

EXPERIMENTAL ANALYSIS OF THE IMPACT OF THE REFRIGERATOR COMPONENTS ON CONDUCTED ELECTROMAGNETIC INTERFERENCE

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EXPERIMENTAL ANALYSIS OF THE IMPACT OF THE REFRIGERATOR COMPONENTS ON CONDUCTED ELECTROMAGNETIC INTERFERENCE

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ABSTRACT

As the number of electronic devices in our daily lives increases day by day, the risk of electromagnetic interference (EMI) between the devices and between the device and the grid increases. Refrigerators are the only devices found in almost every home and work non-stop. Besides refrigerators have many electrical and electronic components that may contribute to EMI. For this reason, refrigerators have importance in terms of electromagnetic interference. In this study, it is aimed to analyze the impacts of the changes in the cable distribution of a refrigerator and the addition of the ferrite filters on the conducted electromagnetic emission test, which is carried out in accordance with the IEC 55014-1 standard and covers frequencies between 150kHz-30 MHz. For this research, three identical refrigerators were prepared. In the first one, AC and DC cables are fully aligned and entangled, in the second one, AC and DC cables are fully separated and in the third one, AC and DC cables are fully entangled on the refrigerator body but separated inside the control board box. The refrigerator with fully entangled AC and DC cables was chosen as the reference product and conducted electromagnetic emission tests were carried out for phase lines and neutral lines to examine the impact of cable distributions on electromagnetic interference. In addition, ferrite core and amorphous core were added to the AC and DC cable groups in the control board box for filtering the electromagnetic noise, and their impacts on the test results were examined when compared with the reference product which has no filtering. While it was seen that completely separating AC and DC cables improved the test results at almost every frequency, the product with AC and DC cables fully entangled on the refrigerator body but separated inside the control board box failed the test. Whether the filter used is ferrite or amorphous, the location of the filter is AC or DC cables, the results are better than the product without a ferrite filter.

ÖZETÇE

Günlük hayatımızda kullandığımız elektronik cihaz sayısı her geçen gün arttıkça cihazlar arasındaki ve cihazlar ile şebeke arasındaki elektromanyetik girişim (EMI) riski de artmaktadır. Buzdolapları hemen hemen her evde bulunan ve hiç durmadan çalışan cihazlardır. Ayrıca buzdolapları elektromanyetik girişime sebep olabilecek çok sayıda elektrikli ve elektronik bileşene sahiptir. Bu nedenle buzdolapları elektromanyetik girişim açısından önem arz etmektedir. Bu çalışmada bir buzdolabının kablo düzenindeki değişimin ve buzdolabına eklenen filtrelerin IEC 55014-1 standardına uygun şekilde yapılan ve 150kHz-30 MHz arasındaki frekansları kapsayan iletim yollu elektromanyetik emisyon testi üzerine etkilerinin incelenmesi amaçlanmıştır. Bu araştırma için AC ve DC kabloları tamamen karışık düzende, AC ve DC kabloları tamamen ayrı düzende ve AC ve DC kabloları buzdolabı gövdesi üzerinde karışık fakat kontrol kartı kutusu içerisinde ayrı düzende olacak şekilde üç adet aynı model buzdolabı hazırlanmıştır. AC ve DC kabloları tamamen karışık yapıda olan ürün referans seçilerek kablo dağılımlarının elektromanyetik girişim üzerindeki etkisini incelemek üzere faz hatları ve nötr hatları için iletim yollu elektromanyetik emisyon testleri yapılmıştır. Ayrıca kontrol kartı kutusu içerisinde bulunan AC ve DC kablo gruplarına filtreleme amaçlı ferrit çekirdek ve amorf çekirdek eklenerek filtresiz referans ürüne göre test sonuçları üzerindeki etkileri incelenmiştir. AC ve DC kabloları tamamen ayırmanın test sonuçlarını hemen hemen her frekansta iyileştirdiği görülürken AC ve DC kabloların gövde üzerinde karışık kontrol kartı kutusu içerisinde ayrı olduğu ürün testten kalmıştır. Ferrit filtre veya amorf filtre kullanımı, AC veya DC konumlandırılmaları fark etmeksizin filtre kullanılmayan referans ürüne göre sonuçları iyileştirmiştir.

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CHAPTER I

INTRODUCTION

Societies have become completely dependent on electronics. All civil infrastructure, including power systems, communication systems, and financial systems, is built on electronics. These devices work with electrical power and any fluctuating current is related to the emission of electrical and electromagnetic conduction or radiation [9]. As the electronic components get smaller due to the advancement of technology and the effort to reduce resource usage, the circuits have started to be placed closer together. As a result, unintentional coupling between the components and wires increased [9]. Electromagnetic environments can even be caused by household items such as microwave ovens, televisions, refrigerators, etc. [10]. Among the devices we use in our daily lives, the refrigerator is the only device found in almost every home and works non-stop. For this reason, refrigerators have importance in terms of electromagnetic interference (EMI).

EMI is the unwanted electrical or electromagnetic energy that has the potential to cause disturbances in electrical and electronic devices [11]. 20 years ago, when a mobile phone rang, the scratchy sound emanating from nearby television, radio or speakers was due to electromagnetic noise from the mobile phone causing interference in the devices. When this is imagined, EMI problems may seem like simple, temporary, and functional problems. However, if electromagnetic interference occurs in a life-sustaining device such as a dialysis machine or cardioverter-defibrillator, or on a control system of an airplane, the results can be fatal [12].

Electromagnetic interference is studied under a larger topic, Electromagnetic Compatibility (EMC) [13]. Electromagnetic Compatibility is regulated for lots of

products in many countries by governments [14]. An appliance is said to be electromagnetically compatible if it does not cause interference with other appliances and the grid, is not susceptible to emissions from other appliances and does not cause interference with itself. Interference to the receptor may be prevented by suppression of the emission at its source or making the receptor less susceptible to the emission [15]. In this research, the focus will be on the suppression of the emission. EMI problems; on the other hand, may arise because of the conductive and radiative emissions. In this research, the focus will be on conducted emissions. This thesis is about one of the conducted emission tests, IEC 55014-1, Disturbance Voltage at the Mains Terminals (150kHz-30MHz), which is generally problematic for refrigerator producers.

The scope of this research is to analyze the impacts of different cable distributions used in a refrigerator on the conducted electromagnetic emission. The research also covers the examination of the impact of different types of ferrite filters in suppressing noise. The thesis includes literature information regarding electromagnetism, electromagnetic interference, conducted emission, and refrigerators. In addition to literature information, all test results with graphs and tables are included.

1.1 Basic Concepts in Electromagnetism

Electricity and magnetism are concepts that need to be studied in-depth, however, when they come together, they form the basis of electromagnetism, an important field of physics. Electromagnetism is used in different examples in many sectors such as televisions, radios, generators, motors, electric vehicles, magnetic levitation devices, magnetic resonance (MR) imaging devices, and wireless communication systems. Electricity is a phenomenon associated with stationary or moving electric charges. The source of charge can be a negatively charged electron, a positively charged proton, an ion, or any larger object with a positive and negative charge imbalance. While positive and negative charges attract each other, similar charges

repel each other. Magnetism is defined as a physical concept created by the movement of electric charges. Conversely, a magnetic field can move charged particles to generate an electric current. Electromagnetic waves have both electrical and magnetic components. Electromagnetism is a fairly important subject, so it's a good idea to have some knowledge of the basic concepts of electromagnetism.

1.1.1 Electric Field

Particles in which the amount of positive and negative electric charge are not in balance are called charged particles. The region where an electric charge of the substance exerts its effect is called the electric field of that charge. In other words, the electric field is the physical field that surrounds the electrically charged particles and exerts a force that attracts or repels all other charged particles in the field. Similar to gravity, the electric field is a force of nature. But unlike gravity, which affects all matter, it only affects substances (particles) that have a property called charge. This means that only charged particles feel the electric field or force. It is known that all matter consists of the basic building block known as the atom and an atom consists of electrons, protons, and neutrons. While the charge on an electron is negative, a proton carries a positive charge of the same magnitude as the electron. Neutrons have almost the same mass as protons but have no charge. The presence of an equal number of protons and electrons means a neutrally charged atom. If an atom loses an electron, it becomes charged and is known as an ion. There are two types of charges, positive and negative. Particles with the same charge repel each other, while particles with opposite charges attract each other. Any charged particle or collection of charged particles creates an electric field [16]. Force is a vector quantity therefore the electric field has magnitude and direction.

Electric field lines are given in Figure 1. An electric field is usually analyzed assuming the test charge is a unit positive charge. Therefore, the test charge experiences a repulsive force from the positive source charge and an attractive force from the negative source charge. In that case, the test charge moves from the positive source charge to the negative source charge. Accordingly, the directions

of the electric field lines are such that they originate from a positive charge and terminate in a negative source charge.

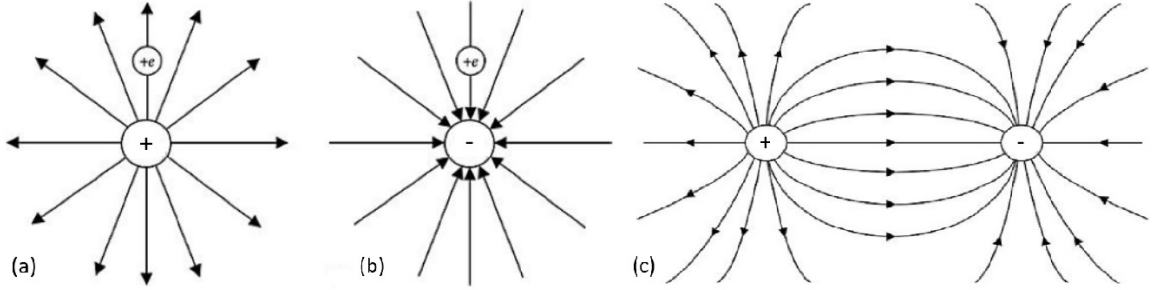


Figure 1: Electric field lines due to (a) positive source charge, (b) negative source charge, (c) pair of positive and negative charges [1]

Figure 1(a) shows electric field lines originating from a positive source charge, while Figure 1(b) shows electric field lines ending on a negative source charge of the same magnitude. Electric field lines show the directions of force exerted by a unit positive charge. Figure 1(c) shows electric field lines originating from positive and negative charges of the same magnitude. Electric field lines originate from a positive charge and terminate at a negative charge.

The electric field is associated with Coulomb's Law, named after the French physicist Charles-Augustin de Coulomb. Coulomb's Law measures the amount of force between two fixed and electrically charged particles, and its formula is as follows in the scalar form:

$$F = (kq_1q_2)/r^2 \quad (1)$$

where F represents the electric field force in Newtons, k represents the Coulomb constant in Nm^2/C^2 , q_1 represents the quantity of charge 1 in Coulombs, q_2 represents the quantity of charge 2 in Coulombs and r represents the distance between the charges in meters.

The electric field is the electric force acting on any charge q . The formula for the electric field is as follows:

$$E = F/q \quad (2)$$

where E represents the electric field in N/C, F represents the electric force in Newtons and q represents the quantity of charge in Coulombs.

1.1.2 Magnetic Field

Unlike the electric field, which is a field created by stationary charges, the magnetic field is a field created by charges that have a uniform linear motion without acceleration. The magnetic field, like the electric field, is a vector quantity. However, unlike the electric field vector, as shown in Figure 2, it does not start at one charge and end at the other. Magnetic field lines surround the current and end on itself. The direction of magnetic field lines can be found with the right-hand rule accepted by scientific authorities. The right-hand rule indicates the direction of the magnetic field vector when the right hand holds the thumb in the direction of the current and the other fingers wrap around the wire.

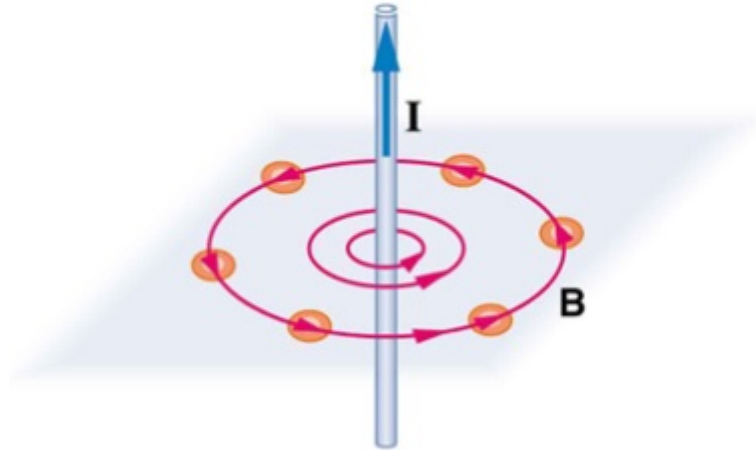


Figure 2: Magnetic field lines

A moving charged particle is subjected to a force in the presence of a magnetic field, this force is calculated by the following formula and this relation is known as the Lorentz force law [17].

$$F = qvB \quad (3)$$

where F represents magnetic field force in Newtons, q represents the quantity of charge in Coulombs, v represents the velocity of the moving charge in m/s and B represents the magnetic flux density in Wb/m².

The magnitude of the magnetic field decreases with the square of the distance from the source.

Different materials in nature react differently to an applied magnetic field according to their atomic and molecular structures, and according to their response, all materials can be generally divided into three groups diamagnetic, paramagnetic, and ferromagnetic.

Diamagnetic materials have a weak and negative susceptibility to magnetic fields. Diamagnetic materials are slightly repelled by a magnetic field. Since all electrons are paired there is no permanent net magnetic moment per atom, and they do not retain their magnetic properties when the external field is removed. Diamagnetic properties arise from the rearrangement of electron paths under the influence of an external magnetic field. Most elements in the periodic table are diamagnetic. Copper, silver, and gold are the best-known examples.

Paramagnetic materials have a small and positive susceptibility to magnetic fields. These materials are slightly attracted by a magnetic field. There are unpaired electrons in such materials, the electron paths are rearranged by the effect of the external magnetic field and the paramagnetic properties of the materials emerge. They do not retain their magnetic properties when the external field is removed. Examples of paramagnetic materials are magnesium, molybdenum, lithium, and tantalum.

Ferromagnetic materials have a large and positive susceptibility to magnetic fields. They are strongly attracted by magnetic fields. Ferromagnetic materials have unpaired electrons. Since the electrons are not paired, they cannot neutralize

each other's magnetic fields, so the atoms have a net magnetic moment. Ferromagnetic materials can retain their magnetic properties after the external field is removed. When no magnetization is applied, the magnetic moments of the atoms of the ferromagnetic material are randomly arranged and the net magnetic field of the material as a whole is zero. When under the influence of magnetism, they align with the magnetic field lines of that magnet and produce a strong magnetic field. Examples of ferromagnetic materials are iron, nickel, and cobalt.

1.1.3 Electromagnetism

Two phenomena, electricity and magnetism, form the basis of electromagnetism. However, electricity and magnetism were for many years thought of as separate forces. Electromagnetism was first discovered in 1820 when Hans Christian Oersted, a Danish scientist, noticed that the needle of a magnetic compass placed near an electric wire moved. The needle was not pulled towards or pushed away from the wire, instead, it tended to stop at right angles. Oersted worked hard to make sense of this situation, but could not explain why. In the end, he just published his findings without any explanation. The relationship between electricity and magnetism, namely electromagnetism, was not explained until James Clerk Maxwell published "A Treatise on Electricity and Magnetism" [18] in 1873.

The electromagnetic theory deals with the forces acting on charge and current. Two types of forces act on an electric charge at a particular point in space. The first of these is an electric force which is independent of the charge's velocity and the second is a magnetic force proportional to its velocity and at right angles to its velocity. Different amounts of force are applied to different charges at the same point in space, and we define the force of the charge is proportional to the magnitude of the force acting on it in a given area [19]. We can define two vectors at every point in space, E electric field strength, and B magnetic field strength. The vector equation of the total force F on the rapidly moving charge q is given as:

$$F = q(E + vxB) \quad (4)$$

where F represents total force applied on a charge in Newtons, q represents the quantity of charge in Coulombs, E represents electric field in N/C, v represents the velocity of the moving charge in m/s and B represents the magnetic flux density in Wb/m². x represents the vector multiplication.

1.2 Electromagnetic Compatibility and Electromagnetic Interference

To understand the concept of electromagnetic compatibility, first, the electromagnetic interference term should be defined. EMI can be defined as electromagnetic energy which affects the functioning of an electronic device. EMC is a measure of a device's ability to operate as intended while not affecting the ability of other devices in the same environment to operate as intended. In fact, electromagnetic interference occurs when there is no electromagnetic compatibility. EMC is regulated for lots of products in many countries by governments and there are measurement methods and limits according to certain standards. Electromagnetic Interference can be considered as if electrical and electronic devices emit electrical and electromagnetic noise to the environment during their operation more than the limits determined by the standards or show more susceptibility to this emission than it should be.

1.2.1 What is EMC and Why It is Needed?

In terms of emission, EMC can be defined as the ability of a device, equipment, or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbance to anything in that environment. In terms of susceptibility, the definition is the ability of systems, subsystems, circuits, and components to function as designed, without malfunction or unacceptable degradation of performance due to electromagnetic interference, within their intended operational environment [20]. All types of equipment should comply

with specifications intended to assure electromagnetic compatibility. An appliance is said to be electromagnetically compatible if it

- does not cause interference with other devices and grid,
- is not sensitive to emissions from other devices,
- does not interfere with itself.

Noise is an electrical signal present in a circuit other than the desired signal [14]. Any electrical or electronic device is a potential source of noise for its environment and this situation creates environmental electromagnetic pollution, which is a serious problem. To control and limit electromagnetic pollution, Electromagnetic Compatibility laws have been issued by governments for many product types in many countries. For example, electromagnetic compatibility is regulated under Directive 2014/30/EU in European Union countries and many countries outside the EU also follow this directive by adapting it into their national directives. To abide by the rules and provide compliance, electromagnetic compatibility has become an important engineering discipline.

The EMC problems may arise from the conductive and radiative emissions and there are four main sub-problems of EMC as shown in Figure 3. While the unintentional release of electromagnetic energy over a medium by means of an electric field or magnetic field is radiation emission, the measurement of a device's capability to function in the presence of radiated emission is called radiated susceptibility. Conducted emission is the electromagnetic interference that is directly coupled through conduction from one device to another device or the grid. It is generated inside the product and transferred through the wires. Conducted susceptibility is the measurement of a device's capability to function in the presence of conducted emission. When talking about EMC issues, the terms, susceptibility, and immunity can be encountered. Although these two terms try to mean the same thing in terms of EMC, there is a nuance between them. Susceptibility is the tendency of electrical equipment to malfunction or deterioration in the presence of unwanted emissions. Immunity, on the other hand, refers to the opposite

of sensitivity, the ability of equipment to operate correctly in the presence of unwanted emissions. When one of the susceptibility issues occurs in life-sustaining devices the consequences can be fatal [12].

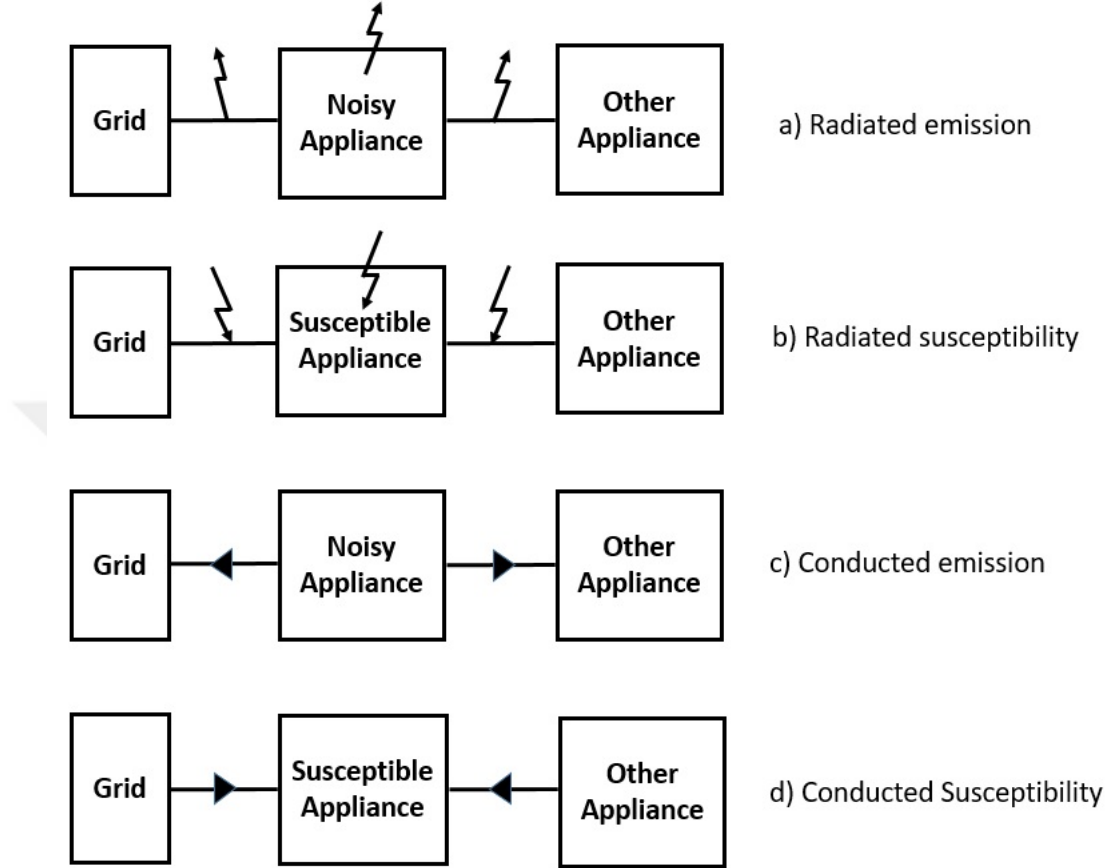


Figure 3: The four basic EMC sub-problems; (a) radiated emissions; (b) radiated susceptibility; (c) conducted emissions; (d) conducted susceptibility

1.2.2 EMI as Part of EMC

According to International Electrotechnical Commission's Vocabulary, the definition of electromagnetic interference is the degradation in the performance of equipment or transmission channel or a system caused by an electromagnetic disturbance. On the other hand, the definition of electromagnetic disturbance is the electromagnetic phenomenon that can degrade the performance of a device, equipment, or system, or adversely affect living or inert matter. These two terms, electromagnetic disturbance and electromagnetic interference represent the cause

and effect and should not be used indiscriminately. The origin of interference is also often called noise. The path of the electrical and electromagnetic noise is given in Figure 4. It originates from a source and reaches the receiver via the transfer path.



Figure 4: Path of electrical noise

Electromagnetic noise can be transmitted from source to receiver in various ways as shown in Figure 5. The first one is the radiated EMI. Radiated EMI occurs when an electrical or electronic device generates a radio frequency that can cause unwanted effects in another device. It can happen in devices that are not electrically connected and are relatively far from each other. Radiated EMI is of two types, narrowband and broadband.

