5	33	27.1
25	33.8	34	29.7	33.9	37.2	30.9	36	34.9	31.3	34.6	33.7	30.2	30.9	35	31.2	34.1	32.2	29.1
26	33.4	33.6	30.1	34.1	36.7	31	35.6	34.7	31	35	33.3	31.2	31.1	33.9	31.4	35	32.7	28.1
27	33.6	34.1	29.5	34	37.1	31.5	35.6	33.5	32.6	35.6	33.4	29.6	20.1	33.4	32.2	33.9	32.9	29.1
28	33.8	34	30.7	34.9	36.8	30.9	35.2	32.9	30.1	34.2	34.5	30.2	32.3	32.9	32.4	35.1	33	30
29	33	34.1	29.9	35.5	36.4	30.9	34.5	33.9	29.7	34.4	33.3	30.4	32.2	32.6	31.2	34.3	32.4	29.7
30	33.3	34.8	29.4	34.6	36.7	32.3	34.6	33.2	30.5	35	35.1	30.7	32.1	32.8	31.9	34.6	32.7	27.1
31	33.6	33.9	29.9	35.2	36.3	31.1	35.6	33.3	31.2	35.7	33.2	31.4	31.7	32.7	31.9	33.1	32.9	27.3
32	34.3	34.7	30.3	34.4	36.6	32.1	35.4	33.4	30.7	35.6	33.7	30.5	31.8	34.1	30.7	34.4	33.1	28.3
33	33	34.3	31.3	34.3	36.7	30.8	36.6	35.4	30.2	36.3	33.9	30.7	31.3	34.6	30.3	34.1	32	27.8

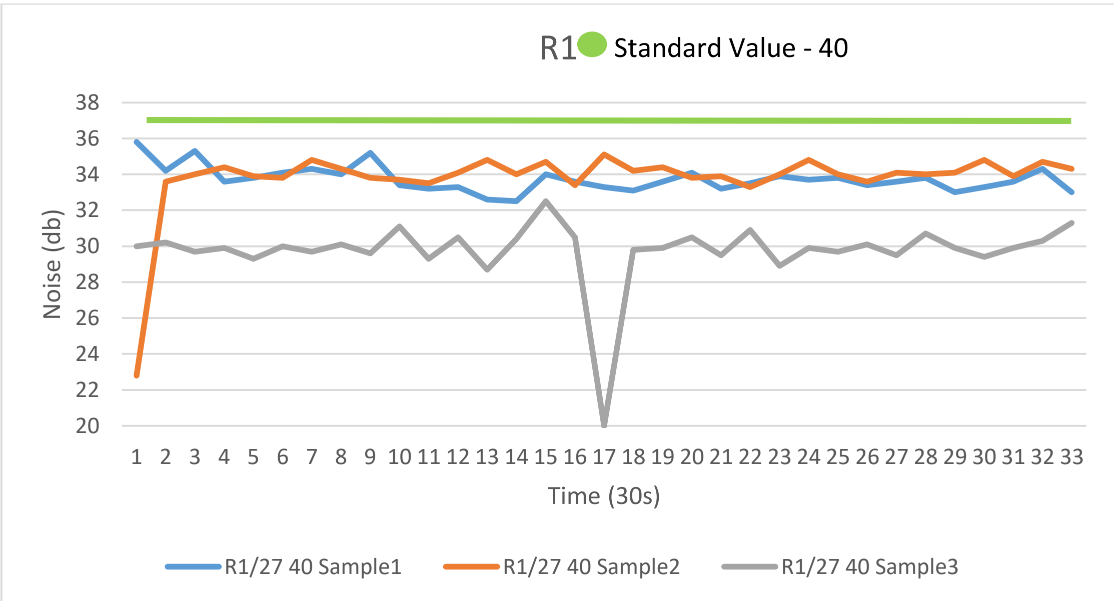


Figure 4.39 Noise result at R1 Speed.

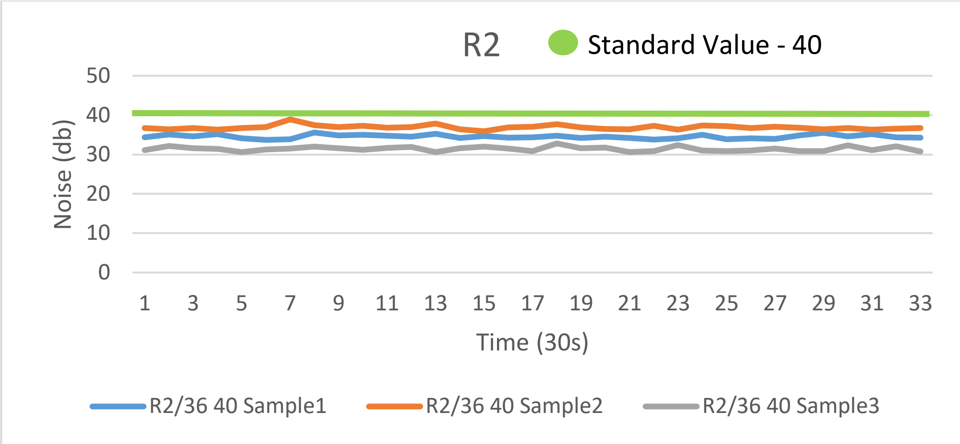


Figure 4.40 Noise result at R2 Speed.