Narrowband EMI affects a narrow range of frequency bands or only a specific radiofrequency. It covers a very small part of the radio frequency spectrum. These signals are usually in the form of continuous sine waves, which can occur intermittently or continuously. Narrowband EMI can be emitted from oscillators, signal generators, test equipment, and even power line.

Broadband EMI affects a large part of the radio spectrum at many frequencies. It can dissipate its energy into hundreds of megahertz. Such signals are narrow pulses with short rise and fall times. They can occur intermittently, transiently, or continuously. Examples of broadband EMI sources are radar and communication transmitters, electrical switch contacts, thermostats, and voltage regulators.

Conducted EMI is the interference transferred from a source to a receiver along a direct route such as cabling, PCB traces, power/ground planes, or parasitic capacitance. In this method, a physical transmission path is required for the transmission of electromagnetic emissions to the victim. Common sources of

conducted EMI are electrical motors, switch-mode power supplies, DC/DC converters, micro-controllers, and ethernet traffic. Conducted EMI occurs in two modes, common and differential.

Common-mode EMI signals are a type of noise that overlaps all the conductors carrying the signal in a transmission line and are generated by magnetic/capacitive coupling. They are in the same direction and phase as the signal lines and each return to a common ground. For example, if a large DC motor is running near the mains cable of an SMPS, interference from the brushes of that DC motor will penetrate both the phase and neutral of the mains cable.

Differential-mode EMI is when noise penetrates only one point of the signal transmission line, it appears in closed-circuit circuits where electric current flows in the opposite direction of the signal line. For example, if filtering is not done well in the rectifier in the power supply, there will be noise superimposed on the supply voltage of the circuit.

That is, the difference between them is, that the common mode is seen everywhere in the circuit, as it impacts from the outside with magnetic/capacitive coupling. The other is local, starting at a point and spreading from there.

Near Field EMI occurs because the source and victim are not electrically connected but are very close to each other. Near Field EMI can occur via induction or capacitance.

Induced or magnetically coupled EMI occurs when there is a varying magnetic field between source and victim and the magnetic field of a conductor causes an unwanted current in a nearby conductor. An example of induced EMI is humming on the audio line because a power cable and an audio cable are close together.

Capacitively coupled EMI occurs when a varying voltage from the source capacitively transfers a load to the victim circuit when the source and victim are very close to each other. It is commonly found on electronic circuit boards or in bundles of cables that are very close to each other over long distances.

The field of interest of the inductive coupling is the magnetic field while the

field of interest of the capacitive coupling is the electric field.

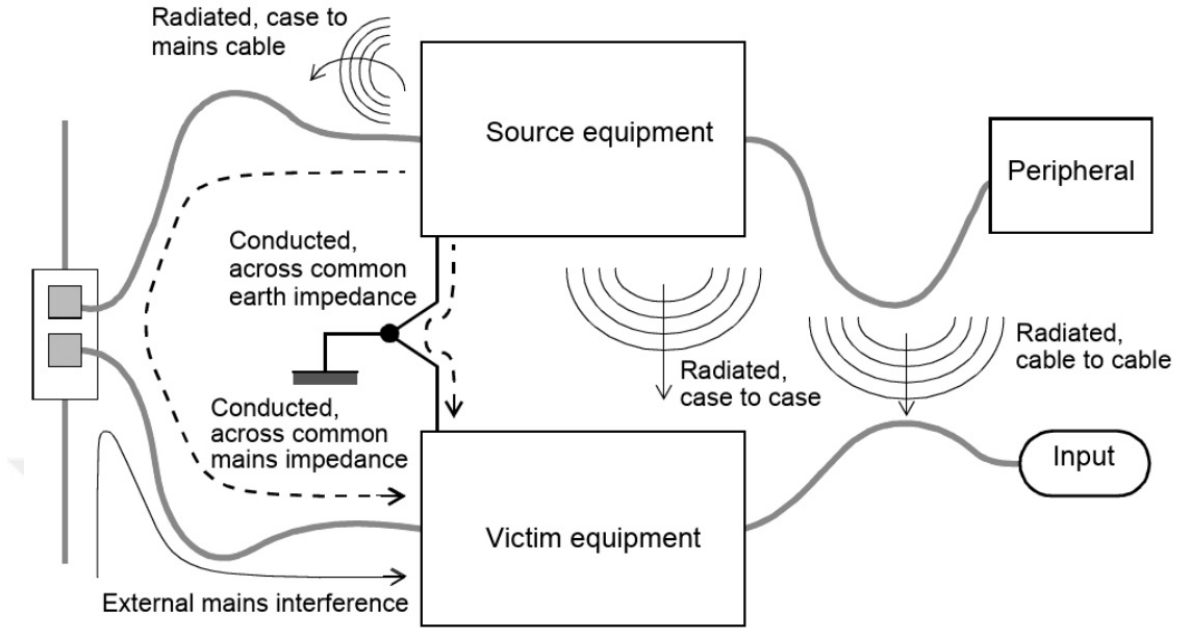


Figure 5: EMI mechanisms [2]

Electromagnetic interference is everywhere and unavoidable. Electromagnetic interference occurs when there is no electromagnetic compatibility. Any object with a time-varying electric or magnetic field, that is, all electrical and electronic equipment, can be a potential source of EMI. These devices also have the potential to become receivers, that is, victims. In an ideal world, a perfect device would not emit any electromagnetic noise or be affected by it, but this is an almost impossible task to achieve due to the way electrical and electronic devices work.

1.2.3 History of EMC and EMI

Radio interference and its correction can be traced back to Marconi's first spark gap experiment in the late 19th century [13]. He developed the first practical spark gap transmitters and receivers for radiotelegraphy communication around 1896. Spark transmitters were first used for ships to communicate with stations on shore. Marconi succeeded in providing the first transoceanic transmission using copper

wires in 1901. At that time, radio receivers were used as receivers, they were few and they were located far from each other. So dealing with an interference problem was relatively easy. In addition to the increasing popularity, due to the Great Depression, the radio became a useful device to have in homes. Thus, the electronics community realized that interference cases were starting to increase. This is because radio receivers and antennas are susceptible to interference from external or internal sources. Articles about radio interference began to be published in various scientific journals. Although these problems were overcome with design improvements, interference from electric motors, electric railways, and similar electrical devices began to become a major problem in the 1930s. World War II accelerated the use of electronic equipment, especially like radios, navigation equipment, and radar. There have been more instances of interference between airplane radios and navigation equipment. However, the most notable increase in interference problems was with the invention of high-density electronic components such as bipolar junction transistors in the 1950s, integrated circuits (ICs) in the 1960s, and microprocessor chips in the 1970s. With the increasing need for voice and data transmission, the use of frequencies in the spectrum has become crowded. Increased switching speed and miniaturization of ICs have meant increased density of spectral content-rich noise sources and, as a result, increased EMI issues.

In 1933, an International Electrotechnical Commission (IEC) meeting was held in Paris. In this meeting, it is decided to establish the International Special Committee on Radio Interference (CISPR) to deal with the EMI problems. Thus, awareness of EMI began to rise in the electronics community, and at the same time, in 1934, CISPR began creating and distributing special requirements. CISPR has produced technical publications covering measurement and testing techniques and recommended emission and immunity limits. These have evolved over the decades and form the basis of many EMC directives today. After the 1960s, researchers became increasingly interested in electromagnetic interference. For example, in

1967 the U.S. military issued the "Mil-Std 461A", which sets basic rules for the testing and verification of electronic equipment used in military applications and includes emission and immunity limits for any new electronic equipment. In 1979, due to the increasing number of digital systems blocking wired and radio communications, the Federal Communications Commission (FCC) placed legal limits on electromagnetic emissions from all digital equipment. In the mid-1980s, the member states of the European Union adopted a series of "new approach directives" to standardize the technical requirements for products, as long as products comply with this directive, there would be no obstacle to the trade within the European Community. One of the new approach directives was the EMC Directive (89/336/EEC). It was a directive covering all devices that could cause electromagnetic disturbances or whose performance was likely to be affected by the disturbance. As the years went on and electronic devices became smaller, faster, and more powerful, these regulations continued to evolve. Many countries today have similar requirements for products to meet some level of electromagnetic compatibility law. These regulations have turned EMC into an important criterion for the salability of electronic products. If a product does not meet these regulations in a particular country, it may not be sold in that country. The fact that a product performs a highly desired function and that customers want to buy it means nothing if it does not meet legal requirements. As technology has evolved, the issue of EMC design has become as critical as any of the traditional aspects of electronic design.

1.2.4 EMI Sources

Any device that transmits, distributes, processes, or otherwise uses electrical energy can be a source of EMI and generate electromagnetic signals that can cause the performance of other devices to degrade. EMI sources are examined as natural [21] and man-made sources according to their formations. Knowing the characteristics of interference sources is very important in terms of determining the measures that can be taken. Major sources of EMI [20] are given in Figure 6.

Although electromagnetic interference is generally thought to be caused by devices, natural events around us can also cause EMI. Such natural sources of EMI may arise from natural activities on Earth and its surroundings, or galactic sources. Natural sources of EMI can be divided into terrestrial and extra-terrestrial.

Examples of terrestrial sources are precipitation statics and atmospheric noise. Precipitation statics is related to the EMI created by aircraft due to substances in nature. It is caused by aircraft in flight moving through a storm or coming into contact with liquid or solid uncharged particles such as rain, snow, fog, hail, volcanic ash, and dust. When the aircraft collides with these particles, the negative charges of the particles are transferred to the aircraft, and a negative charge is formed on the surface of the aircraft. If the aircraft's static discharge systems are not active, problems such as loss of radio communication and navigation, and incorrect magnetic compass readings may be encountered. Atmospheric noise is radio noise caused by natural atmospheric processes, generally caused by lightning and other electrical phenomena in the atmosphere. It occurs randomly by nature and does not belong to a specific frequency band, but spreads over a wide frequency range. Atmospheric noise is added to the original signal and produces false or spurious signals. For this reason, the receiver not only receives the signal it should receive but also receives these fake signals and interference occurs.

Examples of extra-terrestrial sources are solar noise and cosmic noise. Solar noise is electromagnetic noise emitted from the sun. The sun is a very large object with a very high temperature and radiates its energy as noise. This noise occurs over a very wide spectrum, including the frequencies used in radio communications. The sun has a repeating 11-year noise cycle, and the intensity of the noise varies over this time. Cosmic noise is known as galactic radio noise. Distant stars also emit noise, similar to the sun. The Moon and Jupiter are important sources of cosmic noise. In addition, celestial bodies such as quasars, which are super-dense and massive objects, emit electromagnetic waves in their entire spectrum, including radio waves. When a meteorite falls, it burns due to friction with the

Earth's atmosphere, ionizes the gases around it and produces radio waves.

Man-made EMI [22] is the type of noise caused by and covering every electronic assembly from power lines to handheld devices. When these electronic signals meet at the same frequency, they distort each other. The main features of man-made EMI sources can be illustrated with the following examples:

- Radio Transmitters
- Digital Processing and Communications
- Electroheat Applications
- Power Conditioning and Transmission
- Switching Transients
- Electrostatic Discharge (ESD)
- Nuclear Electromagnetic Pulse (EMP)

The frequency spectrum of radio transmitters is allocated for different uses. These allocations are determined by international organizations. For example, the frequency modulation (FM) broadcast band in the UK is in the range of 88-108 MHz, while in Eastern Europe it extends to 76 MHz. In urban environments, the electric field strength from radio transmissions can be around 200mV/m, and radio system transmitters' harmful interference and radiation effects are becoming significantly important and complex [23].

Modern computing and communication use digital signals for the processing and transmission of information. These digital signals have clock speeds of hundreds of MHz. The rise and fall times of these signals can be very short, on the order of nanoseconds. These fast transitions generate high-frequency fields and cause electromagnetic interference in nearby circuits.

Power transmission, power electronics, and electronic drives require the use of large amounts of power, non-linear or intermittent loads, rectifiers, inverters, and similar devices that distort waveforms. These cause harmonics, voltage drops, and spikes, instabilities, and ripples.

Switching transitions occur at a sudden circuit change in power systems. These

transitions are associated with two factors in motor applications. The first is the mechanical energy stored in the rotating machine and the second is the electrical energy stored in the inductive load [24]. These transients are short-lived and oscillating. However, it is extremely important as electrical equipment is exposed to the greatest stress and the greatest interference occurs during this time.

The Electrostatic Discharge (ESD) phenomenon [25] is the result of the triboelectric charge created by the separation of two non-conductive materials. For example, a person walking by rubbing his shoes, paper moving in a printer, and rubber belts in machines can be loaded in this way. The charge separation results in voltage potentials that eventually disintegrate in air, causing an ESD event. ESD can attack in two different ways, conduction and electromagnetic radiation.

The explosion of nuclear devices poses a serious electromagnetic threat [26]. Such bursts produce photons (gamma rays), which, via the Compton Effect [27], generate fast electrons that generate source currents for intense electromagnetic fields which are called nuclear electromagnetic pulses (EMPs).

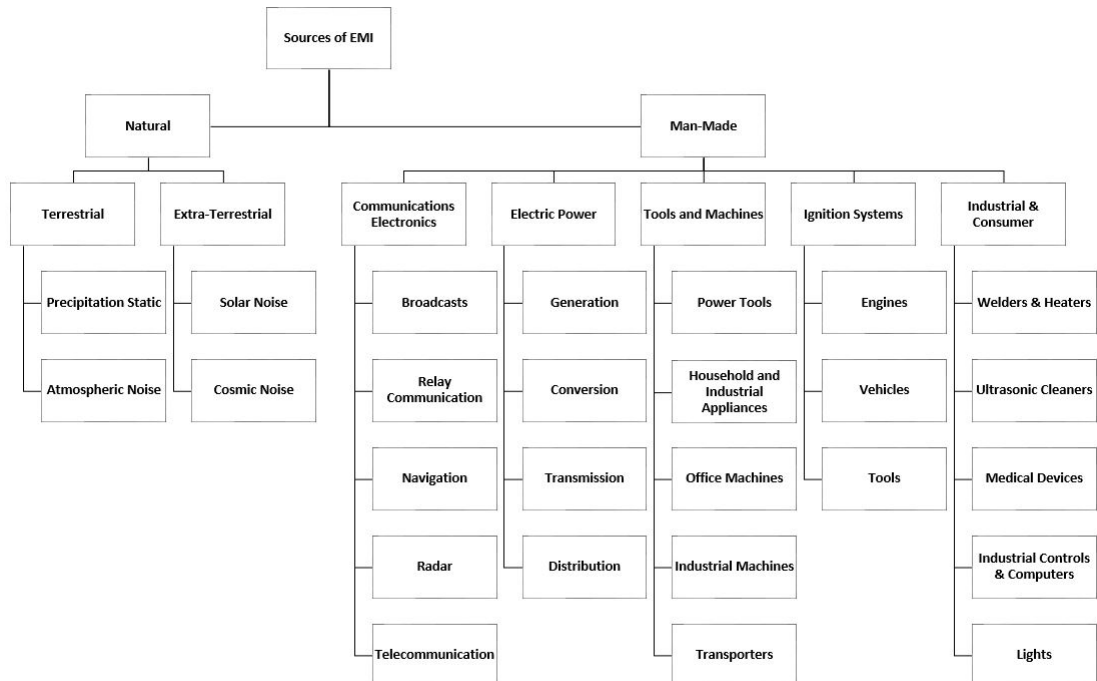


Figure 6: Major EMI sources

1.2.5 EMI Solutions

Since EMI is everywhere and unavoidable, many different solutions have been developed in both emitter and victim devices to manage electromagnetic interference. These solutions are sometimes very simple and sometimes require serious design changes. Noise reduction, and hence electromagnetic compatibility, can be avoided by suppressing the emission at the source, inhibiting coupling paths, or making the receiver less susceptible to emission. Most of the methods used apply to all three issues.

One of the effective ways to get rid of unwanted signals is EMI filters, also known as EMI suppression filters. When EMI filters are added to devices or circuits, they can suppress electromagnetic noise transmitted through conduction. An example of a filter used in white goods is given in Figure 7. Filtering is commonly used to reject noise outside of a predefined frequency range. Electromagnetic noise generally occurs at high frequencies. This means that in a measured signal, for example, in sine waves, the loops will be very close to each other. EMI filters may contain capacitors and inductors to suppress these signals. Capacitors do not allow direct current through which electromagnetic noise is carried but allow alternating current to pass. Inductors, on the other hand, hold the energy by creating a magnetic field and reducing the total voltage. Capacitors used in EMI filters are called shunt capacitors. Shunt capacitor supplies high-frequency current to inductors, and total power and voltage decrease as current passes through each inductor. After filtering, electromagnetic noise is removed by grounding. Since EMI filters are effective against conduction, radiated EMI may continue to occur in the product. So it may be useful to add a shield to the port of the EMI filter. If the distance between the EMI source and the filter is too short, the filter alone may be sufficient.



Figure 7: EMI filter

One of the methods used to prevent electromagnetic noise in source or victim devices is shielding. The principle of shielding is to create a conductive layer that surrounds the object to be shielded [28]. It is called Faraday Cage and invented by Michael Faraday. Faraday, in a study on static electricity, discovered that the charge exists only on the outside of the conductor, and the external charge has no effect on the elements inside the conductor. Shielding examples are shown in Figure 8. The shielding works in both directions, protecting elements inside the shielding from external impacts or protecting external elements from impacts originating from inside of the shielding. It generally involves the use of an enclosure for electronics and cables. Metallic shields are designed to reflect the electric field component while having a high magnetic permeability to absorb the magnetic field component of electromagnetic interference. In cables, the signal wires are surrounded by a grounded outer conductive layer at one or both ends. Ideally, a perfect shielding is an enclosure that is completely sealed so that no waves can propagate in or out. However, needs such as cost, heat management, input and output of data cables make this impractical.

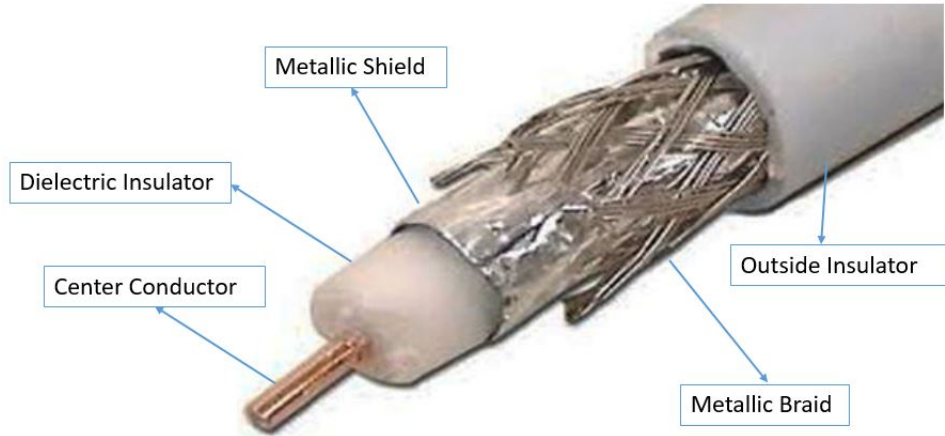


Figure 8: Shielding of a coaxial cable

The connection between an electrical circuit or equipment and the earth or a conductor that acts as the earth is called the ground connection. The main purpose of grounding is safety and protection against electrical shock hazards. Additionally, it can be used as protection against electrostatic discharges and electromagnetic interference. The static charge accumulated on humans and objects can damage electronic components by contact or discharge through the air. With a suitable grounding, this discharge current can be transferred to the earth without damaging the components. Grounding against electromagnetic interference creates an equipotential point that acts as a reference point for components in the circuit. The low impedance path created by grounding allows the current to return to the source of the signal. While designing the grounding, the impedance being as low as possible and the ground loop as small as possible will provide better results. Grounding for EMI purposes can be classified into four categories: single-point grounding, multi-point grounding, hybrid grounding, and floating ground. Single-point grounding requires circuits to be connected to a common grounding point. This type of grounding is suitable for low-frequency circuits below 1 MHz. In multi-point grounding, each circuit must be separately grounded to the nearest low-impedance ground plane. Multi-point grounding is preferred in high-frequency circuits operating above 10 MHz. Hybrid grounding uses single-point

grounding for low-frequency circuits and multi-point grounding for high-frequency circuits. The floating ground option isolates all analog grounds within the supply and brings them to a point, usually provided on the back of the power supply. Grounding techniques for EMI purposes are used in circuit boards [29], cables, and large systems. Grounding techniques against EMI are selected based on a circuit's configuration and operating frequency. These grounding techniques are a cost-effective way to achieve better EMC performance.

A ferrite core, also called a ferrite block, ferrite ring, or ferrite choke, is one of the simplest and least expensive EMI solutions as it can be easily placed around a wire or cable, thus providing an effective solution against electromagnetic interference without having to redesign circuits and products. Ferrite cores are homogeneous structures made of non-conductive ceramic material, consisting of various oxides like zinc, nickel, barium, and manganese, the main component of which is iron oxide [30], and magnetic cores that can be produced in various shapes and sizes as shown in Figure 9 to meet specific magnetic and mechanical requirements. There are many studies on the effectiveness of ferrite beads with different contents [31] and different structures [32]. The cables are wound around the center of the ferrite core, and the number of turns is determined by the frequency to be filtered. Clamp-type ferrite cores are also available, which are simply passed through without winding.

Ferrite cores have high magnetic permeability and low conductivity. A ferrite core is not very effective at low frequencies when used for shielding cables. Above 10 MHz it is effective at attenuating unwanted noise signals, but below 10 MHz it is not very useful for cable emissions as its impedance is quite low at these frequencies. The performance of ferrite cores in eliminating electromagnetic interference varies according to their material. Due to the change of magnetic permeability according to the materials, the impedance will also change. The greater the number of times the cable is passed through the ferrite core, the greater the inductance.

However, as the number of windings through the ferrite core increases, the beginning and the end of the winding will be closer to each other, and the floating capacity will be created between each other. This floating capacity reduces the high-frequency performance of the ferrite core. Therefore, when considering target frequencies for noise reduction, the number of windings should be increased to target the low-frequency range and decreased to target the high-frequency range. The energy generated due to impedance will either be reflected to the cable or will be emitted to the environment as heat.



Figure 9: Ferrite filter examples with different shapes and dimensions

Electromagnetic noise attenuates by the distance from its source. Therefore spacing between the source and the receiver is one of the solutions to decrease electromagnetic interference. Sustaining the separation between cables of different signal levels may reduce the noise. In a printed circuit board (PCB), this means the segregation of board sections according to their functions, keeping the control circuit away from the power circuit, keeping the analog circuit away from the digital circuit, keeping the low-frequency sections away from the high-frequency

sections. Improper tightening, improper soldering, and loose connection may result in a higher impedance and thus leads to noise in the signals. Cables contribute to EMI both as a source acting as an antenna and as a receiver picking the noise from other sources. Cables are also transfer paths for conduction. Therefore shortening the cables will reduce the EMI. Twisting a pair of cables can sometimes be a solution. If signals experience relatively the same interference then the interference will be negated. Also twisting the cables reduces the loop area. So any induced voltages due to the changing magnetic field will be reduced.



CHAPTER II

REFRIGERATOR

Preservation of the foodstuff had had an important role in people's life from past to present. Decreasing the temperature of the foodstuff is an effective way to stop or slow down the activities and reproduction of the microorganisms that cause the spoilage of the foodstuff by biochemical reactions and slow down the enzymatic reactions that cause the ripening and subsequently spoilage of the food. Therefore the taste, appearance, color, flavor, and composition of the foods remain the same for a longer time. Refrigerators are the essential food storage appliances around the world. Refrigerators are used to store foodstuffs between 0°C to -24°C for freezing function and 0°C to 10°C for refrigeration function in general when the ambient temperature is higher. The basic principle of freezing is to convert the water in the food into ice crystals. By doing this the chemical reactions inside the food and microbiological deterioration are reduced or prevented. Refrigerating does a similar job at a lower level by cooling the foodstuff. Freezing and refrigerating functions have advantages and disadvantages according to each other. In the freezing method, the food stays fresh longer than the cooling method, however, the end-user can't use or consume the food immediately after being taken out of the freezer. In the refrigerating method, the end-user can use or consume the food at any time, however, the shelf life of the food is not long as in the freezing method. Even cooling a foodstuff purpose is the same as the refrigerators are categorized as commercial and household refrigerators. While commercial refrigerators are generally used in places like markets, restaurants, pubs, facilities, etc. Household refrigerators are used in homes. Different usage area means different usage habits and different product characteristics. A commercial refrigerator may need to be designed to withstand doors being opened hundreds of times a day and this should

not make any impact on the performance of the product or result in temperature fluctuations, the number of the door open of household refrigerators is much less. While a domestic refrigerator should work more quietly because it is used indoors, there is usually no such need for a commercial refrigerator. At this point, different needs can be met by using different materials and components. So firstly it should be understood how cooling occurs and what kind of components are used to achieve this purpose.

2.1 Refrigeration Methods

Refrigeration is the process of removing heat from an enclosed space, or from a substance, and moving it to a place where it is unobjectionable [33]. According to Rudolf Clausius, a German physicist and mathematician, the tendency of heat is to pass from a warmer to a colder body, and thereby equalize existing differences of temperature, therefore heat cannot, of itself, pass from a colder to a hotter body [34]. That means heat does not tend to flow from cold place to hot place, therefore a work is required to achieve refrigeration purpose. According to Kelvin-Planck statement of second law of thermodynamics, it is impossible to devise a cyclically operating device, the sole effect of which is to absorb energy in the form of heat from a single thermal reservoir and to deliver an equivalent amount of work [35]. That means no heat engine can be 100 percent efficient and a heat engine requires two thermal reservoirs, it absorbs the energy from one reservoir which has higher temperature, converts the part of the energy into work and removes the remaining energy to the other reservoir which has lower temperature. That bring us to the refrigeration methods. There are many cooling methods that have been used from past to present [36]. The most popular cooling methods used today are thermoelectric refrigeration, evaporative cooling, absorption refrigeration systems and vapor-compression refrigeration systems.

2.1.1 Thermoelectric Refrigeration

The first method is thermoelectric refrigeration. Thermoelectric refrigerators are generally known as Peltier coolers which work by the basis of Peltier effect which is found by French physicist, Jean Charles Athanase Peltier. According to Peltier's discovery when electrical current is applied across the junction of two dissimilar metals, heat is removed from one of the metals and transferred to the other metal. This is called as Peltier effect and forms the basis of the thermoelectric refrigerators. As shown in Figure 10 a Peltier cooler consists of two ceramic plates that provides electrical insulation and semi-conductive electrodes between these plates. N type semiconductor has excess of electrons, P-type semiconductor has deficit of electrons. They are electrically connected in series to each other with conducting strips and form thermoelectric couples. A thermoelectric cooler may contain many thermoelectric couples depending on the required cooling value. When the voltage is applied to the junction points of the thermoelectric couples direct electrical current starts to flow and electrons move from P-type semiconductor to N-type semiconductor. The electrons are forced to jump higher energy states therefore they absorb energy as heat from the cold side and this side becomes cooler. Since it is a kind of cyclic process when electrons moves from N-type semiconductor to P-type semiconductor, they drop to a lower energy state and release energy as heat to the hot side. As a result of this process, one side of the device cools down while the other side heats up. By changing the direction of the current, it is possible to choose which side to cool down or which side to heat up.

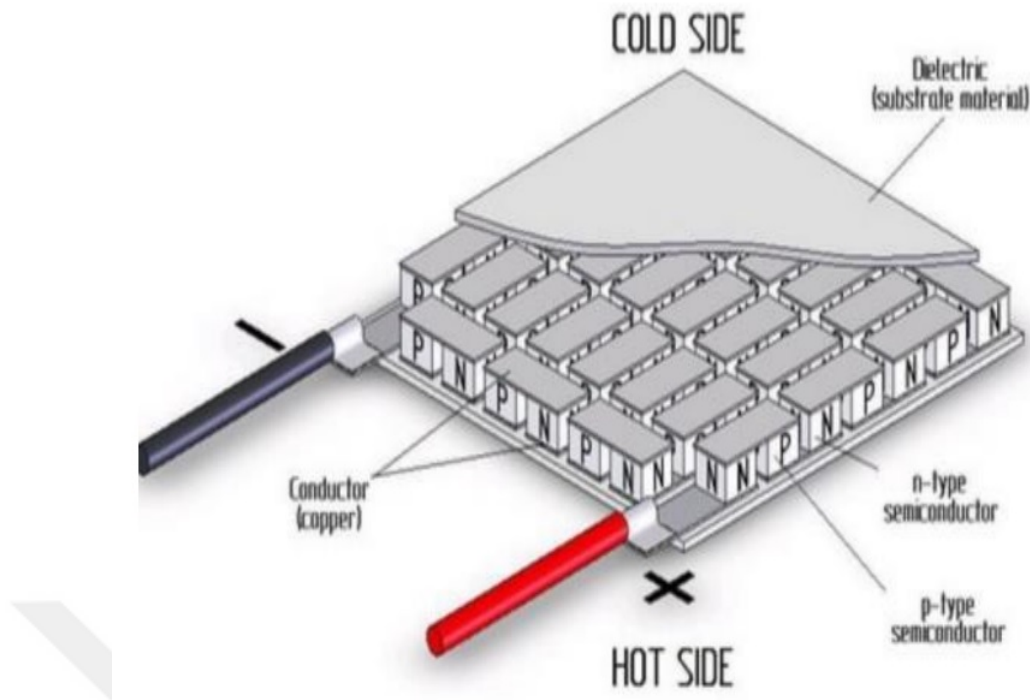


Figure 10: Internal structure of a Peltier plate [3]

Peltier coolers have some advantages. Very little space is required for this cooling system, so that very small, lightweight and portable coolers can be designed. Since it is small and requires less material, it is generally less expensive than devices using other cooling methods. They are usually quiet as they have no moving parts. In addition, this type of cooler does not use refrigerant, which reduces the risk of ignition. However, Peltier coolers have performance-related disadvantages. Their efficiency is lower than other cooling methods. The temperature in the cabinet may be unstable as the cooling is instantaneous. Since the hot side and the cold side of the Peltier plate are very close to each other, it is difficult to provide insulation between the two sides. Considering these advantages and disadvantages, the use of Peltier coolers covers a wide range of areas such as consumer use, industrial use, scientific use and spacecraft use. They are used as portable coolers for camping or cars, small coolers for hotels, for cooling the electronic components, in thermal cyclers and in satellites.

2.1.2 Evaporative Cooling

Although evaporative cooling techniques has been improved over the years and evaporative cooling is mostly used for cooling the air in buildings or water in cooling towers today, it is known as the ancestor of food cooling and is still used today in places where there is no electrical energy or where people prefer this technique due to economic problems. Evaporative cooling is based on the principle of evaporation of water by absorbing heat from the ambient air and cooling the air in the environment. It is especially effective in dry climates. There is evidence that the evaporative cooling system, which is a very old technology, was used in the Ancient Egyptian Kingdom around 2500 BC. In the frescoes, it is seen that slaves fanned water vessels which are called as zeer pots. A zeer pot is an ancient device used to cool things like vegetables or liquids. In Figure 11 it can be seen the schematic diagram of a zeer pot refrigerator. A zeer pot consists of two unglazed clay pots, they have the same shape but their sizes are different. Smaller pot is placed inside the larger pot and the space between the two pots is filled with sand. Water is added over the sand which retains the water. Food is placed inside the interior pot, the top of the system is covered with a wet cloth that will cover both pots. As the water inside the sand evaporates it absorbs heat from the interior pot, therefore the interior pot and food inside this pot cools down. Clay is chosen as the material because the porous structure is necessary for water to evaporate. In order to increase the efficiency of the system, the ambient air should be as dry as possible and there will be sufficient level of air flow. In addition a ventilation can be used to increase the efficiency. Thus, the water can evaporate effectively and the cooling process takes place.

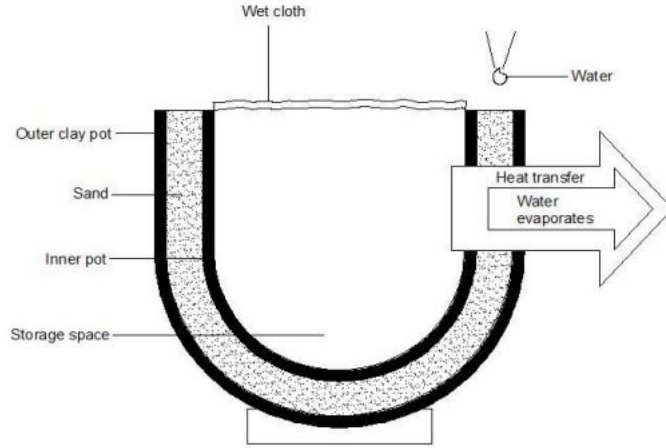


Figure 11: Schematic diagram of a zeer pot refrigerator [4]

Evaporative coolers either perform poorly or do not work at all in ambient conditions with high air humidity because water cannot evaporate at the desired level under these conditions. This is the reason that this method is used in arid regions. Evaporative cooling method is still in use today in areas like North Africa, India and Pakistan. Because these are the regions that potable water is precious and scarce if the inner pot can be waterproofed by glazing or other means, non-potable water, renewed water or sea water can be used inside the sand to perform the cooling process without contaminating the food. Evaporative cooling devices are simple and inexpensive ways to keep vegetables fresh without the use of electricity. Since the required components are only a large porous clay pot, smaller clay pot, sand, water and a piece of cloth the cost of the system is extremely low. The zeer pots are generally used for household purposes since they are small sized equipments. However as it is shown in Figure 12 they can be constructed for large capacity storage purposes which are called as evaporative cooling chambers. The structure behind the evaporative cooling chambers is very similar to zeer pots. They consist of two separate layers of brick walls. The cavity between the two walls is filled with wet sand. The top of the system is covered with a wood frame and the wood frame is covered with straw, dry grass, or burlap sack. If the system is installed outside of a building a shed should be constructed

to provide shade.

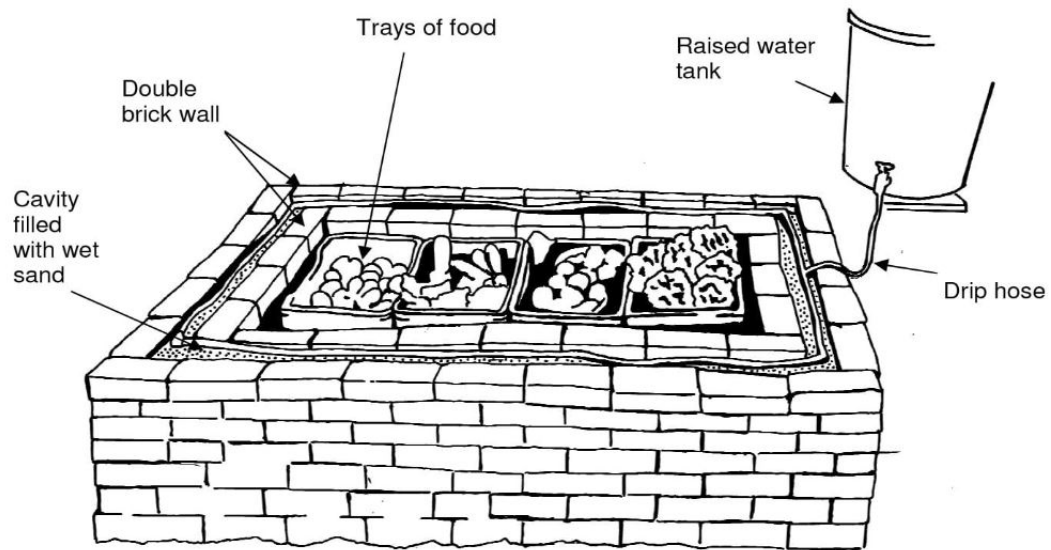


Figure 12: Evaporative cooling chamber [5]

2.1.3 Absorption Refrigeration Systems

Absorption means the confinement of a substance by another substance. The process of reducing the temperature of a substance or environment below the surrounding volume temperature and taking its heat is called refrigeration. As its name suggests, this cooling process takes place when the substance with high absorbency from two substances with different evaporation temperatures absorbs the substance with low absorbency into its body. The absorption cooling system was first invented by Ferdinand Carre and he patented his discovery in USA in 1860. In the first years of the twentieth century, the absorption cooling system became very popular and found application areas. Although it lost its popularity with the cheapening of electricity in the 1950s, it has started to attract attention again in industrial and domestic use in recent years. The reason for this is the trends that have emerged in recent years, such as the efficient use of natural resources and the protection of the ozone layer. Figure 13 shows the schematic diagram of a single effect absorption refrigeration cycle which is the simplest and commonly used design. A basic absorption refrigerator requires an absorber

and a refrigerant. The most common working fluids are lithium bromide/water (LiBr/H₂O) and water/ammonia (H₂O /NH₃) where the components are given as absorbent/refrigerant. Additionally, the system consists of these components; evaporator, condenser, generator, solution heat exchanger, pump, and two throttle valves. In addition to the components the system should have a heat source for the energy required to drive the cooling process. By the preferred heat source the refrigerant-absorbent solution is heated in the generator which is at the high-pressure part of the system. The high-pressure refrigerant vapor is separated from the solution and enters the condenser. The refrigerant vapor removes its heat to the environment until it condenses on the condenser. Then the refrigerant which is at the liquid phase passes through a throttle valve and enters the evaporator which is at the low-pressure part of the system. While passing through the throttling valve the pressure of the liquid refrigerant decreases. In the evaporator the liquid refrigerant absorbs the heat from the medium that is desired to be cooled and vaporized. The cooling of the medium occurs at this stage. The remaining refrigerant-absorbent solution in the generator flows down to the absorber by passing through a throttling valve. Low pressure refrigerant vapor in the evaporator enters the absorber. The solution absorbs the refrigerant vapor in the absorber. Then the new solution is pumped back into the generator to continue the cyclic operation. A solution heat exchanger is installed between generator and absorber and there is a heat exchange between the refrigerant-weak solution and the refrigerant-rich return solution. This process increases the system efficiency by preheating the refrigerant-rich return solution before entering the generator by using the thermal energy of the refrigerant-weak solution leaving the generator and decreases the necessary amount of heat to vaporize the refrigerant in the generator. Besides the refrigerant-weak solution cools down and shows a better absorption performance in the absorber.

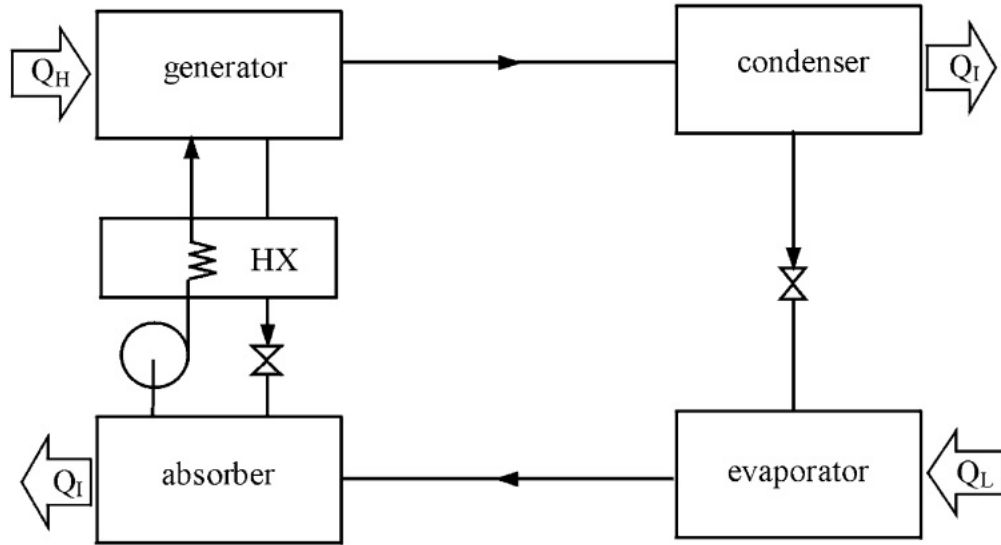


Figure 13: A single-effect LiBr/water absorption refrigeration system [6]

Absorption refrigerators use heat energy instead of electrical energy as the energy source. Among the sources that can be used as heat energy are the geothermal energy, solar energy, residual heat of steam power plants and heat from the combustion of petroleum products. Since these are renewable or waste energies the energy cost of these systems is generally low. In addition absorption refrigeration systems use a pump to send the solution to the generator, as a result the work input is very small and since the pump is for liquid it is also silent. However absorption refrigeration systems are generally expensive according to the other refrigeration systems. They are more complex, have more components and need more space and more investment. The efficiency of the absorption refrigerators is lower than the vapor compression refrigerators which have similar refrigeration cycles.

2.1.4 Vapor Compression Refrigeration Systems

The first working vapor compression refrigeration system was built in 1834 by Jacob Perkins who has patented a closed-loop ice machine by using some volatile fluids such as ether as a refrigerant. Although a prototype of this ice machine was made, it was never put into commercial production. Today every home has one vapor compression refrigerator and vapor compression refrigeration system is the

most used refrigeration system. This system is based on the temperature, pressure and phase changes of the refrigerant which R600a (isobutane) is mainly used in household refrigerators nowadays because of its environment friendly characteristics. The refrigerant is circulated in a hermetically sealed system. This system contains electrical and mechanical components that are used to change the temperature, pressure and phase of the refrigerant in order to provide the cooling impact. This system is called as basic refrigeration cycle and shown in Figure 14. The main components of the basic refrigeration cycle are compressor, condenser, expansion valve and evaporator. The first step is the compression. The refrigerant enters the compressor as a gas with low pressure and temperature. By the compression effect the gas leaves the compressor with high pressure and high temperature. The second step is the condensation. The condenser is generally in contact with ambient air and has large surface area to increase the heat transfer. When the gas enters the condenser it goes a long way and during this trip the temperature of the gas decreases and condensation happens. The refrigerant leaves the condenser as high pressure and low temperature liquid. Then the refrigerant reaches to the expansion device. Expansion device is responsible for the rapid decrease in the pressure of the refrigerant and this decrease in the pressure causes a dramatic decrease in the temperature of the refrigerant. With the pressure decrease the refrigerant becomes a cold liquid and vapor combination. As the last step of the refrigeration cycle, the refrigerant enters into the evaporator. As its name suggests this is the place where the evaporation of the refrigerant occurs by absorbing the heat from the environment that is desired to be cooled. Similar as condenser, the evaporator has a very large surface area in order to increase the efficiency of the heat transfer.

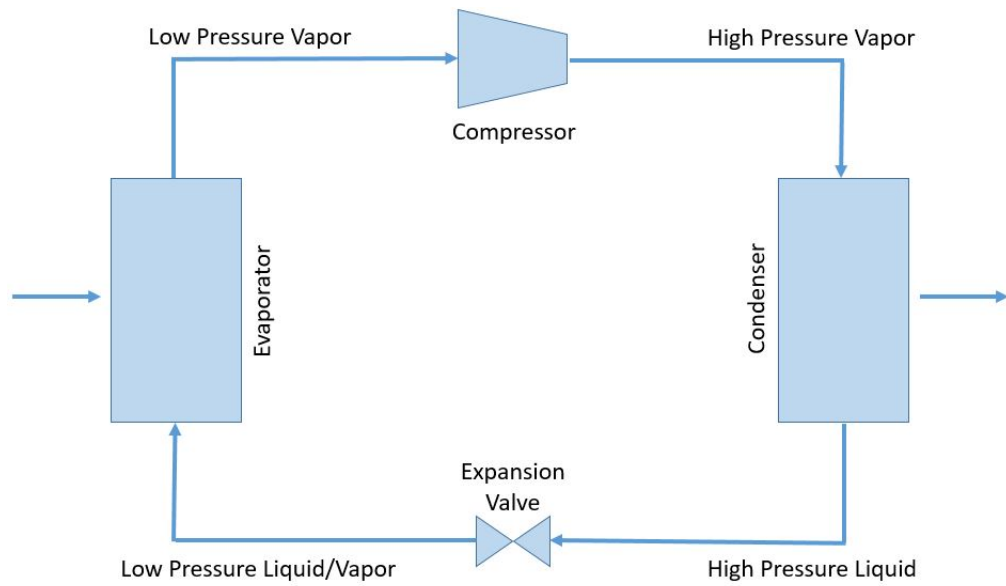


Figure 14: Basic refrigeration cycle

Figure 15 shows the visuals of the basic refrigeration cycle components of household refrigerators. The refrigeration cycle is very similar to the abovementioned. The capillary tube plays the role of the expansion valve. The inside diameter and the length of the capillary tube are calculated for the throttling effect to control the flow of the refrigerant, hence to control the pressure decrease. Since the inside diameter of the capillary tube is very small a filter which is called as dryer is used before the capillary tube in order to remove any impurities that the refrigerant may have. Capillary tube and filter are generally made of copper. The condenser is made of black painted steel and is curved as much as possible so that the occupied volume is small but the refrigerant path is long. It is made of steel because it is usually used outside of the refrigerator and is vulnerable to external impacts. Evaporator is made of aluminum which is one of the materials with high heat transmission coefficient.