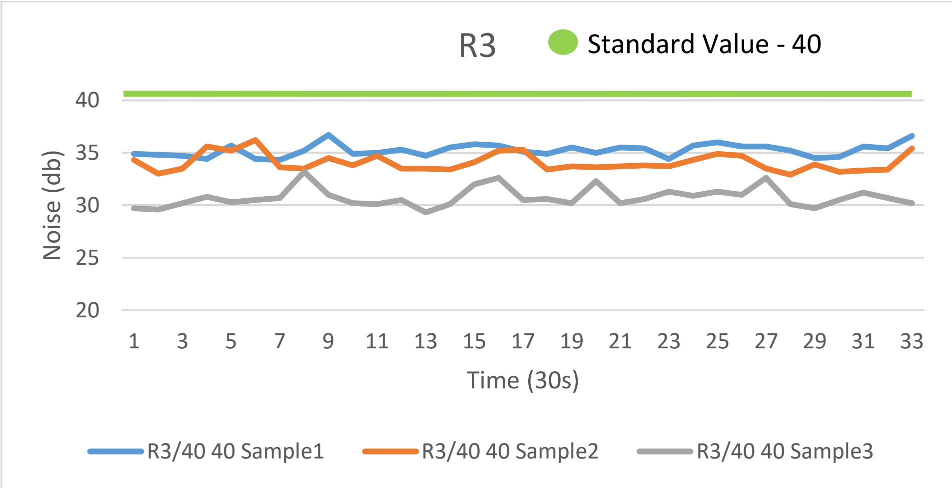


Figure 4.41 Noise result at R3 Speed.

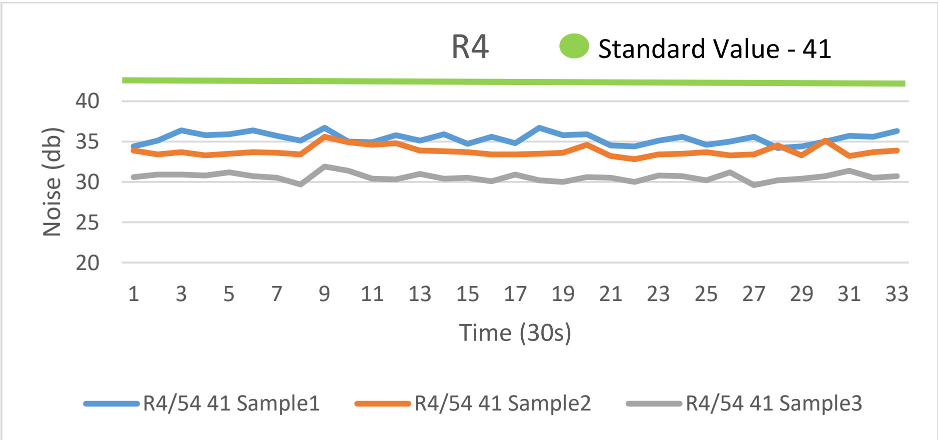


Figure 4.42 Noise result at R4 Speed.

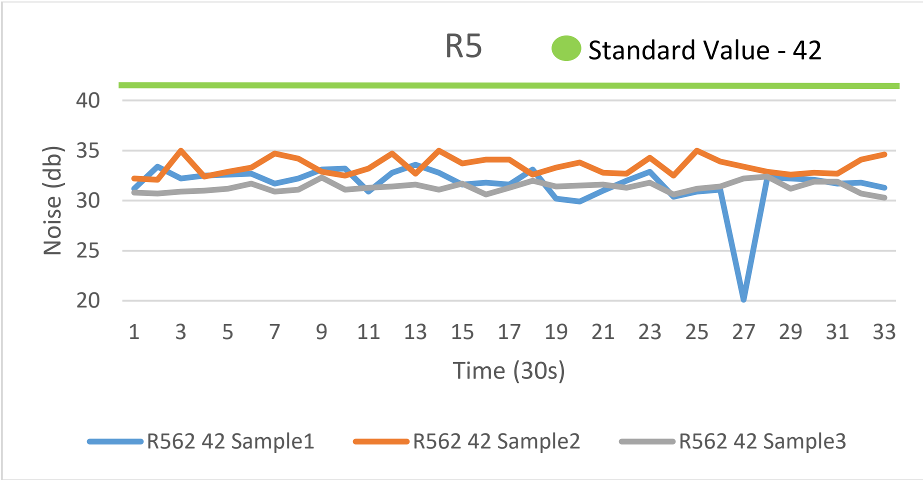


Figure 4.43 Noise result at R5 Speed.

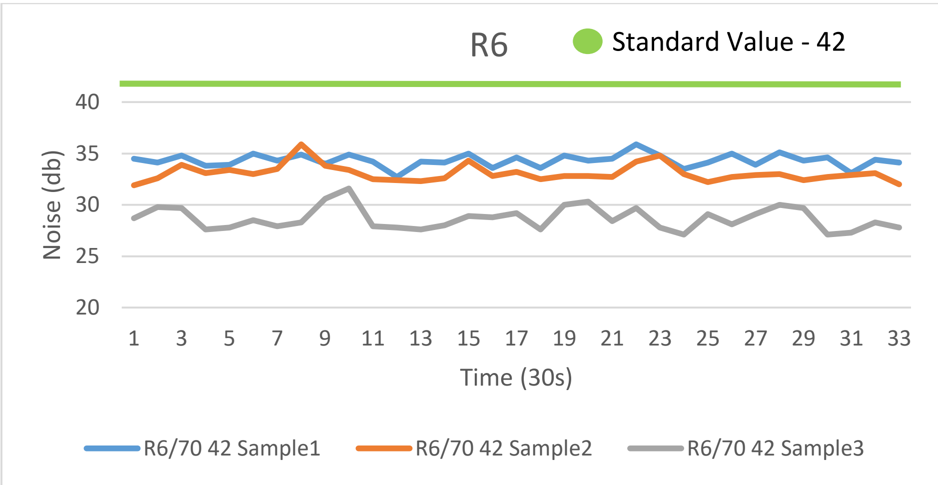


Figure 4.44 Noise result at R6 Speed.

As we can see above the results of the noise test are in figure 4.39, figure 4.40, figure 4.41, figure 4.42, figure 4.43, and figure 4.44 in graphical format with spec values. While performing this test the results are good and pass all the criteria. But when we record the noise of the refrigerator samples from the PCB case it also records the condenser noise that's why the noise result are upper side.

4.4 Analysis of Energy consumption and performance enhancement compared with the old model.

During energy testing with the new development PCB, we saw the change in the off time in the cycle which significantly impacted the results of energy. So, firstly I am going to show in figure 4.45 and in figure 4.46 the difference between the off times of both the PCB.

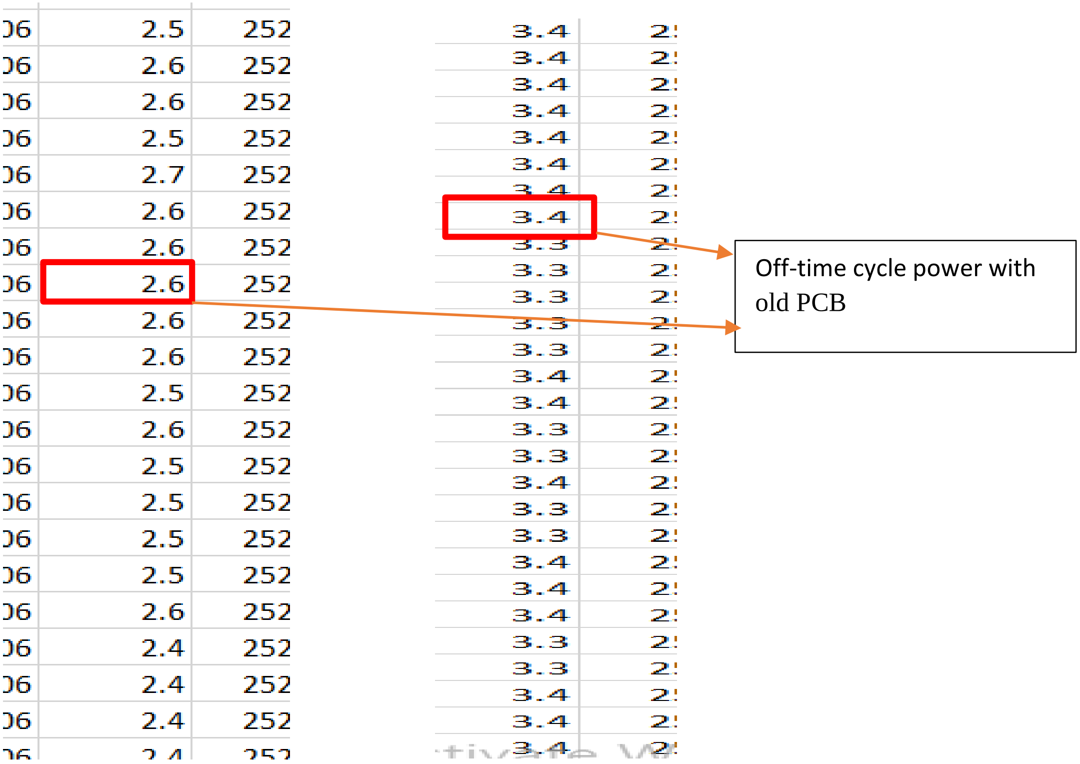


Figure 4.45 off-time cycle power consumption with old developed PCB is around 2.6 to 3.4 watt