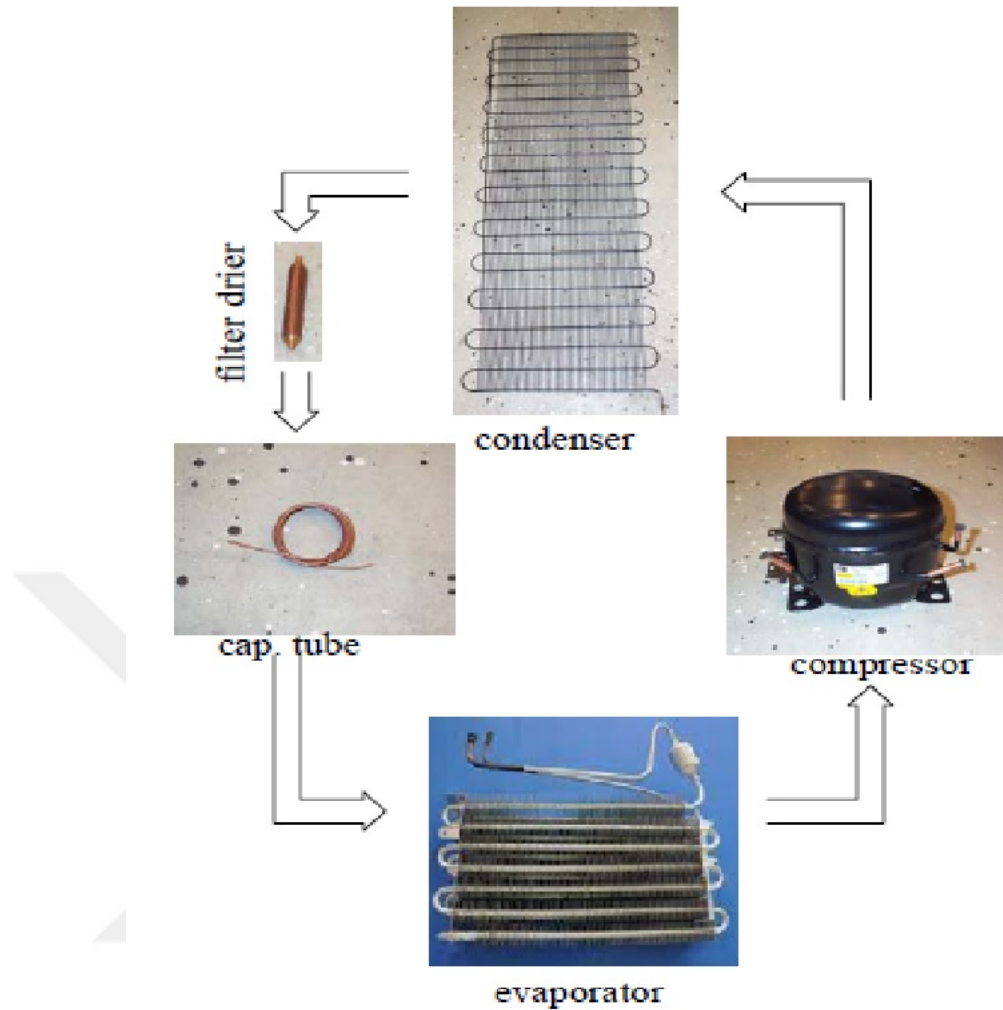


Figure 15: Basic refrigeration cycle

Vapor compression refrigerators are not only used for household purpose, they are also used also used in commercial refrigeration, cold storage, food processing, transport refrigeration and medical refrigeration. They use electricity as the energy source and relatively inexpensive according to the other methods in terms of components. Vapor compression refrigerators are very efficient and they do not cause temperature fluctuations in the area to be cooled, temperature is well distributed. Even they use small amount of refrigerants there are still environmentally hazardous refrigerants continued to be used.

2.2 Main Electrical and Electronic Components Used in Refrigerators

As the refrigerators are electrical operated appliances there are electrical and electronic components used to achieve the cooling purpose. Refrigerators can be categorized as mechanically and electronically controlled appliances. Mechanically controlled refrigerators are more basic than the electronically controlled versions in general. The end user uses a knob to change the position of a thermostat in order to adjust the desired temperature value. Mechanical thermostat is a kind of switch and makes the switching action according to the movement of the metal plates which have different thermal expansion coefficients. Mechanical thermostat uses a metal bulb with a gas in it to sense the temperature of the environment and conducts this temperature to the metal plates. Compressor starts to run by this switching operation. Mechanically controlled models does not cause electromagnetic interference issues in general. In electronically controlled refrigerators the end user adjusts the temperature by changing the values on the electronic display board. The signal goes to the electronic main board which control the electrical components on the refrigerators and main board commands to the compressor to run or not. The temperature of the environment is sensed by the sensors. All the signals are sent to the main board. Figure 16 shows the components of an electronically controlled refrigerator. Some parts are common in both electronically and mechanically controlled products. Refrigerator fan motor is used for the homogeneous distribution of the cool air in the refrigerator compartment and freezer fan motor is used for the same goal in the freezer compartment. Condenser fan motor is placed near the condenser and removes the heat on the condenser to facilitate the condensation of the refrigerant. It removes the heat by blowing or sucking the air according to its location. Led strips or bulbs can be used for the lighting purpose and the lights run by opening of the refrigerator door which activates the door switch. Some refrigerators may have a function called as no-frost in the market. This function requires a heater that melts the ice accumulated on

the evaporator and runs according to the software in the main board. The heater is activated at certain intervals and works for a certain period of time. Since the heater is powerful, this can pose a safety risk if it does not turn off. For this reason, a thermal fuse is placed on the heater that will cut the circuit in case of overheating. Compressors may have electrical part that consists of an over load protector and positive temperature coefficient or a PCB called as inverter board. Since electronically controlled refrigerators are introduced as higher technology products, they usually contain more electronic components. That means more sources of electromagnetic interference. In this thesis the experimental analysis is done on an electronically controlled model. Below some details are given about more critical parts of a refrigerator in terms of electromagnetic interference.



Figure 16: Main electrical and electronic components of a refrigerator

2.2.1 Supply Cable and Plug

Supply cable and plug set refers to any electrical utilization equipment that uses a flexible cord and an attachment plug to connect the refrigerator and nearly all type of electrical and electronic equipment into the socket outlets in buildings to energize the products. In general, a supply cable consists of copper wires representing the phase, neutral and grounding lines of the product, and electrical insulation material, usually polyvinylchloride, covering these copper wires. The copper wire diameter and insulation thickness may change according to the laws of the different countries around the world. A plug has pins that make the connection to the socket outlet. These pins can be thought of as extensions of the phase, neutral, and ground lines in the cable. It has a frame inside so that the pins can be fixed and connected with copper wires. It is also covered with electrical insulation material. There are different plug types in different countries in terms of pin types, pin numbers, voltage rating, current rating, shape and size based on the electrical installations of the houses. Two different supply cable and plug sets are shown in Figure 17. While left one is a standard type which is mostly used in Europe, Russia and some countries of North Africa, right one is used in Israel. Conducted electromagnetic interference leads with conduction through cables. Supply cable and plug set is the connection between the product and the grid. That means the whole electromagnetic noise produced by a refrigerator passes to the grid and to other appliances around through the supply cable and plug. That also means the supply cable is one of the parts that the measures can be taken for the electromagnetic interference suppression. As shown in Figure 17 ferrite magnets may be used on the supply cables in order to suppress of the electromagnetic noise that the appliance produces. Generally, the ferrite magnet is applied in such a way that the cable takes a few turns through the ferrite magnet.

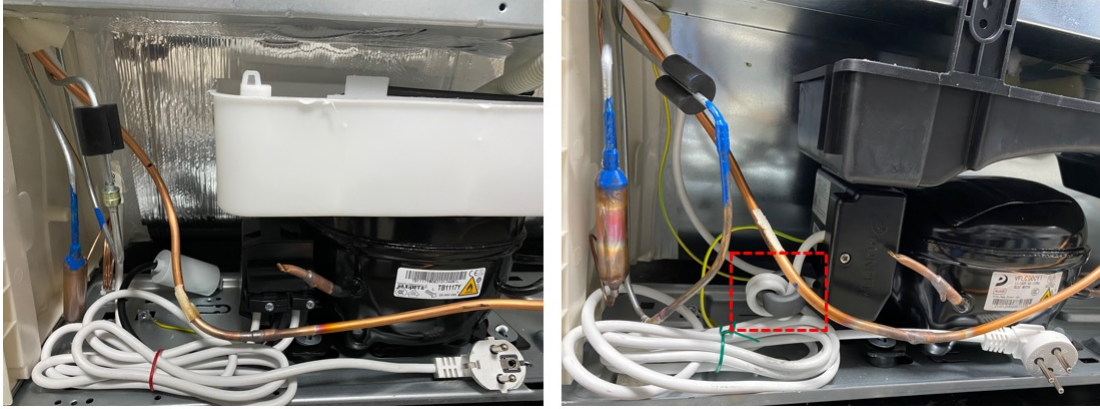


Figure 17: Supply cable and plug set of (a) European type (b) Israeli type

2.2.2 Compressor and Accompanying Electrical Parts

Compressor is a mechanical device that is used to increase the pressure of the refrigerant and secure the movement of the refrigerant in a closed refrigeration cycle system. Compressors are known as the heart of vapor compression refrigeration systems. Compressors can be hermetic, semi-hermetic, or open types according to leak proofing structures. In hermetically sealed systems the compressor and the motor are integrated. The compressor also contains lubricating oil and refrigerant. Compressor housings are welded, so internal components may not be accessed for maintenance or service purposes. These systems are used for small capacities and they are low-cost systems, ideal for household refrigerators and air conditioners. Hermetic compressors work for long periods without gas leakage. Semi hermetic compressors are similar to hermetic compressors. However the shell of the compressor is not welded, instead the shell is sealed with bolts and gasket therefore the structure allows servicing and maintenance. These compressors also do not cause a leakage problem. They are suitable for middle and large sized refrigeration and air conditioning applications. Open compressors can be serviced without opening any part of the refrigerant system. Although open compressors have seals they are more susceptible to leak the refrigerants over time. Open compressors are preferred for large capacities.

Compressors are classified according to the working mechanisms as positive displacement compressors and dynamic compressors [36]. In Figure 18 a hermetic reciprocating compressor which is generally used in household refrigerator systems is given. The reciprocating compressor uses a continuously moving piston to draw in air and then compress it. The rotational motion of the drive motor is converted into linear motion by a crank-connecting rod system. Reciprocating compressors can be driven by engines such as DC or AC current electric motors, steam or gas turbine, gasoline or diesel engine. In this type of compressors, the suction valves are opened with the downward movement of the piston in the cylinder to draw the refrigerant vapor. The refrigerant vapor is compressed by the upward movement of the piston, and the fluid is ejected when the pressure in the cylinder rises above the condensing pressure. The required power for the compressor is supplied either directly by the motor or indirectly by a belt or gear drive. In these compressors, the main parameters affecting the efficiency are cylinder void volume, compression ratio, suction superheat, valve pressure drop, and refrigerant and oil properties. The choice of cooling method depends on the discharge temperature. In general, air cooling is chosen for low exit temperatures and water cooling is used for high exit temperatures. The reciprocating compressor can compress a wide variety of gases, including refrigerant, hydrogen and natural gas. Therefore, it finds use in a wide range of applications in many different industries.

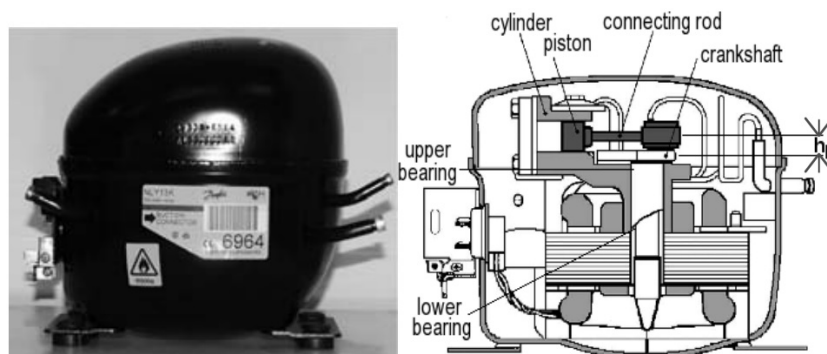


Figure 18: (a) Picture of a hermetic reciprocating compressor (b) schematic draw of a hermetic reciprocating compressor [7]

Rotary compressor makes a rotary or circular motion rather than a reciprocating motion to compress the fluid. It works on rotors rotating on an eccentric shaft. The fluid enters the suction port through a gap between the rotor and the cylinder. Thanks to the eccentric arrangement of the rotor and cylinder, the fluid is compressed as the rotor rotates and pressurized fluid is released through a discharge port. The rotary positive displacement compressor is the most common type of compressor in use today. These compressors are common in industrial applications and replace conventional reciprocating compressors in applications where larger volumes of compressed fluid are required. Since the cavity volume of the rotary compressor is negligible, its volumetric efficiency is high compared to the reciprocating compressor. One of the most important features of the rotary compressor is the absence of suction and discharge valves as in the reciprocating compressor. Rotary compressor is compact and light. It does not exhibit vibration and shaking forces as that of the reciprocating compressor. It operates at high speed, so it can handle a large quantity of fluid. Lubrication is simple, and the output fluid is free from dirt and oil. Unlike the reciprocating compressor which discharges intermittently, the rotary compressor supply compressed air continuously. However the discharge pressure per stage is low compared to the reciprocating compressor which can be considered as a disadvantage.

A dynamic compressor increases the pressure of a refrigerant by continuously exchanging angular momentum between a rotating mechanical element and a compressed fluid. Rather than physically reducing the volume of the entrapped air pocket, dynamic displacement compressors increase the velocity of the air and then restrict the airflow, so the reduction in velocity causes the pressure to increase. Unlike a positive displacement compressor which works with a constant flow, a dynamic compressor works at a constant pressure. Dynamic compressors include axial and centrifugal types. Centrifugal compressors are generally designed for use at higher capacities. Air or fluid enters the compressor through the inlet and is drawn into the center of a centrifugal impeller rotor, then pushed towards the

center by centrifugal force in order to increase the kinetic energy. The next component, downstream of the impeller within a simple centrifugal compressor is the diffuser. The diffuser converts the fluid's kinetic energy into increased potential energy by gradually slowing the fluid's velocity. They are often used in industries such as oil refineries, chemical and petrochemical plants, and natural gas processing plants. Another category of dynamic compressor, the axial compressor, is generally preferred for very high capacity systems. The working principle is similar to the centrifugal compressor. In axial compressors, the flow enters the compressor axially and exits axially. Axial compressors compress the working fluid by first accelerating the fluid and then increasing the pressure by diffusion. The acceleration of the fluid is ensured by the series of rotors which are rotating blades and distributed to a series of stationary blades. In axial flow compressor the flow direction is parallel to the axis of the shaft, in centrifugal compressor the inlet flow direction is parallel to the shaft but outlet flow direction is perpendicular to the shaft. The mass flow rate in axial flow compressor is very high according to the centrifugal compressor.

In household refrigerators, the hermetic reciprocating compressor, one of the mentioned compressor types, is used. The electrical operation of this type of compressor is provided by the electrical box which includes an overload protector and positive temperature coefficient (OLP-PTC) combination or provided by an inverter electronic board. As its name implies OLP protects the compressor circuit due to voltage overload or thermal overload conditions. A PTC is responsible for providing power to the auxiliary winding for a brief moment to help start the compressor. A PTC can be a thermistor or a simple electronic board which is called an e-PTC. E-PTC may contribute to the electromagnetic noise. An inverter board is used in products that require energy efficiency and it is used to control the voltage and frequency of the power supply and adjust the rotation speed of the compressors in refrigerators. Inverter boards are one of the important sources of electromagnetic noise in refrigerators.

2.2.3 Cable Harness

As in all electrical and electronic products, electrical power and signals between components are carried through electrical cables in refrigerators. These cables are divided into two AC carrying and DC carrying. Compressor, heater, and electronic board cables can be given as examples of cables carrying AC, while cables of sensors, some switches, and lighting equipment can be given as examples of cables carrying DC. To make the assembly of these cables easy in the production lines, the cables are brought together and grouped with durable materials such as electrical tape, rubber, and rope. This grouped state of cables is called a cable harness [37]. It is also called wire harness, cable assembly, or wiring assembly. Although bringing the cables together provides convenience in terms of assembly, it often causes a disadvantage in terms of electromagnetic compatibility. Cables can act as transfer paths of electromagnetic noise, and the closer the cables, the closer the electromagnetic noise source and receiver are to each other. Therefore, keeping all cables as far apart as possible or at least separating power cables and signal cables is one of the methods used in the industry to ensure the electromagnetic compatibility of products. Being close to each other rarely results in the attenuation of noises of similar frequency and improvement in terms of EMC.

2.2.4 Electronic Main Board and Display Board

Electronic boards are used to collect and process the data detected by the sensors and to transmit commands to the relevant components according to the designed algorithm in the light of this data. As shown in Figure 19 it consists of a laminated sandwich structure of conductive and insulating layers and many components such as transistors, diodes, IC chips, resistors, capacitors, and connectors affixed to this structure. Electronic boards are one of the main reasons for more complex products to fail EMC tests. Often this is related to design flaws that cause interference between tracks, paths, coils, and other elements. Maximizing the ground area, avoiding right angles for the traces, keeping signals separate, shortening return

paths, separating analog and digital parts, using shields, being careful with the high-speed components, and using filters can be the solutions to overcome EMI problems. A display board is an electronic board that provides an interface for the end-user to set the temperature and modes of the refrigerator. In general, it is the victim component, not the source component. Changes in the temperatures and modes set in the interface due to electromagnetic noise, loss of the image, and failure of the adjustment buttons to fulfill their duties are examples of immunity problems.

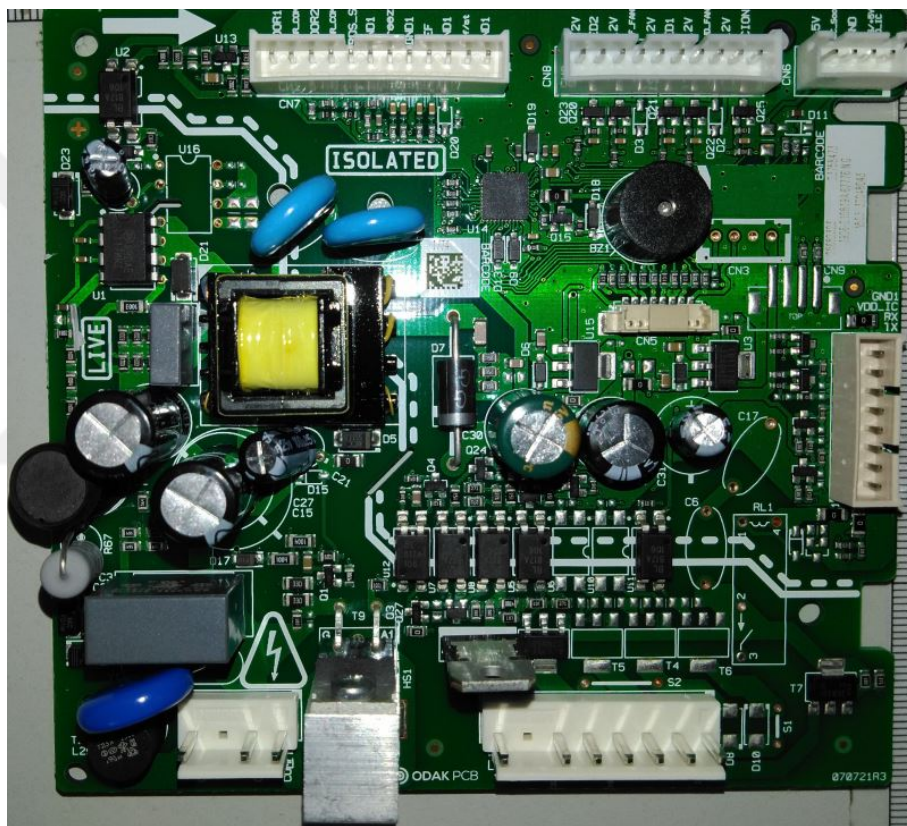


Figure 19: A refrigerator electronic board

CHAPTER III

ELECTROMAGNETIC COMPATIBILITY AND CONDUCTED ELECTROMAGNETIC INTERFERENCE

The devices generate electromagnetic energy and a certain portion of it will be conducted to the local grid through a power supply cord and from the grid to other devices in the same environment. To restrict electrical and electromagnetic noise that the device conducts, the noise conducted by the device is measured and verified that comply with specified limits. This ensures that the local power supply remains relatively clean and devices in the same environment are not affected.

3.1 EMC Rules in Different Regions

Electromagnetic compatibility is regulated under Directive 2014/30/EU in European Union (EU) countries. This directive is one of the directives that must be followed so that CE marking can be added to the products and these products can be traded in Europe. In addition, many countries around the EU also follow this directive by adapting it to their national directives. Besides there lot of countries that create their own rules for EMC. Member states of the European Union, Member States of the European Free Trade Association (EFTA), Member states of the Gulf Cooperation Council (GCC), United Kingdom (UK) countries that left the EU by Brexit, and other countries from different continents all set EMC rules and require compliance with these rules to free movement of the products in those countries. Table 1 shows the broad list of countries that set EMC rules for the products such as household appliances, industrial appliances, medical devices, etc. Every country or union has the competent authority to set the rules [2].

For a country to set rules regarding EMC, the technology and installation

infrastructure in that country must be appropriate. For example, in some countries, there is no grounding in homes, which is one of the most important safety requirements. In such a country, it may be a problem to impose restrictions on electromagnetic emissions and comply with these rules. When a manufacturer adds a filter to the product to prevent electromagnetic emission, this filter will increase the leakage current in the product and this will disturb the end-user if the leakage current is at a perceptible level even if it is within safe limits. So the lack of grounding in homes can make it difficult to enact laws regarding EMC.

3.2 Conducted Emission Test Equipment and Test Procedure

Directives set the rules, standards specify ways to comply with the rules, and bring harmonization for testing. EMC standards and norms define terms, rules, and test methods for EMC. Furthermore, they specify limits and minimum test levels for electrical and electromagnetic emissions and immunity of electromechanical and electronic products. Table 2 describes the conducted emission tests applicable for a refrigerator according to the European Union rules. This thesis is about one of the conducted emission tests, IEC 55014-1, Disturbance Voltage at the Mains Terminals (150kHz-30MHz), which is generally problematic for refrigerator producers.

Figure 21 is a typical conducted emissions test setup. It consists of a line impedance stabilization network (LISN), an isolation transformer, a transient limiter, and a spectrum analyzer. A LISN is a low-pass filter placed between the power source and the Equipment Under Test (EUT) to create a known impedance to the EUT's power line terminals over the frequency range of 150kHz to 30MHz. Impedance should be known to ensure the replication of the tests. The power sources have different impedances, so a LISN standardizes this impedance between setups. Figure 20 shows the 50 μ H LISN circuit which is generally used for conducted emissions test setups. C2 capacitor on the power line side of the LISN shorts the variable impedance of the power line from the mains and ensures

Table 1: The countries that have EMC rules around the world

<i>Region/Union</i>	<i>Country</i>	<i>Region/Union</i>	<i>Country</i>
EU Countries	Austria	North America	USA
	Belgium		Canada
	Bulgaria	South America	Brasil
	Croatia		Argentina
	Cyprus		Colombia
	Czechia		Mexico
	Denmark	GCC Countries	Kuwait
	Estonia		UAE
	Finland		Saudi Arabia
	France		Yemen
	Germany		Oman
	Greece		Bahrain
	Hungary	UK Countries	England
	Ireland		Wales
	Italy		Northern Ireland
	Latvia		Scotland
	Lithuania	Asia	Japan
	Luxembourg		Korea
	Malta		China
	Netherlands		Uzbekistan
	Poland		Taiwan
	Portugal		Vietnam
	Romania		India
	Slovakia	Middle East/Africa	South Africa
	Slovenia		Israel
	Spain	Australia	Australia
	Sweden		New Zealand
EFTA Countries	Norway		
	Iceland		
	Liechtenstein		
	Switzerland		
Other Countries	Turkey		
	Russia		

that the test results are not affected. L1 inductor provides an impedance at a frequency similar to power line impedance measurements. C1 capacitor provides the connection between the conducted emission measurement device and the power line. R1 resistor discharges its capacitors when LISN is disabled. This prevents the charged capacitors of the LISN from creating an electric shock hazard. The

Table 2: Conducted emission tests applicable for a refrigerator

<i>Standard</i>	<i>Description</i>
IEC 55014-1	Disturbance Voltage at the Mains Terminals (150kHz-30MHz)
IEC 55014-1	Disturbance Power (30MHz-300MHz)
IEC 55014-1	Discontinuous Disturbance Test
IEC 61000-3-2	Limits for harmonic current emissions (equipment input current 16 A per phase)
IEC 61000-3-3	Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current 16 A per phase and not subject to conditional connection

measuring instrument places a 50-ohm shunt resistor against resistor R1 and limits the LISN's rising impedance versus frequency. A LISN is also useful if the power source is noisy, it filters the unwanted RF signals from the power supply source so the setup can measure only the noise from the EUT clearly.

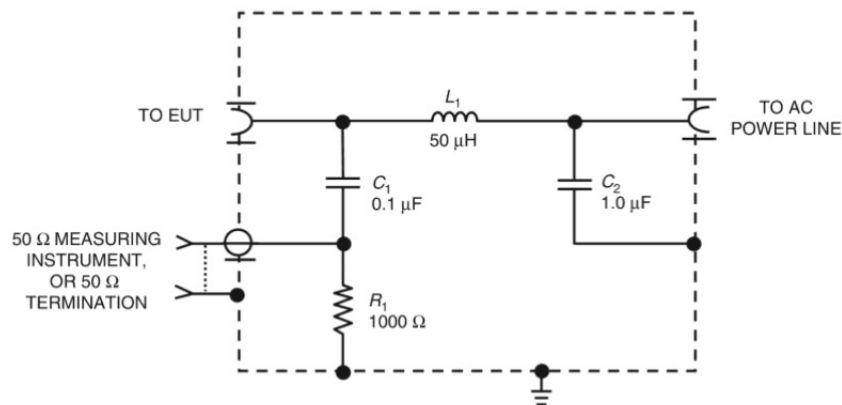


Figure 20: Circuit of a LISN [8]

The isolation transformer is used to transfer electrical power from the grid to the LISN. It is used for two main purposes. First, the isolation transformer provides a safety measure against electric shock by isolating the LISN from the power supply. There is no direct transmission path, energy is exchanged between sections by capacitance, induction, or electromagnetic waves. Isolation transformers with a 1:1 ratio of primary and secondary windings are used in EMI test systems.

Second, the isolation transformer is used to reduce transients and harmonics and isolate the setup from the power source.

The transient limiter protects the spectrum analyzer input from transients that pass through the LISN. Because the RF signal must be passed through, any short transients (a few microseconds or less) on the power supply lines will also be passed through. The supply mains is a source of transients and the input of a spectrum analyzer can easily be damaged by these transients. The LISN circuit attenuates these transients to a certain level, but cannot ensure that they remain within certain limits. In addition, switching operations within the EUT can generate large transient currents and these currents can be sent directly to the analyzer without being attenuated. For this reason, although it is not mandatory it is essential to add a transient limiter in the signal cable between the spectrum analyzer and the LISN. A transient limiter usually consists of a high pass filter and a 10 dB attenuator.

The spectrum analyzer measures the magnitude of an input signal versus frequency within the full frequency range of the instrument. The primary use is to measure the power of the spectrum of known and unknown signals. The spectrum analyzer converts the signals to the graphs and values so comparisons and interpretations can be made.

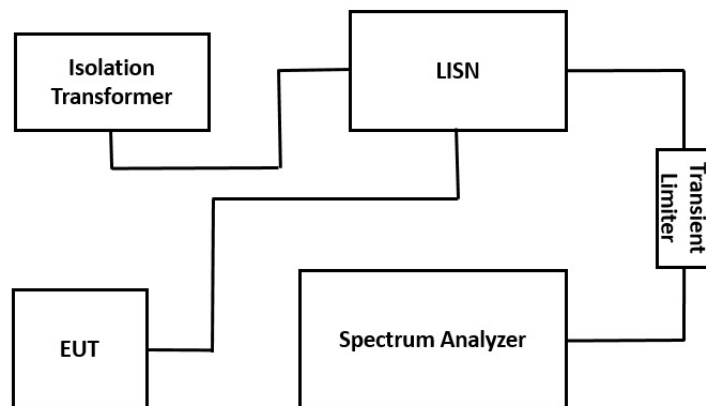


Figure 21: Test setup for the disturbance voltage test at the mains terminals (150kHz-30MHz)

Noise can occur between any two lines of the system. In a single-phase system this could be between phase (P) and neutral (N) lines. Therefore noise values are measured for both phase and neutral lines separately. EMI receivers generally have three noise detectors; peak, quasi-peak, and average. The peak detector measures the peak amplitude of the signal (noise). It is independent of the pulse repetition frequency. It only outputs the max amplitude of the signal. A Quasi Peak Detector weighs the signal according to its repetition rate and outputs accordingly. If the EMI receiver measures more pulses within a certain time it shows higher quasi-peak values. The Average Detector indicates proportional to the pulse repetition frequency. In related conducted emission standards for household appliances, the limits are given for quasi-peak and average measurements.

EMI tests can be evaluated in two branches full compliance tests and pre-compliance tests. After the products are finalized and before they are put on the market, a full compliance test is required. These tests are carried out by the relevant national and international standards, without any deviation, by fully equipped experts, using fully equipped test equipment, in appropriate measurement environments. Products are certified as a result of full compliance tests. Full compliance testing must be done at a fully accredited facility. Because full compliance testing is often done shortly before a product is manufactured, failure in testing can result in product redesign and delay in production. Full compliance testing can be extensive, time-consuming, and expensive. Instead of testing in fully accredited laboratories, pre-compliance tests can be an alternative for design evaluation. Pre-compliance testing provides a fast and cost-effective way to evaluate the design at earlier stages of the design. While the product is in development, pre-compliance testing can be used to catch the problems early and increase the probability of successfully passing the full-compliance tests by making the necessary design changes before the product is finalized. The purpose of pre-compliance testing is to mimic full compliance testing within an acceptable margin to uncover potential problems and reduce the risk of failure before the

expensive full compliance testing phase.

3.3 Units in Measurements and Testing

EMC engineers use decibel (dB) as the noise measurement unit. dB refers to one-tenth of a unit called Bel. Decibel is often used to express the ratio of quantities such as power, current, and voltage, and for comparison on a logarithmic scale. It is most commonly used for the ratio of output power (P2) to input power (P1) to calculate the gain of an amplifier.

$$\text{The ratio of output power to input power} = 10\log_{10}(P_2/P_1) \quad (5)$$

$$\text{The ratio of output power to input power} = 10\log_{10}[(V_2/V_1)^2(R_1/R_2)] \quad (6)$$

$$\text{The ratio of output power to input power} = 10\log_{10}[(I_2/I_1)^2(R_2/R_1)] \quad (7)$$

$$\text{The ratio of output voltage to input voltage} = 20\log_{10}(V_2/V_1) + 10\log_{10}(R_1/R_2) \quad (8)$$

$$\text{The ratio of output current to input current} = 20\log_{10}(I_2/I_1) + 10\log_{10}(R_2/R_1) \quad (9)$$

The unit, dB, represents gain or loss, i.e. a change. Actual values are expressed in dBm, dB μ V, and dB μ A for power, voltage and current respectively. It is calculated with the following formulas, taking the input information as 1.

$$\text{Actual noise value in terms of power} = \text{dBm} = 10\log_{10}(P/1\text{mW}) \quad (10)$$

$$\text{Actual noise value in terms of voltage} = \text{dBV} = 20\log_{10}(P/1\mu\text{V}) \quad (11)$$

$$\text{Actual noise value in terms of current} = \text{dBA} = 20\log_{10}(P/1\mu\text{A}) \quad (12)$$

Limits of disturbance voltage at the mains terminals (150kHz-30MHz) test for household refrigerator products are as in Table 3 according to IEC 55014-1 standard.

Table 3: Limits for the mains port of motor operated tools

$P \leq 700W$		
Frequency Range (MHz)	Quasi-Peak (dB μ V)	Average (dB μ V)
0,15 to 0,30	66 to 59	59 to 49
0,35 to 5	59	49
5 to 30	64	54
Decrease in noise limits takes place linearly with the logarithm of the frequency The lower limit applies at the transition frequencies P = rated power of the motor only		

CHAPTER IV

EXPERIMENTAL ANALYSIS

Seven different experiments were conducted to examine the impacts of cable distribution change and ferrite usage on EMI in refrigerator products. Seven experiments can be described below.

- 1) Conducted emission test of entangled AC-DC cables inside the body and control box
- 2) Conducted emission test of entangled AC-DC cables inside the body but separated at the control box entrance
- 3) Conducted emission test of separated AC-DC cables during the whole path
- 4) Conducted emission test of ferrite core on AC cables
- 5) Conducted emission test of amorphous core on AC cables
- 6) Conducted emission test of ferrite core on DC cables
- 7) Conducted emission test of amorphous core on DC cables

The reasons for choosing the above-mentioned test methods are given below.

- Separating the cables carrying AC and DC is expected to prevent the risk of coupling between cables (cross-talk). When the cables are adjacent to each other, the one carrying high-frequency signals can couple to an adjacent one through stray capacitance formed between these two cables. Stray capacitance is the unintended generation of charge in a circuit or non-capacitive component. Since the impact of electromagnetic energy attenuates with the distance it is expected to decrease the risk of this unintentional coupling. Similar cables are expected to behave similarly. Therefore segregation of the cables can be made depending upon their application, voltage or current levels, frequency of signals they carry, types of signals they carry, components to which they are connected, etc. Cables can of course be divided into more detailed groups according to their properties. But it

will not be a practical method for production facilities. For this reason, the cables are separated according to their AC and DC carrying characteristics.

- Ferrite beads are used as a passive low-pass filter which allows low-frequency signals to pass. By passing the cables through the ferrite core a kind of inductor and thus impedance is created. The impedance prevents the flow of higher frequency signals and the energy is either reflected in the cable or dissipated as low-level heat. Ferrites are classified according to their magnetizations and crystalline structures. In electrical applications generally, soft ferrites are used. Soft ferrite magnets can quickly and easily change their magnetic orientation when they are exposed to external magnetic force. In this study, it is expected to observe the impacts of two soft ferrites that have different production techniques and crystalline structures.

The experiments were carried out in a laboratory with international accreditation on the IEC 55014-1 standard. The test setup is shown in Figure 22. The refrigerator was set to 2 °C, the coldest value of the refrigerator compartment, and to -24 °C, the coldest value of the freezer compartment. Thus, it was aimed that the components work at the maximum level. Rohde & Schwarz branded ESCI 7 model was used as EMI receiver. Rohde & Schwarz branded ESH2-Z5 model was used as LISN. Rohde & Schwarz branded ESH3-Z2 model was used as transient limiter.

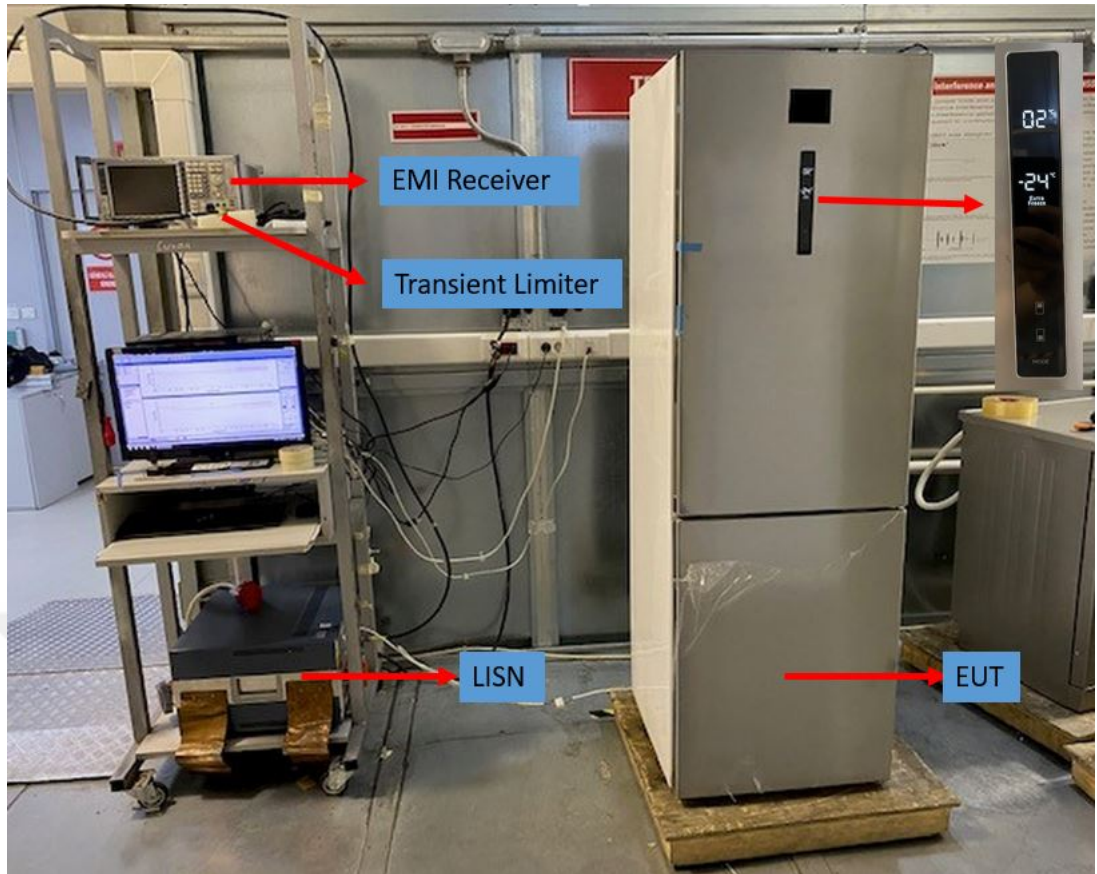


Figure 22: Conducted emission test setup

4.1 *The Impact of Cable Alignment*

By changing the distribution of cables in a refrigerator model, tests were carried out to observe the impact of these changes on the conducted electromagnetic emission test results. 3 units of the same model refrigerator were produced, the only difference was the cable distribution. The differences between the cable distributions are as follows:

- AC and DC cables are aligned entangled inside the refrigerator and control box.
- AC and DC cables are aligned entangled inside the refrigerator but separated at the control box entrance.
- AC and DC cables are separated during the whole path inside the refrigerator and the control box.

4.1.1 Entangled AC-DC Cables Inside the Body and the Control Box

A refrigerator body plastic and a control box are shown in Figure 23. The route of the cables on the refrigerator body plastic and control box for the first sample is shown. Red arrow on the left shows the AC carrying cables and blue arrow on the right shows the DC carrying cables. AC and DC cables align adjacent to each other along the refrigerator body and both groups of cables enter the control box from the same hole and stay adjacent.



Figure 23: AC & DC cables entangled on the body and control box

Figure 24 is the graph for the phase line measurement. The red line shows the quasi-peak limit, while the pink line shows the average limit. Therefore the blue lines should not go above the red line and the green lines should not go above the pink line for the product to comply with the standard. According to the graph, the blue and green lines are far below the red and pink limit lines so the product has passed the phase line test according to the international standards. The peaks seem to be accumulated at around 1 MHz and 4-5 MHz. The exact values can be checked in Table 4.

The exact noise values for pre-defined frequencies can be seen in Table 4 for phase line. The closest value to the limit is 6.48 dB at 0.9 MHz and 6.9dB at 4 MHz at average measurements which are both far from the limits and the result is a clear pass according to the international standards. The rest of the margin values at other frequencies are above 9 dB.

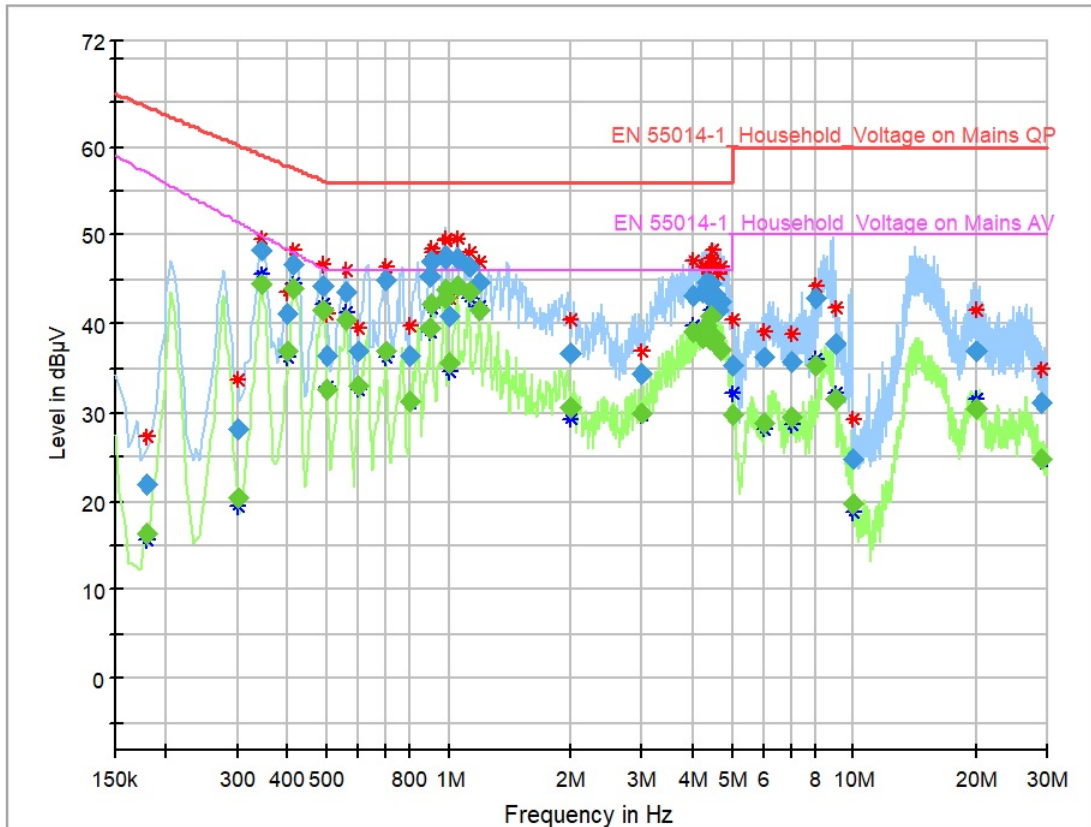


Figure 24: AC & DC cables entangled - Phase line measurement graph

Table 4: AC & DC cables entangled - Phase line test results

<i>Frequency</i> (MHz)	<i>QuasiPeak</i> (dBV)	<i>Average</i> (dBV)	<i>Limit</i> (dBV)	<i>Margin</i> (dB)
0.18	—	16.34	57.03	40.69
0.18	21.85	—	64.49	42.64
0.3	—	20.41	51.52	31.11
0.3	28.30	—	60.24	31.94
0.4	—	37.02	48.41	11.39
0.4	41.17	—	57.85	16.68
0.5	—	32.56	46.00	13.44
0.5	36.56	—	56.00	19.44
0.6	—	33.18	46.00	12.82
0.6	36.84	—	56.00	19.16
0.7	—	36.94	46.00	9.06
0.7	44.92	—	56.00	11.08
0.8	—	31.34	46.00	14.66
0.8	36.43	—	56.00	19.57
0.9	—	39.52	46.00	6.48
0.9	45.41	—	56.00	10.59
1	—	35.57	46.00	10.43
1	40.92	—	56.00	15.08
2	—	30.74	46.00	15.26
2	36.59	—	56.00	19.41
3	—	30.05	46.00	15.95
3	34.41	—	56.00	21.59
4	—	39.10	46.00	6.90
4	43.07	—	56.00	12.93
5	—	29.85	46.00	16.15
5	35.33	—	56.00	20.67
6	—	28.78	50.00	21.22
6	36.20	—	60.00	23.80
7	—	29.51	50.00	20.49
7	35.80	—	60.00	24.20
8	—	35.40	50.00	14.60
8	42.85	—	60.00	17.15
9	—	31.53	50.00	18.47
9	37.78	—	60.00	22.22
10	—	19.60	50.00	30.40
10	24.79	—	60.00	35.21
20	—	30.45	50.00	19.55
20	36.97	—	60.00	23.03
29	—	24.93	50.00	25.07
29	31.16	—	60.00	28.84

Figure 25 shows the graph for the neutral line measurement. The image of the graph is similar to the image of the phase line graph between 0.5 MHz and 10 MHz frequencies, however, the noise values are lower at neutral line measurement than at phase line measurement below 0.5 MHz frequency and above 10 MHz frequency. From the graph it can be seen that the blue lines are below the red line and the green lines are below the pink line, therefore it can be understood the product passes the test even without looking at the exact values.

Table 5 shows the noise values. The closest value to the limit is 4.87 dB 5 MHz at average measurement. There is also very close value of 5.32 dB at 0.9 MHz which is around 1 dB worse according to the phase line measurement. In any case, the worst result is far from the limits and the product complies with the international standards.