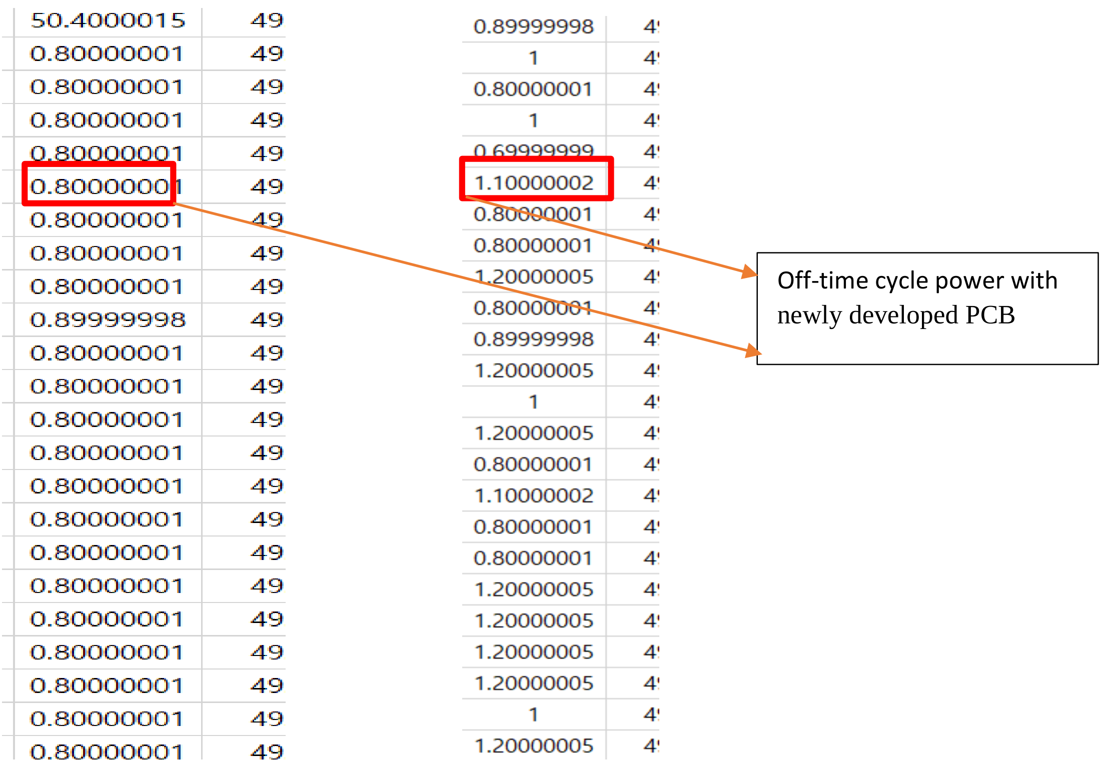


Figure 4.46 off-time cycle power consumption with newly developed PCB is around 0.8 to 1.2 watt

As I said above about the off-cycle time difference in the development PCB the off-time is around 0.8 to 1.2 watts and the off-time of mass production is 2.6 to 3.4.

Now, I am going to show the energy graphs of both PCBs from defrost to defrost which we are using to calculate the energy.

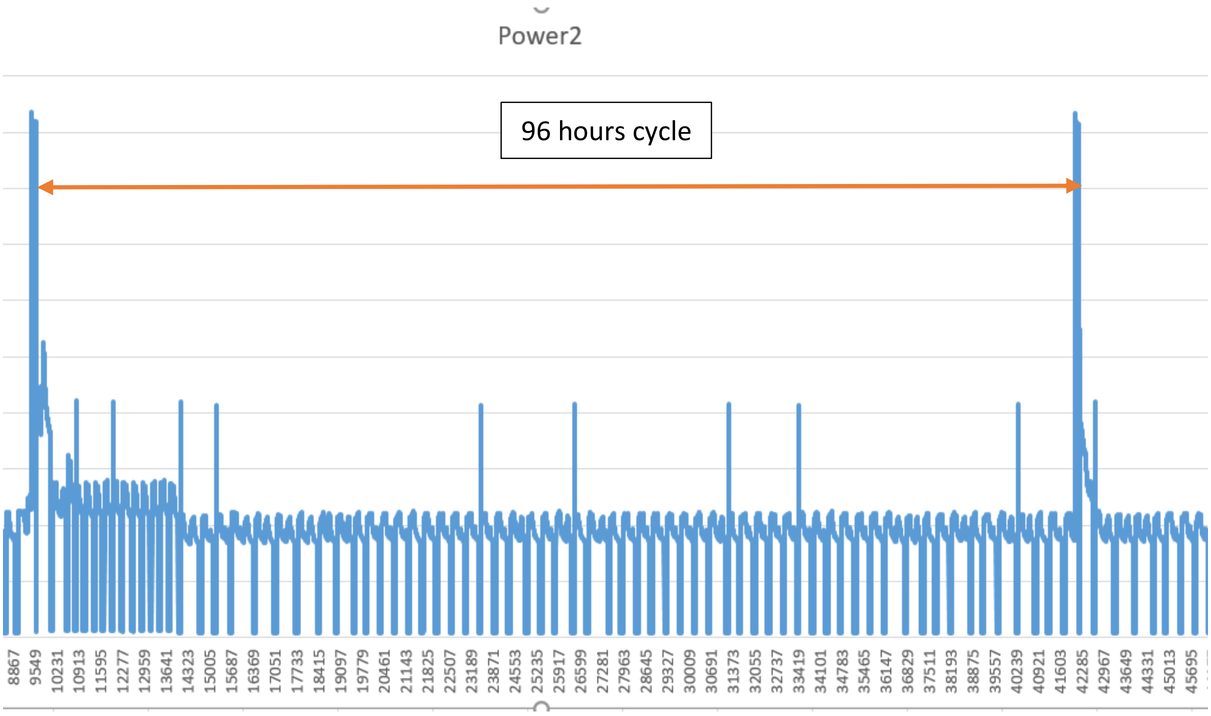


Figure 4.47 Energy graph of mass production PCB

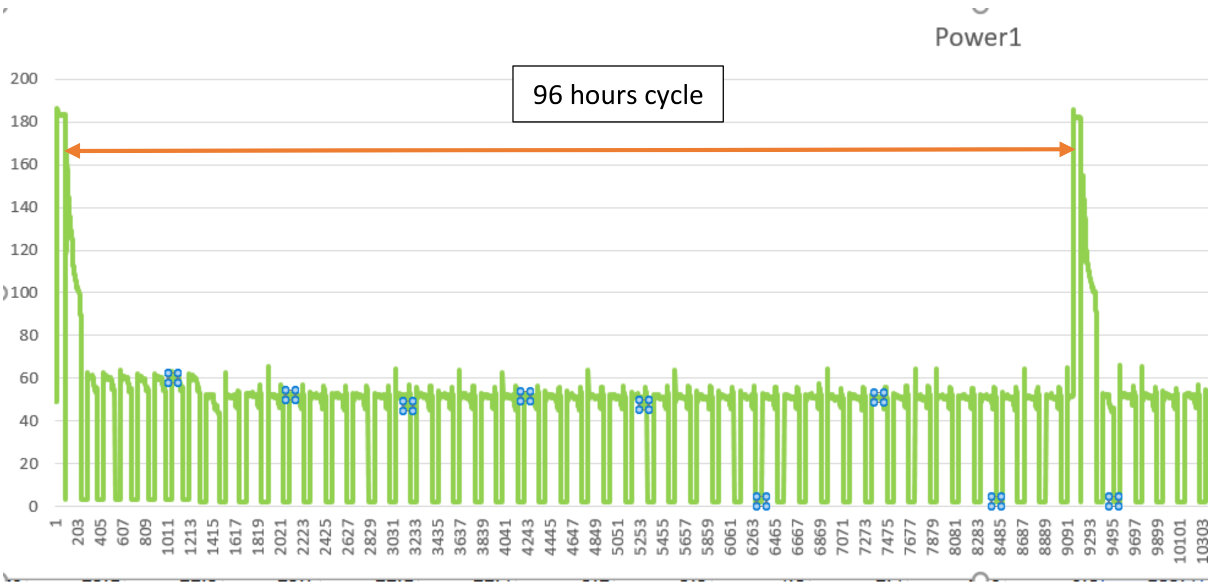


Figure 4.48 Energy graph of newly developed PCB.

From the above graphs shown in Figure 4.47 and in Figure 4.48 we can see that there is not much difference but when we calculate the energy we can see the difference. Below I calculated the energy for both cold and warm and we can see the significant difference.