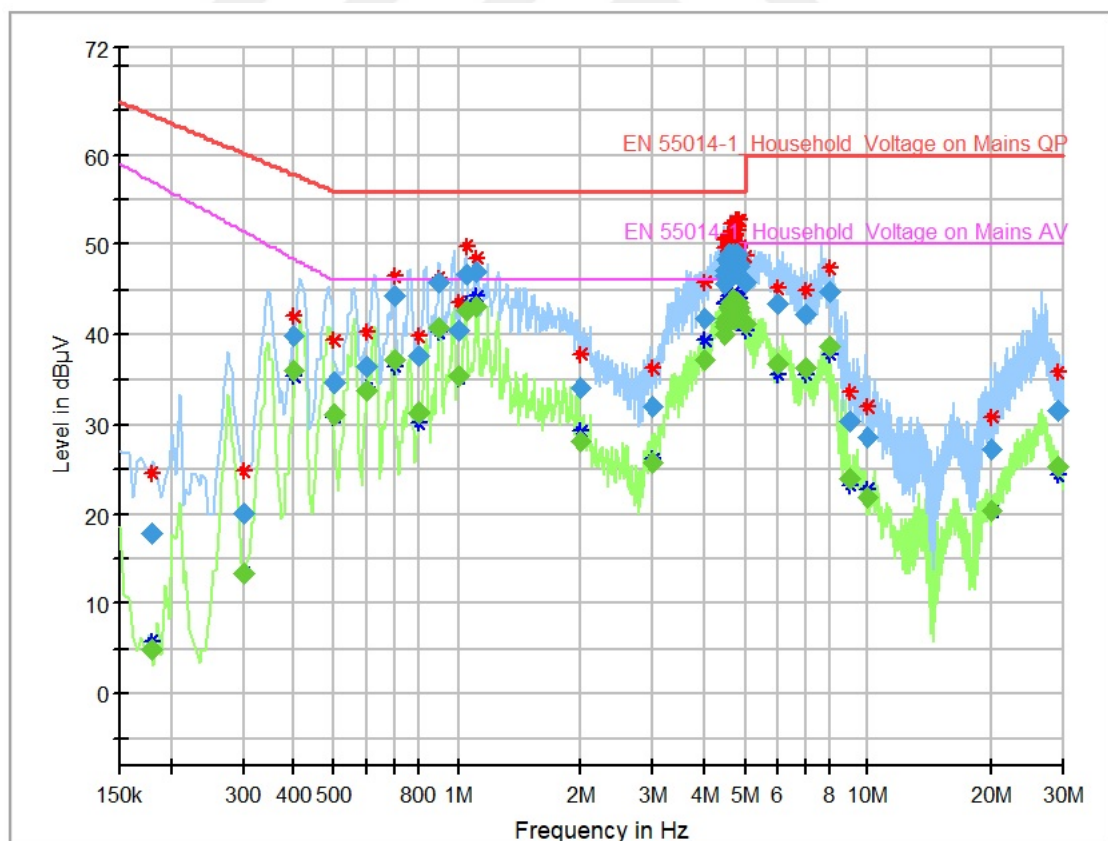


Figure 25: AC & DC cables entangled - Neutral line measurement graph

Table 5: AC & DC cables entangled - Neutral line test results

<i>Frequency (MHz)</i>	<i>QuasiPeak (dBV)</i>	<i>Average (dBV)</i>	<i>Limit (dBV)</i>	<i>Margin (dB)</i>
0.18	—	4.94	57.03	52.09
0.18	18.03	—	64.49	46.46
0.3	—	13.47	51.52	38.05
0.3	20.09	—	60.24	40.15
0.4	—	36.13	48.41	12.28
0.4	39.78	—	57.85	18.07
0.5	—	31.07	46	14.93
0.5	34.77	—	56	21.23
0.6	—	33.88	46	12.12
0.6	36.4	—	56	19.6
0.7	—	37.05	46	8.95
0.7	44.22	—	56	11.78
0.8	—	31.35	46	14.65
0.8	37.51	—	56	18.49
0.9	—	40.68	46	5.32
0.9	45.77	—	56	10.23
1	—	35.28	46	10.72
1	40.53	—	56	15.47
2	—	28.28	46	17.72
2	34.08	—	56	21.92
3	—	25.7	46	20.3
3	31.92	—	56	24.08
4	—	37.25	46	8.75
4	41.84	—	56	14.16
5	—	41.13	46	4.87
5	45.93	—	56	10.07
6	—	36.64	50	13.36
6	43.4	—	60	16.6
7	—	36.15	50	13.85
7	42.19	—	60	17.81
8	—	38.65	50	11.35
8	44.8	—	60	15.2
9	—	24.03	50	25.97
9	30.35	—	60	29.65
10	—	21.86	50	28.14
10	28.58	—	60	31.42
20	—	20.44	50	29.56
20	27.32	—	60	32.68
29	—	25.22	50	24.78
29	31.46	—	60	28.54

4.1.2 Entangled AC-DC Cables Inside the Body but Separated at the Control Box Entrance

The route of the cables on the refrigerator body and control box is shown in Figure 26. As it can be seen from the red and blue arrows AC and DC cables align adjacent to each other on the refrigerator body however they are separated just before entering the control box. AC and DC cables enter the control box from two separate holes which are in opposite directions.

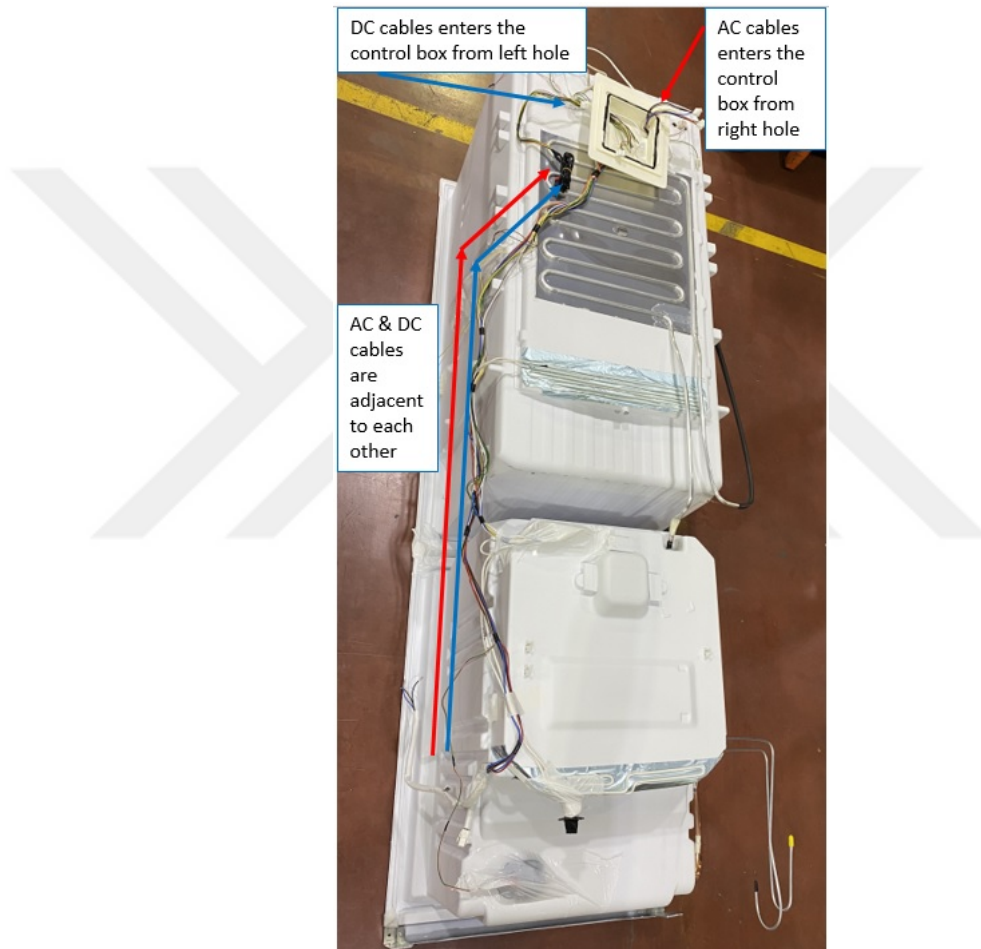


Figure 26: AC & DC cables entangled on the body, separate at control box

Figure 27 shows the graph for the phase line measurement. In this graph, the peak values seem to be accumulated around 4-5 MHz. Since the result lines are below the limit lines the test results are positive.

As it is seen from the graph that the intensity about peaks is around 4-5 MHz it is also seen from Table 6 closest value to the limits is 2.74 dB at 4 MHz at

average measurement. Even if this value is in line with international standards, test laboratories generally change the minimum requirement to pass the test to a 3 dB margin by taking into account the deviations between labs and instruments. If we consider this information the result is deemed as a fail.

Normally it is expected better results when the cables are separated because the risk of unintentional coupling over the cables is minimized. In this case, even though the noise levels are lower according to the sample of entangled cables the noise at the 4 MHz level is very close to the international limit. That means the separation of cables is not enough on its own, other parameters should also be checked. Cables that enter the control box from separate points may be touching an undesirable point on the control board. On the other hand, the entanglement of cables may be creating a magnetic field and suppress electromagnetic energy at certain frequencies.

As a result in this case the impact of the separation of the cables at the control box was not good.

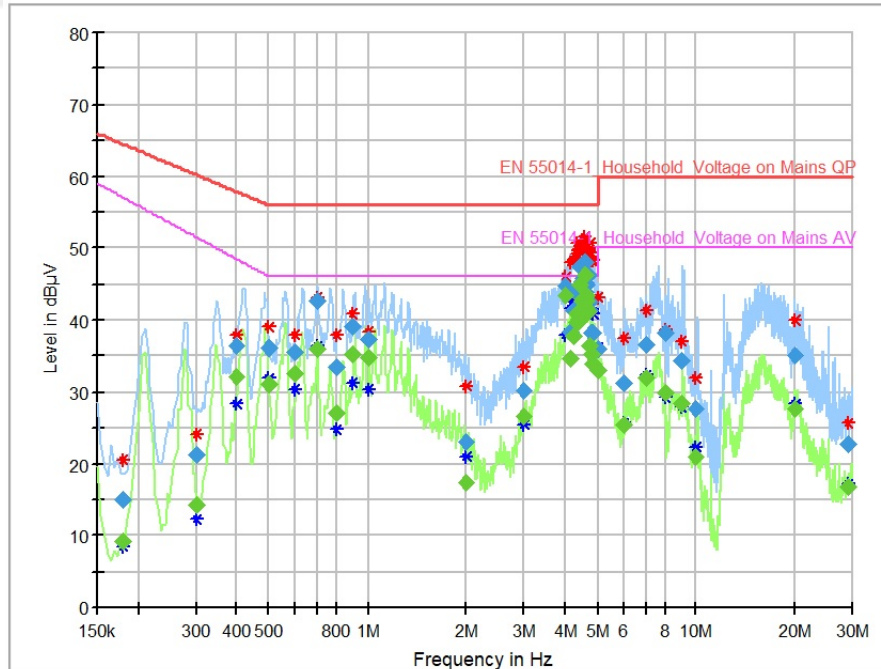


Figure 27: AC & DC cables are separate at control box - Phase line measurement graph

Table 6: AC & DC cables are separate at control box - Phase line test results

<i>Frequency (MHz)</i>	<i>QuasiPeak (dBV)</i>	<i>Average (dBV)</i>	<i>Limit (dBV)</i>	<i>Margin (dB)</i>
0.18	—	9.1	57.03	47.93
0.18	15.08	—	64.49	49.41
0.3	—	14.29	51.52	37.23
0.3	21.23	—	60.24	39.01
0.4	—	32.12	48.41	16.29
0.4	36.53	—	57.85	21.32
0.5	—	31.11	46	14.89
0.5	36.13	—	56	19.87
0.6	—	32.72	46	13.28
0.6	35.48	—	56	20.52
0.7	—	36.08	46	9.92
0.7	42.73	—	56	13.27
0.8	—	27.01	46	18.99
0.8	33.62	—	56	22.38
0.9	—	35.4	46	10.6
0.9	39.14	—	56	16.86
1	—	34.75	46	11.25
1	37.43	—	56	18.57
2	—	17.53	46	28.47
2	22.91	—	56	33.09
3	—	26.69	46	19.31
3	30.14	—	56	25.86
4	—	43.26	46	2.74
4	44.66	—	56	11.34
5	—	33.15	46	12.85
5	35.93	—	56	20.07
6	—	25.53	50	24.47
6	31.29	—	60	28.71
7	—	31.96	50	18.04
7	36.72	—	60	23.28
8	—	29.88	50	20.12
8	38.27	—	60	21.73
9	—	28.43	50	21.57
9	34.43	—	60	25.57
10	—	21.11	50	28.89
10	27.74	—	60	32.26
20	—	27.79	50	22.21
20	35.07	—	60	24.93
29	—	16.7	50	33.3
29	22.7	—	60	37.3

According to Figure 28 which shows the graph for the neutral line measurement of the sample which AC-DC cables are aligned entangled on the body and separated before entering the control box the peak values seem to be over the international limits at two different frequency levels, 4-5 MHz and 8 MHz.

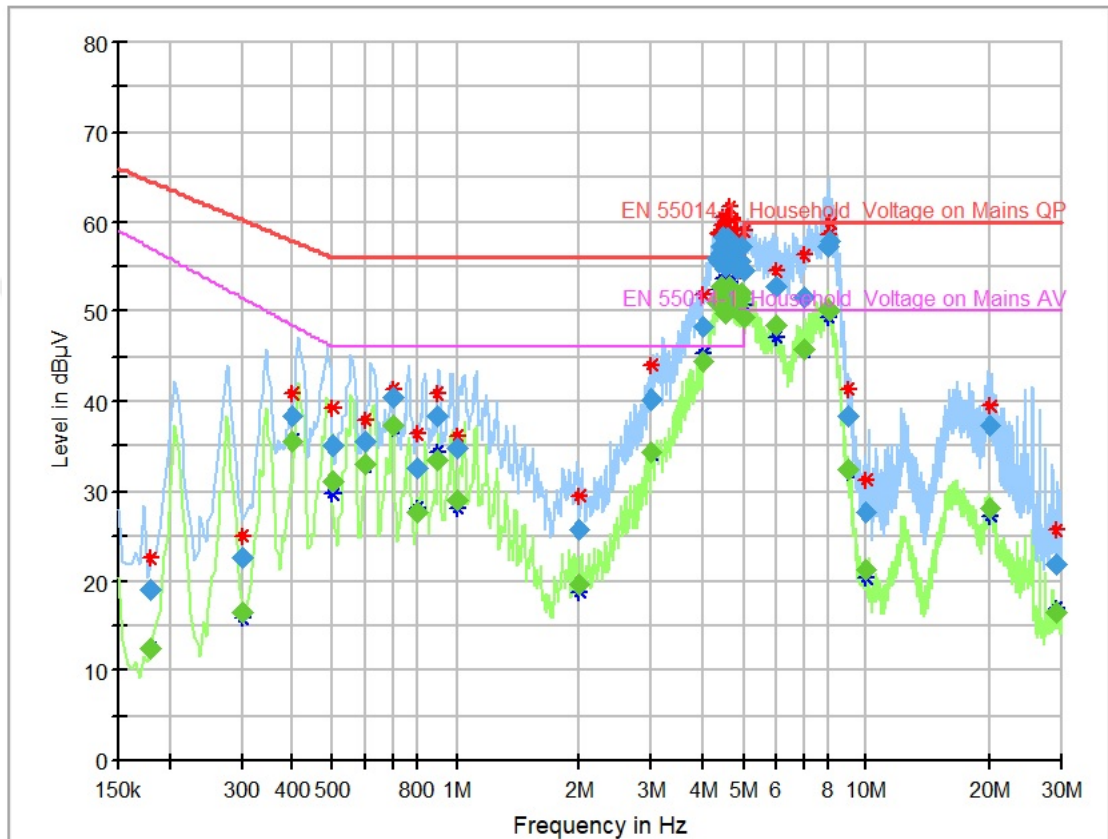


Figure 28: AC & DC cables are separate at control box - Neutral line measurement graph

According to Table 7, there are two points where the margins are below zero. The product fails from the international standard at neutral line measurement because of -3.38 dB at 5MHz and -0.17 dB at 8 MHz at average values. Similar to the phase line measurement, separation of the cables generated more EMI at certain frequencies and caused the product to fail the test.

Table 7: AC & DC cables are separate at control box - Neutral line test results

<i>Frequency (MHz)</i>	<i>QuasiPeak (dBV)</i>	<i>Average (dBV)</i>	<i>Limit (dBV)</i>	<i>Margin (dB)</i>
0.18	—	12.46	57.03	44.57
0.18	19.08	—	64.49	45.41
0.3	—	16.51	51.52	35.01
0.3	22.63	—	60.24	37.61
0.4	—	35.48	48.41	12.93
0.4	38.5	—	57.85	19.35
0.5	—	30.98	46	15.02
0.5	35.04	—	56	20.96
0.6	—	33.02	46	12.98
0.6	35.63	—	56	20.37
0.7	—	37.41	46	8.59
0.7	40.46	—	56	15.54
0.8	—	27.61	46	18.39
0.8	32.7	—	56	23.3
0.9	—	33.59	46	12.41
0.9	38.47	—	56	17.53
1	—	28.99	46	17.01
1	34.94	—	56	21.06
2	—	19.66	46	26.34
2	25.66	—	56	30.34
3	—	34.33	46	11.67
3	40.33	—	56	15.67
4	—	44.48	46	1.52
4	48.37	—	56	7.63
5	—	49.38	46	-3.38
5	54.5	—	56	1.5
6	—	48.44	50	1.56
6	52.8	—	60	7.2
7	—	45.91	50	4.09
7	51.61	—	60	8.39
8	—	50.17	50	-0.17
8	57.15	—	60	2.85
9	—	32.39	50	17.61
9	38.45	—	60	21.55
10	—	21.15	50	28.85
10	27.67	—	60	32.33
20	—	28.25	50	21.75
20	37.29	—	60	22.71
29	—	16.51	50	33.49
29	21.96	—	60	38.04

4.1.3 Separated AC-DC Cables Along the Whole Path

The route of the cables is shown in Figure 29. AC and DC cables are planned to be separated on the refrigerator body and inside the control box. As it can be seen from the red and blue arrows AC cables are aligned on the right side and DC cables are aligned on the left side of the refrigerator body plastic at the upper portion. However, due to the assembly, AC and DC cables are still close to each other at the below part of the product. AC and DC cables enter the control box from two separate holes which are in opposite directions.

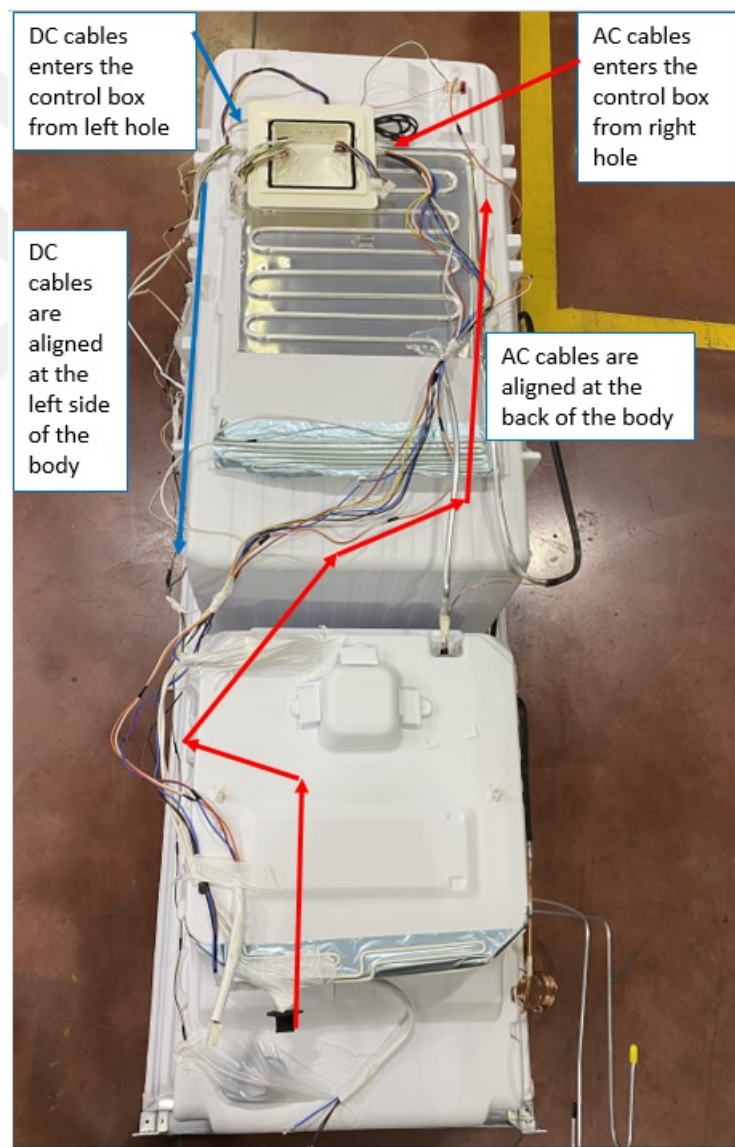


Figure 29: AC & DC cables are completely separated

Figure 30 shows the graph for the phase line measurement. It can be seen from the figure that blue and green lines are below the red and pink lines respectively. The peak point is around 8-10 MHz however it is far from the limit. The refrigerator with completely separated cable alignment complies with the international limits.

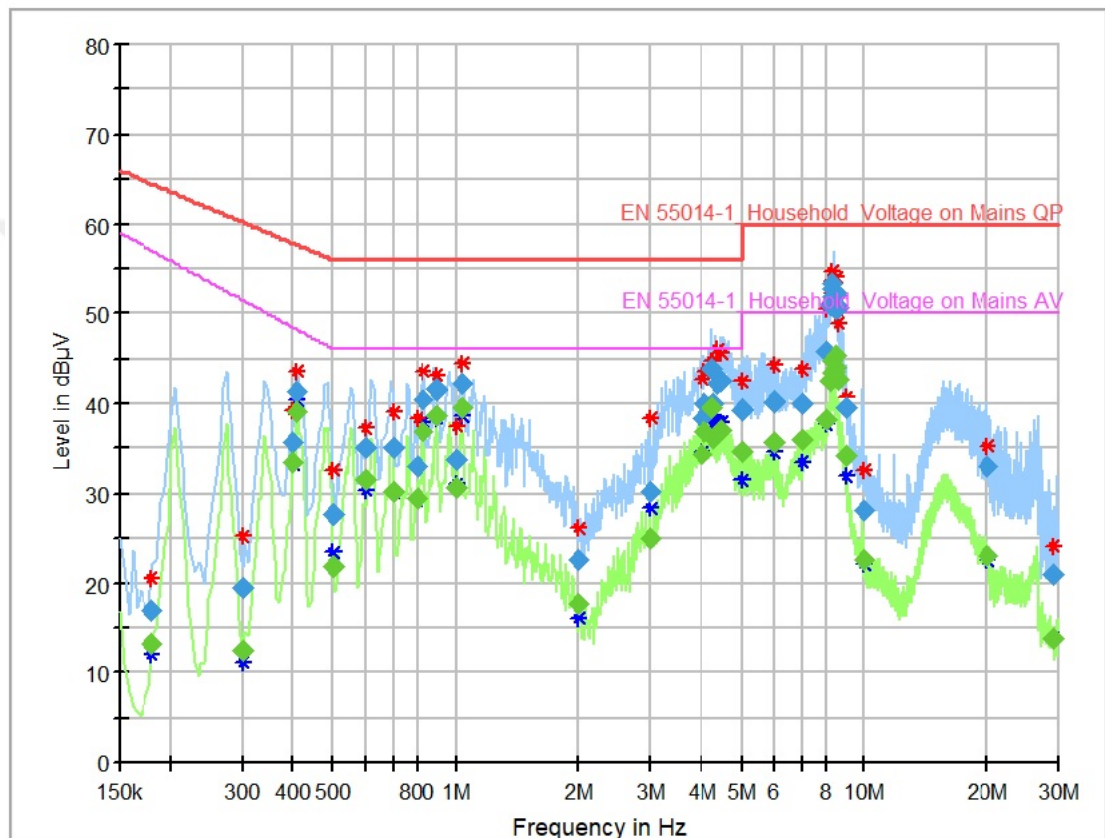


Figure 30: AC & DC cables are completely separated - Phase line measurement graph

When the frequencies between 5-10 MHz are checked from Table 8 it is seen that the noise values are worse than the noise values of the refrigerator sample with entangled cables, however, the noise values at these frequencies are far from the limits and this is the graph that shows the best overall result among the samples. When checked from the table the closest value to the limits is 7.29 dB at 0.9 MHz at average measurement.