Energy Test As Per IS 17550 (Part 3):2021 2 Point Interpolation

Model Name-NR-TG35 3Star (V1W comp)		LAB-3	
		Location-06	Sample-232
	Start Date	26-02-2024	
Comp-V1W	End Date	04-03-2024	
Temp Nomencluture	**Specifications**	**COLD**	**WARM**
Average Freezer compartment temperature during steady state (°C) (-18±2)	-18 °C	-18.67	-17.86
Average Fresh Food compartment temperature during steady state (°C) (4±2)	4 °C	2.67	4.23
Steady state power consumption-P_{ss} (W) [Case SS1 / Case SS2]	Case SS1	30.32	30.09
Additional energy consumed during Defrost and recovery period	(Wh)	90.85	111.68
Accumulated temperature during defrost and recovery period in fresh food compartment	(°C)	-0.54	0.31
Accumulated temperature during defrost and recovery period in freezer compartment	(°C)	4.03	5.81
Defrost Interval	(h)	40.00	40.00
Daily Energy Consumption	WHr/Day	782.17	789.09
Average Freezer compartment temperature	(°C)	-18.57	-17.72
Average Fresh Food compartment temperature	(°C)	2.65	4.24
Interpolation Method			
Step 1	Compartment Interpolation Factor	Fresh food (FF)	Freezer (FZ)
	Calculate fi	0.851	0.668
	Criteria	TRUE	TRUE
Step 2	Interpolated Temp. for Freezer compartment and Fresh Food compartment.	Tj FF (Ta)	Tj FZ (Tb)
	Calculate Tj	4.00	-18.00
	Criteria	TRUE	TRUE
Step 3	Less than or equal to target of temp.	Tj FF	Tj FZ
		4.00	-18.00
	Criteria	TRUE	TRUE
E Daily	WHr/Day	788.06	
Annual Energy Consumption (KWh/year)		**287.64**	
	BEE LIMIT	306	
	ENERGY LIMIT	290	

Parameter	Requirement	Actual COLD	Actual WARM
Specific Test conditions			
Ambient temperature (°C)	Average: T±0.5	32.02	31.99
	Standard deviation: < 0.5	0.30	0.17
Relative Humidity (%)		55.00	55.00
Supply voltage (V)	Average: 230±1%	230.32	230.29
	2*Standard deviation: xxx	0.24	0.23
Supply frequency (Hz)	Average: 50±1%	49.99	49.99
	Standard deviation: xxx	0.0	0.0

Figure 4.49 Annual energy consumption result of mass production PCB (287.64)

Energy Test As Per IS 17550 (Part 3):2021 2 Point Interpolation

Model Name-NR-TG35 3Star		LAB-2	
		Location-1	Sample-182
		Start Date	26-02-2024
Comp-V1W		End Date	04-03-2024
Temp Nomencluture	**Specifications**	**COLD**	**WARM**
Average Freezer compartment temperature during steady state (°C) (-18±2)	-18 °C	-18.64	-17.16
Average Fresh Food compartment temperature during steady state (°C) (4±2)	4 °C	2.84	4.22
Steady state power consumption-P_{ss} (W) [Case SS1 / Case SS2]	Case SS1	30.89	29.14
Additional energy consumed during Defrost and recovery period	(Wh)	85.60	90.68
Accumulated temperature during defrost and recovery period in fresh food compartment	(°C)	-0.54	0.02
Accumulated temperature during defrost and recovery period in freezer compartment	(°C)	4.37	3.72
Defrost Interval	(h)	40.00	40.00
Daily Energy Consumption	WHr/Day	792.76	753.77
Average Freezer compartment temperature	(°C)	-18.53	-17.06
Average Fresh Food compartment temperature	(°C)	2.82	4.22
Interpolation Method			
Step 1	Compartment Interpolation Factor	Fresh food (FF)	Freezer (FZ)
	Calculate fi	0.843	0.360
	Criteria	TRUE	TRUE
Step 2	Interpolated Temp. for Freezer compartment and Fresh Food compartment.	Tj FF (Ta)	Tj FZ (Tb)
	Calculate Tj	4.00	-18.00
	Criteria	TRUE	TRUE
Step 3	Less than or equal to target of temp.	Tj FF	Tj FZ
		4.00	-18.00
	Criteria	TRUE	TRUE
E Daily	WHr/Day	759.88	
Annual Energy Consumption (KWh/year)		**277.36**	
	BEE LIMIT	306	
	ENERGY LIMIT	290	

Parameter	Requirement	Actual COLD	Actual WARM
Specific Test conditions			
Ambient temperature (°C)	Average: T±0.5	31.86	31.88
	Standard deviation: < 0.5	0.24	0.22
Relative Humidity (%)		41.11	39.81
Supply voltage (V)	Average: 230±1%	230.44	230.43
	2*Standard deviation: xxx	0.15	0.16
Supply frequency (Hz)	Average: 50±1%	50	50
	Standard deviation: xxx	NA	NA

Figure 4.50 Annual energy consumption result of development PCB (277.36)

From the above readings in Figure 4.49 and Figure 4.50, we got the results that the development PCB showed improvement by 10 KWh/year, and the result summary is shown below in Table 4.9.

Table 4.9 Energy result summary

Model:- TG35	Unit-1	Unit-2
BEE LIMIT	306	
ENERGY LIMIT	290	
Energy Consumption (KWh/year)	287.1	277.4

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

5.1 CONCLUSION

The results of the development PCB were compared with the mass production PCB to determine how accurate they were. The safety properties of PCBs were examined using a variety of safety tests, and we then checked their performance with a frost-free refrigerator while keeping the testing parameters the same as Japanese and Indian standards in every case. The results of the test done on the development PCB have been validated. Based on the study results, the below conclusion has been summarized.

- Based on the findings, when we compare the IGBT and driver IC for the inverter circuit, the parameters and specifications of the components remain the same. We observe that as we increase the rpm of the compressor, it does not impact the performance, and when we change the speed on and off of the compressor, it takes less time as compared to mass production speed. We found the IGBT and driver IC cheaper and more reliable than the current ones. We see a cost reduction in PCB of around 200 rupees / 2.50 USD approximately.
- After the safety testing, we check or test the PCB with the refrigerator, and the results are as follows:
    1. While performing the notch test, we can see that the developed PCB performed very well from 1℃ to 2℃. The main highlight of the test is that we reduced the notch time from 13 hours to 12 hours.
    2. By increasing the RPM of the compressor from 60 to 66 RPM at R6. Therefore, the maximum cooling achieved and the difference between the cooling is about 4°C to 5°C for different locations of the compartment in the refrigerator
    3. As we test the refrigerator for temperature rise, noise, and vibration, we get the results as per standards and pass the criteria with the new PCB.
- Finally, evaluating refrigerators for energy efficiency suggests that maximizing off-time during the cycle can dramatically reduce power usage, resulting in an annual savings of 4% to 5%.

5.2 FUTURE SCOPE

The results of this work indicate that energy efficiency can be further enhanced by upgrading components. However, due to the high purchasing costs and meeting the quantity of components make it currently impossible. But, in the future, as advancements in component development occur and meet the number of components, these improved components may be considered for use in frost-free refrigerators.

REFERENCES

1. Gilleo, Ken, and Jerry Murray. "The Definitive History of the Printed Circuit." *PC Fab* (1999): 1-16.

2. J. T. Harvel, "Classification of PCB Types for Cost Effective Solutions," 15th Design Automation Conference, Las Vegas, NV, USA, 1978, pp. 444-445, doi: 10.1109/DAC.1978.1585209. keywords:

3. J. Branson, J. Naber and G. Edelen, "A simplistic printed circuit board fabrication process for course projects," in IEEE Transactions on Education, vol. 43, no. 3, pp. 257-261, Aug. 2000, doi: 10.1109/13.865197.

4. D. Slee, J. Stepan, W. Wei and J. Swart, "Introduction to printed circuit board failures," 2009 IEEE Symposium on Product Compliance Engineering, Toronto, ON, Canada, 2009, pp. 1-8, doi: 10.1109/PSES.2009.5356012.

5. He, Xiaofei, et al. "An Evaluation of the Insulation Resistance and Surface Contamination of Printed Circuit Board Assemblies."2012

6. Montrose, Mark I. *Printed circuit board design techniques for EMC compliance*. Vol. 1. Piscataway, NJ: IEEE press, 1996

7. Seol, Byong-Su, et al. "A circuit model for ESD performance analysis of printed circuit boards." *2008 Electrical Design of Advanced Packaging and Systems Symposium*. IEEE, 2008.

8. Standler, Ronald B. "Design and performance of surge suppressors." *1993 International Symposium on Electromagnetic Compatibility*. IEEE, 1993.

9. Akintunde, M. A. "Validation of a vapour compression refrigeration system design model." *American Journal of Scientific and Industrial Research* 2.4 (2011): 504-510.
10. CHATZAKIS, J., et al. "Spike Production Circuit for Electrical Appliance Testing."(2007).

11. Peiravi, Ali. "Testing and reliability improvement of high reliability consumer electronics products manufactured on printed circuit boards." *Journal of American Science* 5.3 (2009): 95-105.

12. Arabi, Faical, et al. "Vibration test and simulation of printed circuit board." *2018 19th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE)*. IEEE, 2018.

13. Lahokallio, Sanna, Kirsi Saarinen, and Laura Frisk. "Effect of high-humidity testing on material parameters of flexible printed circuit board materials." *Journal of electronic materials* 42 (2013): 2822-2834.