Table 8: AC & DC cables are completely separated - Phase line measurement results

<i>Frequency (MHz)</i>	<i>QuasiPeak (dBV)</i>	<i>Average (dBV)</i>	<i>Limit (dBV)</i>	<i>Margin (dB)</i>
0.18	—	13.12	57.03	43.91
0.18	17.09	—	64.49	47.4
0.3	—	12.41	51.52	39.11
0.3	19.55	—	60.24	40.69
0.4	—	33.47	48.41	14.94
0.4	35.69	—	57.85	22.16
0.5	—	21.81	46	24.19
0.5	27.61	—	56	28.39
0.6	—	31.52	46	14.48
0.6	35.1	—	56	20.9
0.7	—	30.12	46	15.88
0.7	35.12	—	56	20.88
0.8	—	29.51	46	16.49
0.8	33.02	—	56	22.98
0.9	—	38.71	46	7.29
0.9	41.49	—	56	14.51
1	—	30.58	46	15.42
1	33.76	—	56	22.24
2	—	17.55	46	28.45
2	22.48	—	56	33.52
3	—	24.97	46	21.03
3	30.19	—	56	25.81
4	—	34.37	46	11.63
4	38.34	—	56	17.66
5	—	34.67	46	11.33
5	39.34	—	56	16.66
6	—	35.83	50	14.17
6	40.3	—	60	19.7
7	—	36.01	50	13.99
7	40.06	—	60	19.94
8	—	38.12	50	11.88
8	45.89	—	60	14.11
9	—	34.12	50	15.88
9	39.61	—	60	20.39
10	—	22.48	50	27.52
10	28.22	—	60	31.78
20	—	22.97	50	27.03
20	33.06	—	60	26.94
29	—	13.93	50	36.07
29	21.06	—	60	38.94

The neutral line measurement graph is shown in Figure 31. Results are under the limit lines. The peak points are around 4-5 MHz and 8-10 MHz. The product complies with international standards. The exact values can be checked from Table 9.

When we compare the exact noise values of neutral line measurements between 3 refrigerators with different cable alignments the refrigerator with totally separated cables is better than the others. As it can be checked from Table 9 The closest value to the limits is 6.09 dB at 5 MHz at average measurement which is even two times farther than the laboratory limits.

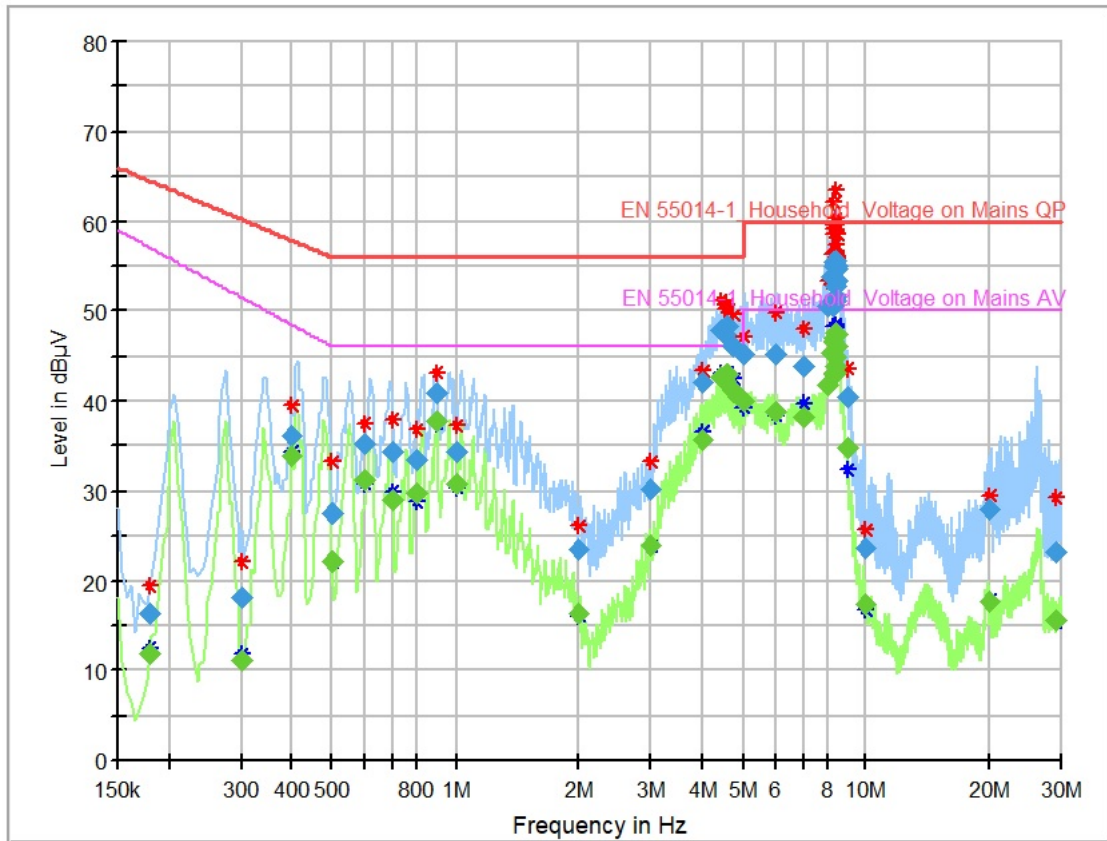


Figure 31: AC & DC cables are completely separated - Neutral line measurement graph

Table 9: AC & DC cables are completely separated - Neutral line measurement results

<i>Frequency (MHz)</i>	<i>QuasiPeak (dBV)</i>	<i>Average (dBV)</i>	<i>Limit (dBV)</i>	<i>Margin (dB)</i>
0.18	—	11.89	57.03	45.14
0.18	16.32	—	64.49	48.17
0.3	—	11.14	51.52	40.38
0.3	18.18	—	60.24	42.06
0.4	—	33.87	48.41	14.54
0.4	36.12	—	57.85	21.73
0.5	—	22.2	46	23.8
0.5	27.4	—	56	28.6
0.6	—	31.25	46	14.75
0.6	35.25	—	56	20.75
0.7	—	28.97	46	17.03
0.7	34.5	—	56	21.5
0.8	—	29.79	46	16.21
0.8	33.48	—	56	22.52
0.9	—	37.84	46	8.16
0.9	40.99	—	56	15.01
1	—	30.88	46	15.12
1	34.5	—	56	21.5
2	—	16.37	46	29.63
2	23.37	—	56	32.63
3	—	23.8	46	22.2
3	30.06	—	56	25.94
4	—	35.7	46	10.3
4	42.11	—	56	13.89
5	—	39.91	46	6.09
5	45.24	—	56	10.76
6	—	38.78	50	11.22
6	45.16	—	60	14.84
7	—	38.16	50	11.84
7	43.72	—	60	16.28
8	—	41.78	50	8.22
8	50.48	—	60	9.52
9	—	34.87	50	15.13
9	40.35	—	60	19.65
10	—	17.37	50	32.63
10	23.66	—	60	36.34
20	—	17.65	50	32.35
20	27.83	—	60	32.17
29	—	15.74	50	34.26
29	23.19	—	60	36.81

4.1.4 Comparison Of the Results

To compare the results of the experiments better, the results obtained from the tests with 3 different cable distributions are combined in Table 10 for phase line measurements and Table 11 for neutral line measurements. Among the abbreviations in the tables, FS represents the results of the product with completely separate cables, FE represents the results of the product with completely entangled cables, and SS represents the results of the product with cables entangled along the body but separated before entering the control box. This cable structure can be called semi-separated. The table contains the margin values therefore the larger the value, the better the result. It is seen that the complete separation of the AC-DC cables works at many frequencies, especially below 5 MHz and above 10 MHz, and improves the noise values by 1-3 dB, compared to the example where the AC-DC cables are fully entangled. The refrigerator where the AC-DC cables are completely entangled gave better results in the 5-9 MHz frequency range. Although the refrigerator with semi-separate cables gave better results at some frequencies than the other two samples, it gave measurements that failed from the test in the 5-9 MHz frequency region, whereas the fully entangled product gave good results. According to international standards, it can be said that this method is a worse option than the other two examples. It can be thought that the cables entangled in the control board box provide an improvement in the frequency range of 5-9 MHz. The value of 6.48 dB at 0.9 MHz and 6.9 dB at 4 MHz at average measurements are the worst margin values measured in the tests of the product with entangled cable, which is determined as the reference product. At this point, the full separation of the AC-DC cables improved the results by 1.5-3 dB, while the semi-separated cable improved the value at 0.9 MHz, worsened the result at 5 MHz, and even failed the test.

Since the impact of electromagnetic energy attenuates with distance and the risk of unintentional coupling between the cables would have been minimized, better results are expected when AC and DC cables are more separated from

Table 10: Comparison of the tests - Phase line measurement results

	<i>FS</i>	<i>FE</i>	<i>SS</i>
<i>Frequency</i> (<i>MHz</i>)	<i>Margin</i> (<i>dB</i>)	<i>Margin</i> (<i>dB</i>)	<i>Margin</i> (<i>dB</i>)
0.18	43.91	40.69	47.93
0.18	47.4	42.64	49.41
0.3	39.11	31.11	37.23
0.3	40.69	31.94	39.01
0.4	14.94	11.39	16.29
0.4	22.16	16.68	21.32
0.5	24.19	13.44	14.89
0.5	28.39	19.44	19.87
0.6	14.48	12.82	13.28
0.6	20.9	19.16	20.52
0.7	15.88	9.06	9.92
0.7	20.88	11.08	13.27
0.8	16.49	14.66	18.99
0.8	22.98	19.57	22.38
0.9	7.29	6.48	10.6
0.9	14.51	10.59	16.86
1	15.42	10.43	11.25
1	22.24	15.08	18.57
2	28.45	15.26	28.47
2	33.52	19.41	33.09
3	21.03	15.95	19.31
3	25.81	21.59	25.86
4	11.63	6.9	2.74
4	17.66	12.93	11.34
5	11.33	16.15	12.85
5	16.66	20.67	20.07
6	14.17	21.22	24.47
6	19.7	23.8	28.71
7	13.99	20.49	18.04
7	19.94	24.2	23.28
8	11.88	14.6	20.12
8	14.11	17.15	21.73
9	15.88	18.47	21.57
9	20.39	22.22	25.57
10	27.52	30.4	28.89
10	31.78	35.21	32.26
20	27.03	19.55	22.21
20	26.94	23.03	24.93
29	36.07	25.07	33.3
29	38.94	28.84	37.3

Table 11: Comparison of the tests - Neutral line measurement results

	<i>FS</i>	<i>FE</i>	<i>SS</i>
<i>Frequency</i> (<i>MHz</i>)	<i>Margin</i> (<i>dB</i>)	<i>Margin</i> (<i>dB</i>)	<i>Margin</i> (<i>dB</i>)
0.18	45.14	52.09	44.57
0.18	48.17	46.46	45.41
0.3	40.38	38.05	35.01
0.3	42.06	40.15	37.61
0.4	14.54	12.28	12.93
0.4	21.73	18.07	19.35
0.5	23.8	14.93	15.02
0.5	28.6	21.23	20.96
0.6	14.75	12.12	12.98
0.6	20.75	19.6	20.37
0.7	17.03	8.95	8.59
0.7	21.5	11.78	15.54
0.8	16.21	14.65	18.39
0.8	22.52	18.49	23.3
0.9	8.16	5.32	12.41
0.9	15.01	10.23	17.53
1	15.12	10.72	17.01
1	21.5	15.47	21.06
2	29.63	17.72	26.34
2	32.63	21.92	30.34
3	22.2	20.3	11.67
3	25.94	24.08	15.67
4	10.3	8.75	1.52
4	13.89	14.16	7.63
5	6.09	4.87	-3.38
5	10.76	10.07	1.5
6	11.22	13.36	1.56
6	14.84	16.6	7.2
7	11.84	13.85	4.09
7	16.28	17.81	8.39
8	8.22	11.35	-0.17
8	9.52	15.2	2.85
9	15.13	25.97	17.61
9	19.65	29.65	21.55
10	32.63	28.14	28.85
10	36.34	31.42	32.33
20	32.35	29.56	21.75
20	32.17	32.68	22.71
29	34.26	24.78	33.49
29	36.81	28.54	38.04

each other. However, the product with semi-separated cables gave worse results according to the product with fully entangled cables. Since the impact of the production personnel on the placement of the cables cannot be eliminated cables that enter the control box from separate points may be touching an undesirable point on the control board in particular to this product with semi-separated cables. On the other hand, twisting a pair of cables can sometimes be a solution. If signals experience relatively the same interference then the interference will be negated. The twisting of cables may be creating a magnetic field and suppress electromagnetic energy at certain frequencies on the product with fully entangled cables.

4.2 The Impact of Ferrite Filters

Ferrite core and amorphous core used in the tests are shown in Figure 32. The first black one is a conventional crystalline ferrite core. The remaining images represent the amorphous cut core and its paper-like structure. Soft ferrite, which has low coercivity and thus easily magnetizes and demagnetizes, is used as the ferrite core. Its material is nickel-zinc. It has an outer diameter of 31 mm, an inner diameter of 19 mm, and a thickness of 16 mm. Amorphous metals are produced using rapid solidification technology, in which the molten metal is cooled at an extraordinarily rapid rate and poured into thin solid strips. It is in the form of amorphous ferrite sheets and is placed in plastic housing. Most metals are crystalline in the solid state, that is, their atomic structures are highly ordered. Amorphous metals are not crystalline and have a glass-like structure. It has good electrical conductivity, unlike typical glass structures. Amorphous metal is usually an alloy rather than a pure metal. An amorphous ferrite with an outer diameter of 26 mm, an inner diameter of 10 mm, and a thickness of 16 mm was used.

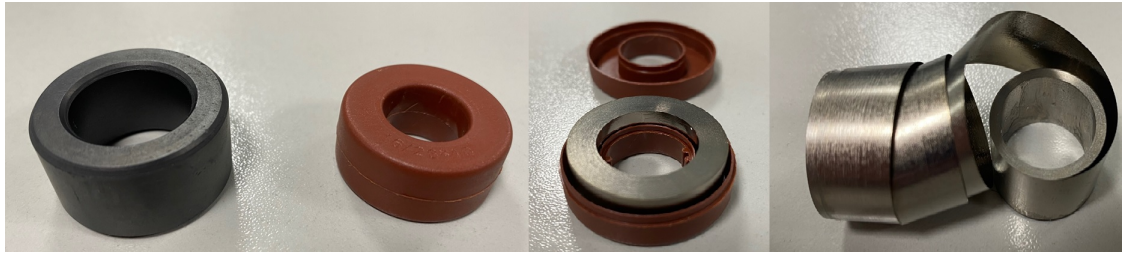


Figure 32: Ferrite core and amorphous core

Tests were carried out by positioning the ferrite core and amorphous core on different cables on the product where AC and DC cables aligned entangled inside the refrigerator and control box. Two types of ferrite filters were used; ferrite core and amorphous core. AC and DC cables inside the control box were wound in these cores for 2 rounds and their impact on the conducted emission test was examined. Conducted emission tests for frequencies between 150 kHz and 30 MHz have been performed for both phase and neutral lines. The tests were carried out in the following ways:

- Ferrite core on AC cables
- Amorphous core on AC cables
- Ferrite core on DC cables
- Amorphous core on DC cables

4.2.1 Ferrite Core on AC Cables

Figure 33 shows the position of the ferrite core. The cables coming from the refrigerator body come out from a single point in the control box housing and are connected to the control board. The control board is located on the cover. In the control box, the cable group containing the phase, neutral, and compressor cables was passed through the middle of the ferrite core and wrapped around it for 2 turns. No filtering was applied to the other cables.

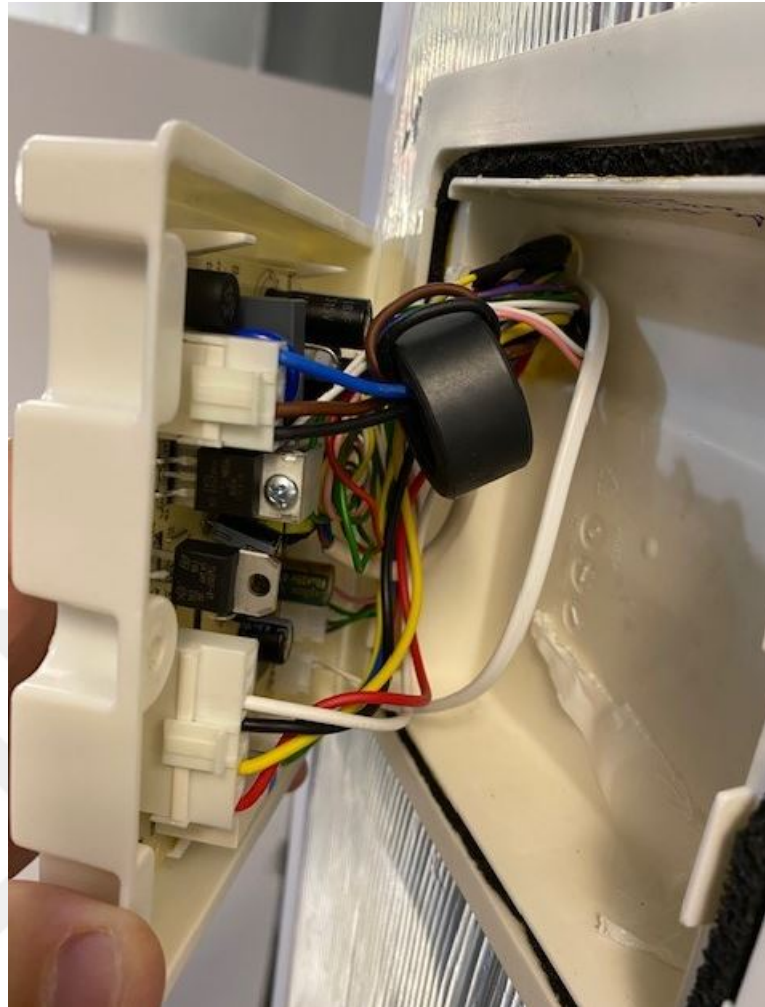


Figure 33: Ferrite core on AC cables

Figure 34 shows the phase line measurement graph of the sample in which the ferrite core is located on AC cables. As can be seen from the graph, the test result is a pass according to the international standards. Blue and green graphs are far below the red and pink limit lines. The ferrite core, in which AC cables are wrapped 2 turns, improved the results so much that even the quasi-peak graph remained below the average limit line. The highest point in the graph seems to be around 1 MHz and the exact value can be checked in Table 12.

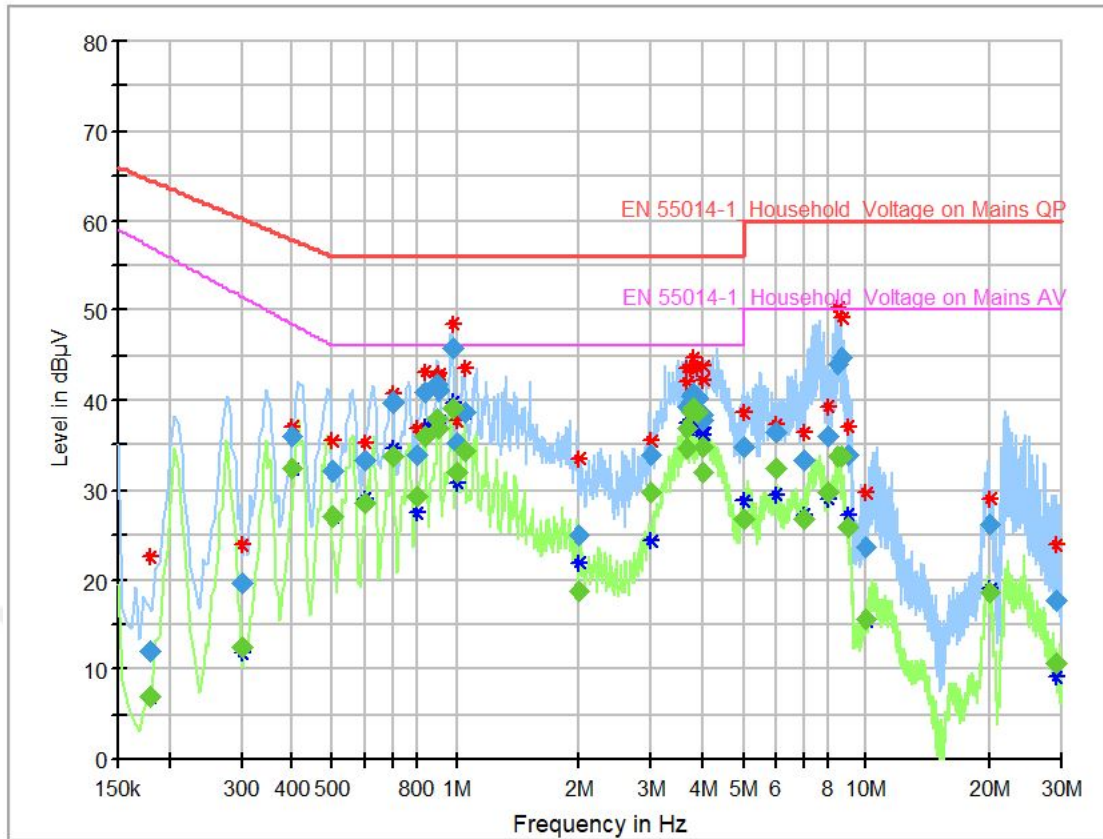


Figure 34: Ferrite core on AC cables - Phase line measurement graph

Table 12 shows the exact values of the phase line measurements on specific frequencies for the sample in which the ferrite core is located on AC cables. All the margin values are far from the limits for all frequencies and the test result is a clear pass according to international standards. When it is checked from the table the closest value to the limits is 8.11 dB at 0.9 MHz at average measurement and 14.28 dB at 0.9 MHz at quasi-peak measurement. When the test results of the product with a ferrite filter and the product without a ferrite filter are compared, it is seen that the product with a ferrite filter gives better results at almost every frequency. The worst point on the noise measurements of the sample without a ferrite filter is 6.49 dB at 0.9 MHz at average measurement. Therefore the addition of ferrite core improved the worst point around 1.5 dB. The improvement in other frequencies is up to 14 dB.

Table 12: Ferrite core on AC cables - Phase line measurement results

<i>Frequency</i> (MHz)	<i>QuasiPeak</i> (dBV)	<i>Average</i> (dBV)	<i>Limit</i> (dBV)	<i>Margin</i> (dB)
0.18	—	11.89	57.03	45.14
0.18	16.32	—	64.49	48.17
0.18	—	7.02	57.03	50.01
0.18	12.11	—	64.49	52.38
0.3	—	12.48	51.52	39.04
0.3	19.58	—	60.24	40.66
0.4	—	32.36	48.41	16.05
0.4	36.03	—	57.85	21.82
0.5	—	27.05	46	18.95
0.5	32.24	—	56	23.76
0.6	—	28.7	46	17.3
0.6	33.35	—	56	22.65
0.7	—	33.66	46	12.34
0.7	39.72	—	56	16.28
0.8	—	29.38	46	16.62
0.8	34	—	56	22
0.9	—	37.89	46	8.11
0.9	41.72	—	56	14.28
1	—	31.86	46	14.14
1	35.31	—	56	20.69
2	—	18.75	46	27.25
2	24.94	—	56	31.06
3	—	29.61	46	16.39
3	33.96	—	56	22.04
4	—	34.8	46	11.2
4	38.37	—	56	17.63
5	—	26.8	46	19.2
5	34.8	—	56	21.2
6	—	32.35	50	17.65
6	36.45	—	60	23.55
7	—	26.88	50	23.12
7	33.36	—	60	26.64
8	—	29.73	50	20.27
8	36.04	—	60	23.96
9	—	25.85	50	24.15
9	33.94	—	60	26.06
10	—	15.67	50	34.33
10	23.69	—	60	36.31
20	—	18.46	50	31.54
20	26.16	—	60	33.84
29	—	10.81	50	39.19
29	17.57	—	60	42.43

Figure 35 shows the neutral line measurement graph. The neutral line measurement graph is very similar to the phase line measurement graph. As can be seen from the graph, the test result is a pass according to the international standards. Again, the blue and green measurement lines are far below the red and pink limit lines.