14. E. L. Owen, "History [origin of the inverter]," in *IEEE Industry Applications Magazine*, vol. 2, no. 1, pp. 64-66, Jan.-Feb. 1996, doi: 10.1109/2943.476602

15. N. Iwamuro and T. Laska, "IGBT History, State-of-the-Art, and Future Prospects," in *IEEE Transactions on Electron Devices*, vol. 64, no. 3, pp. 741-752, March 2017, doi: 10.1109/TED.2017.2654599.

16. Lahlaci, M. E., M. Miloudi, and H. Miloudi. "Experimental electromagnetic compatibility of conducted electromagnetic interferences from an IGBT and a MOSFET in the power supply." *Electrical Engineering & Electromechanics* 3 (2024): 38-43.

17. A. Albanna, A. Malburg, M. Anwar, A. Guta and N. Tiwari, "Performance comparison and device analysis Between Si IGBT and SiC MOSFET," *2016 IEEE Transportation Electrification Conference and Expo (ITEC)*, Dearborn, MI, USA, 2016, pp. 1-6, doi: 10.1109/ITEC.2016.7520242.

18. Chang, Wen Ruey, et al. "The components and control methods for implementation of inverter-controlled refrigerators/freezers." (2004).

19. J. Li, M. Zhou, Y. Sha, W. Jiang and L. Wang, "Influence of Temperature and Humidity on IGBT Module Internal Stress," *2024 IEEE 4th International Conference*

on Power, Electronics and Computer Applications (ICPECA), Shenyang, China, 2024, pp. 557-562, doi: 10.1109/ICPECA60615.2024.10471161

20. A. H. Sabry and P. J. Ker, "DC Environment for a Refrigerator With Variable Speed Compressor; Power Consumption Profile and Performance Comparison," in *IEEE Access*, vol. 8, pp. 147973-147982, 2020, doi: 10.1109/ACCESS.2020.3015579

21. Badr, O., P. W. O'Callaghan, and S. D. Probert. "Vapour-compression refrigeration systems." *Applied Energy* 36.4 (1990): 303-331.

22. Ariffen, A. M., et al. "The Modelling of Hybrid Surge Protection Circuit with Effect of Adding a Filter." *International Review on Modelling and Simulations* 4.5 (2011).

23. Ding, Guo-liang. "Recent developments in simulation techniques for vapour-compression refrigeration systems." *International journal of refrigeration* 30.7 (2007): 1119-1133.

24. BEE 5 star rating frost-free refrigerator details and tests.

25. IS 15750 (2006): Household frost-free refrigerating appliances - Refrigerators cooled by internal forced air circulation - Characteristics and test methods [MED 3:1 Refrigeration and Air Conditioning]

26. IS 17550 : Part 1 : 2021 HOUSEHOLD REFRIGERATING APPLIANCES — CHARACTERISTICS AND TEST METHODS PART 1 GENERAL REQUIREMENTS

27. IS 17550 : Part 2 : 2021 HOUSEHOLD REFRIGERATING APPLIANCES — CHARACTERISTICS AND TEST METHODS PART 2 PERFORMANCE REQUIREMENTS

28. IS 17550 : Part 3 : 2021 HOUSEHOLD REFRIGERATING APPLIANCES — CHARACTERISTICS AND TEST METHODS PART 3 ENERGY CONSUMPTION AND VOLUME

29. Khandpur, Raghbir Singh. "Printed Circuit Boards Design, Fabrication, and Assembly." (2006).

30. Dalaguit, Angelo, and Mary Ann Dalaguit. *Instructional Model for Power Surge*. LAP LAMBERT Academic Publishing, 2017

31. Borikar, Sanjaykumar A., et al. "A case study on experimental and statistical analysis of energy consumption of domestic refrigerator." *Case Studies in Thermal Engineering* 28 (2021): 101636.

32. Sood, Bhanu. "Printed Circuit Board Inspection and Quality Control." *EPCON Asia–Electronic Packaging Convention*. 2022.

Thesis for plaig check.pdf

ORIGINALITY REPORT

4%	3%	1%	0%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	tudr.thapar.edu:8080 Internet Source	1%
2	tmi.yokogawa.com Internet Source	<1%
3	Wang, Gangyao, Fei Wang, Gari Magai, Yang Lei, Alex Huang, and Mrinal Das. "Performance comparison of 1200V 100A SiC MOSFET and 1200V 100A silicon IGBT", 2013 IEEE Energy Conversion Congress and Exposition, 2013. Publication	<1%
4	J. Branson, J. Naber, G. Edelen. "A simplistic printed circuit board fabrication process for course projects", IEEE Transactions on Education, 2000 Publication	<1%
5	Akio Imamura. "Recovery of mycorrhizas of a fungus, Cenococcum geophilum, after urea treatment in warm temperate forests in Japan", Mycoscience, 10/2004 Publication	<1%