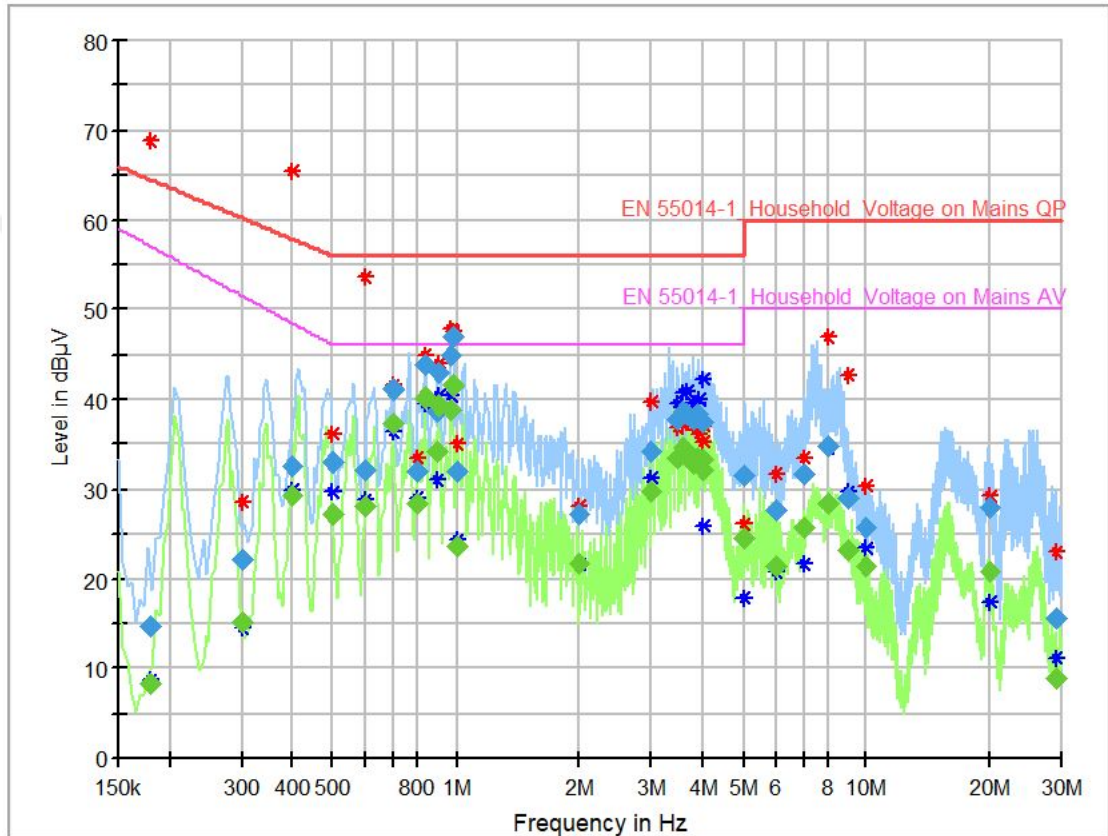


Figure 35: Ferrite core on AC cables - Neutral line measurement graph

Table 13 shows the exact values of the neutral line measurements on specific frequencies. All the margin values are far from the limits. When checked from the table the closest value to the limits is 8.72 dB at 0.7 MHz at average measurement. The test results are better in most of the frequencies when compared with the sample without ferrite filter.

Table 13: Ferrite core on AC cables - Neutral line measurement results

<i>Frequency</i> (MHz)	<i>QuasiPeak</i> (dBV)	<i>Average</i> (dBV)	<i>Limit</i> (dBV)	<i>Margin</i> (dB)
0.18	—	8.36	57.03	48.67
0.18	14.78	—	64.49	49.71
0.3	—	15.15	51.52	36.37
0.3	22.13	—	60.24	38.11
0.4	—	29.17	48.41	19.24
0.4	32.71	—	57.85	25.14
0.5	—	27.17	46	18.83
0.5	33.11	—	56	22.89
0.6	—	28.16	46	17.84
0.6	32.15	—	56	23.85
0.7	—	37.28	46	8.72
0.7	41.13	—	56	14.87
0.8	—	28.41	46	17.59
0.8	31.87	—	56	24.13
0.9	—	34.08	46	11.92
0.9	38.62	—	56	17.38
1	—	23.62	46	22.38
1	31.89	—	56	24.11
2	—	21.67	46	24.33
2	27.26	—	56	28.74
3	—	29.73	46	16.27
3	34.28	—	56	21.72
4	—	33.39	46	12.61
4	37.6	—	56	18.4
5	—	24.6	46	21.4
5	31.52	—	56	24.48
6	—	21.52	50	28.48
6	27.62	—	60	32.38
7	—	25.62	50	24.38
7	31.63	—	60	28.37
8	—	28.34	50	21.66
8	34.78	—	60	25.22
9	—	23.33	50	26.67
9	29.1	—	60	30.9
10	—	21.41	50	28.59
10	25.69	—	60	34.31
20	—	20.86	50	29.14
20	27.85	—	60	32.15
29	—	9.05	50	40.95
29	15.58	—	60	44.42

4.2.2 Amorphous Core on AC Cables

The location of the amorphous core is shown in Figure 36. In the control box, the cable group containing the phase, neutral, and compressor cables was passed through the middle of the amorphous core and wrapped around it for 2 turns. No filtering was applied to the other cables.

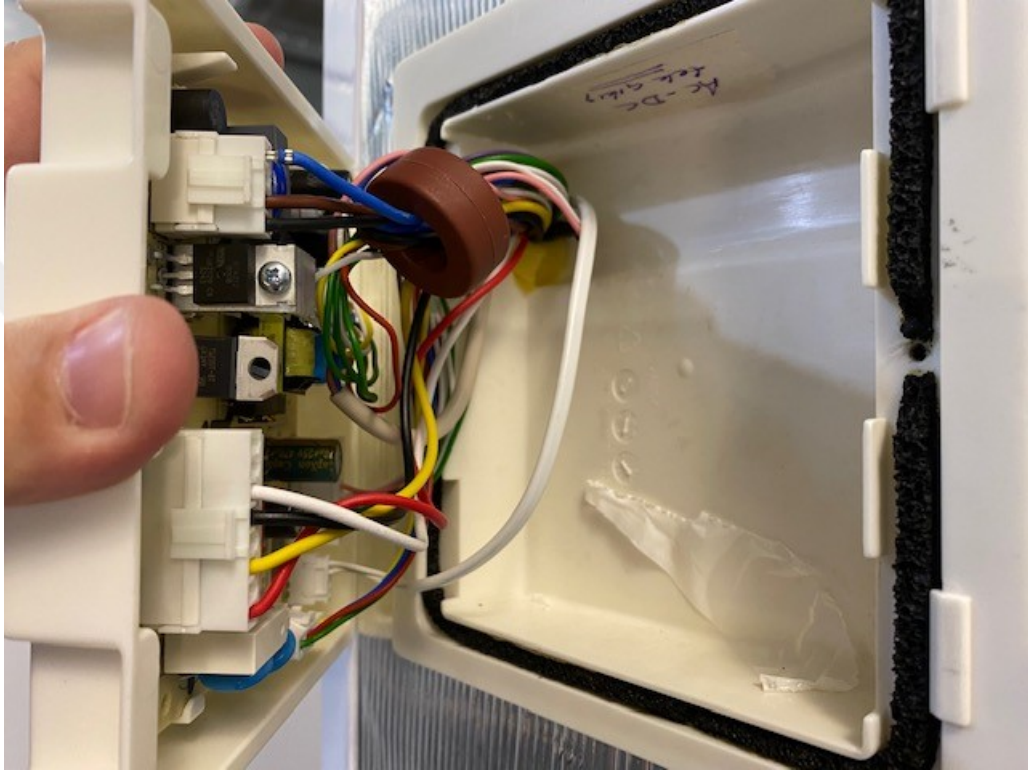


Figure 36: Amorphous core on AC cables

Figure 37 shows the phase line measurement graph of the sample in which the amorphous core is located on AC cables. Blue and green graphs are far below the red and pink limit lines and the product passes the test. It is seen from the graph that filtering the product with an amorphous core improved the noise levels when compared with the unfiltered sample.

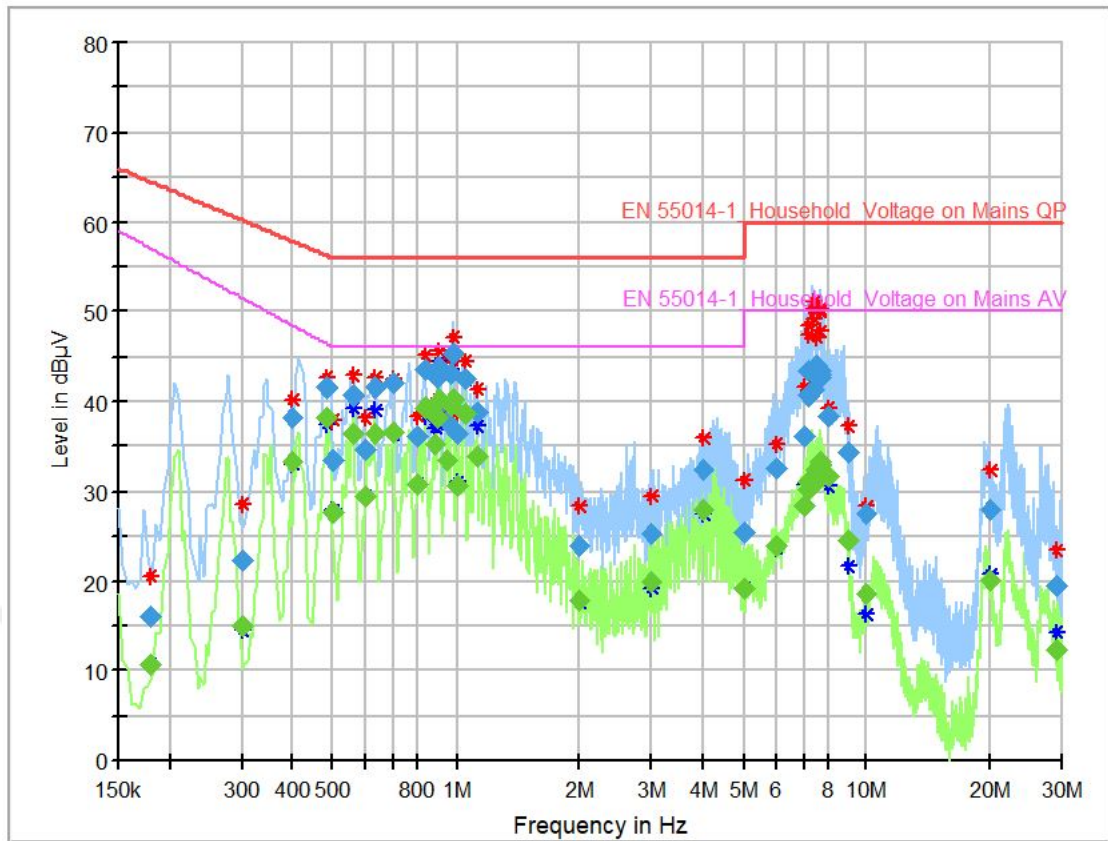


Figure 37: Amorphous core on AC cables - Phase line measurement graph

Table 14 shows the exact values of the phase line measurements on specific frequencies for the sample in which the amorphous core is located on AC cables. It is seen from the table that the noise values are far from the limits. When it is checked from the table the closest value to the limits is 7.77 dB at 0.9 MHz at average measurement. The margin values at other frequencies are above 9 dB. Amorphous core improved the noise levels between 0.5 dB – 12 dB according to the unfiltered product. When the test results of the product with an amorphous core, the product with a ferrite core, and the product without a ferrite filter are compared, it is seen that the product with a ferrite core gives better results at the frequencies between 150 kHz - 1 MHz and 7 MHz – 30 MHz. The product with an amorphous core has the best results between 1 MHz and 7 MHz. The product without filters did not give better noise values than the products with filters at any frequency.

Table 14: Amorphous core on AC cables - Phase line measurement results

<i>Frequency</i> (MHz)	<i>QuasiPeak</i> (dBV)	<i>Average</i> (dBV)	<i>Limit</i> (dBV)	<i>Margin</i> (dB)
0.18	—	10.73	57.03	46.3
0.18	15.98	—	64.49	48.51
0.3	—	15.07	51.52	36.45
0.3	22.32	—	60.24	37.92
0.4	—	33.36	48.41	15.05
0.4	38.12	—	57.85	19.73
0.5	—	27.82	46	18.18
0.5	33.41	—	56	22.59
0.6	—	29.42	46	16.58
0.6	34.62	—	56	21.38
0.7	—	36.61	46	9.39
0.7	41.95	—	56	14.05
0.8	—	30.78	46	15.22
0.8	36.17	—	56	19.83
0.9	—	38.23	46	7.77
0.9	42.79	—	56	13.21
1	—	30.51	46	15.49
1	36.42	—	56	19.58
2	—	17.89	46	28.11
2	23.99	—	56	32.01
3	—	19.88	46	26.12
3	25.2	—	56	30.8
4	—	27.89	46	18.11
4	32.32	—	56	23.68
5	—	19.15	46	26.85
5	25.44	—	56	30.56
6	—	23.91	50	26.09
6	32.52	—	60	27.48
7	—	28.4	50	21.6
7	36.21	—	60	23.79
8	—	31.75	50	18.25
8	38.48	—	60	21.52
9	—	24.69	50	25.31
9	34.45	—	60	25.55
10	—	18.56	50	31.44
10	27.46	—	60	32.54
20	—	20.17	50	29.83
20	27.92	—	60	32.08
29	—	12.29	50	37.71
29	19.4	—	60	40.6

Figure 38 shows the neutral line measurement graph. As the peak points are observed from the graph, the test result is a pass according to the international standards. The blue and green measurement lines are far below the red and pink limit lines.

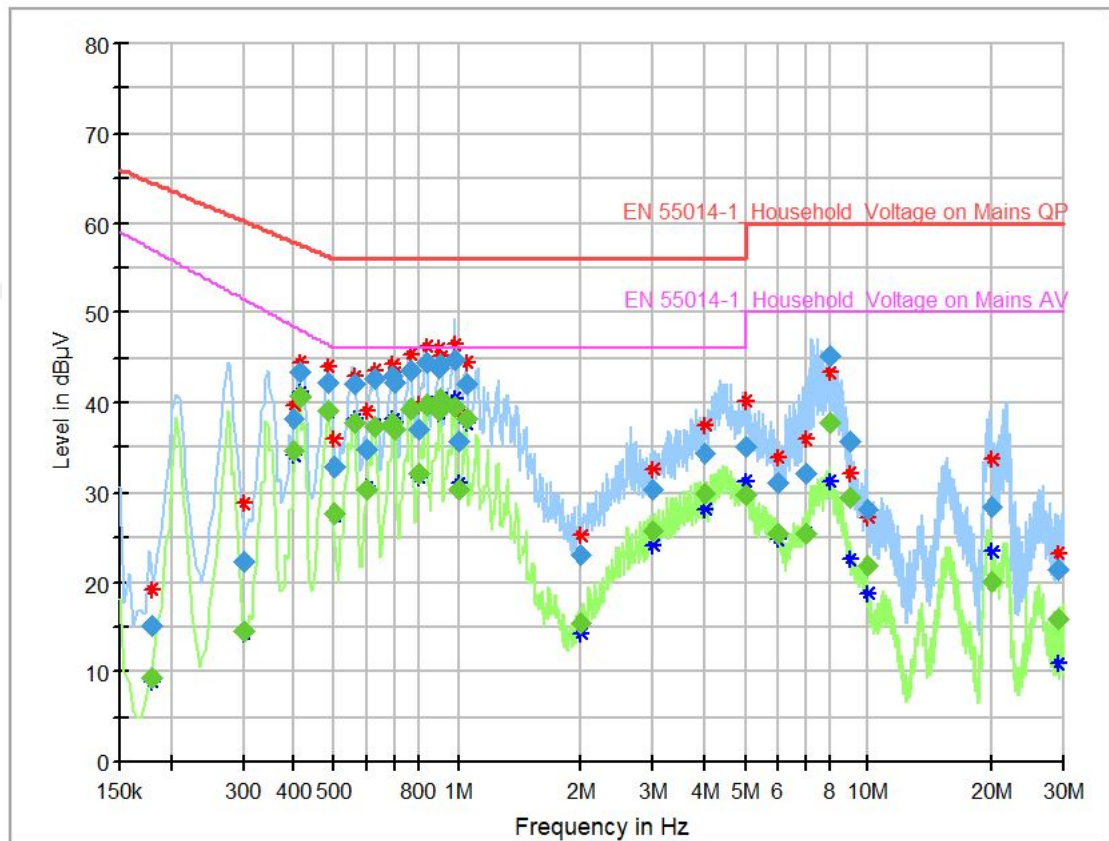


Figure 38: Amorphous core on AC cables - Neutral line measurement graph

Table 15 shows the exact values of the neutral line measurements on specific frequencies. When the noise values are checked from the table the closest value to the limits is 6.79 dB at 0.9 MHz at average measurement. The noise levels at the rest of the frequencies are better. When compared with the neutral line measurements of the product without a ferrite filter, the amorphous core improved the noise levels between 1 MHz and 7 MHz however there is not a significant difference at the rest of the frequencies.

Table 15: Amorphous core on AC cables - Neutral line measurement results

<i>Frequency</i> (MHz)	<i>QuasiPeak</i> (dBV)	<i>Average</i> (dBV)	<i>Limit</i> (dBV)	<i>Margin</i> (dB)
0.18	—	9.36	57.03	47.67
0.18	15.15	—	64.49	49.34
0.3	—	14.6	51.52	36.92
0.3	22.32	—	60.24	37.92
0.4	—	34.73	48.41	13.68
0.4	38.2	—	57.85	19.65
0.5	—	27.66	46	18.34
0.5	32.93	—	56	23.07
0.6	—	30.4	46	15.6
0.6	34.79	—	56	21.21
0.7	—	37.11	46	8.89
0.7	42.31	—	56	13.69
0.8	—	32.08	46	13.92
0.8	37.07	—	56	18.93
0.9	—	39.21	46	6.79
0.9	43.73	—	56	12.27
1	—	30.33	46	15.67
1	35.74	—	56	20.26
2	—	15.38	46	30.62
2	23.02	—	56	32.98
3	—	25.8	46	20.2
3	30.33	—	56	25.67
4	—	30.04	46	15.96
4	34.34	—	56	21.66
5	—	29.68	46	16.32
5	35.13	—	56	20.87
6	—	25.52	50	24.48
6	31.15	—	60	28.85
7	—	25.37	50	24.63
7	32.15	—	60	27.85
8	—	37.76	50	12.24
8	45.22	—	60	14.78
9	—	29.56	50	20.44
9	35.85	—	60	24.15
10	—	22.01	50	27.99
10	28.11	—	60	31.89
20	—	20.05	50	29.95
20	28.37	—	60	31.63
29	—	15.91	50	34.09
29	21.56	—	60	38.44

4.2.3 Ferrite Core on DC Cables

Figure 39 shows the position of the ferrite core on DC carrying cables. Cables are passed through the middle of the ferrite core and wrapped around it for 2 turns. No filtering was applied to the other cables. The filtered cable group includes the receiver and transmitter cables for the communication between the control board and the display board, ground cable, and +12 V supply cable.

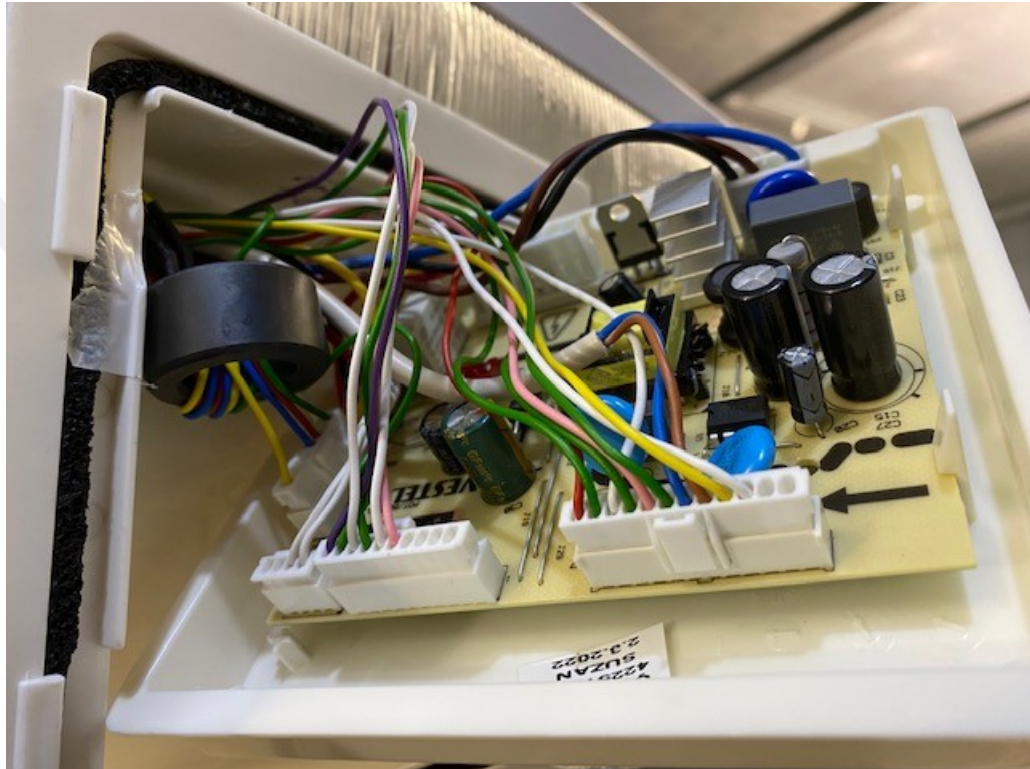


Figure 39: Ferrite core on DC cables

Figure 40 shows the phase line measurement graph of the sample in which the ferrite core is located on DC cables. Blue and green graphs are far below the red and pink limit lines and the product passes the test. The general view of the graph is similar to the phase line measurement graph of the sample in which the ferrite core is located on AC cables.

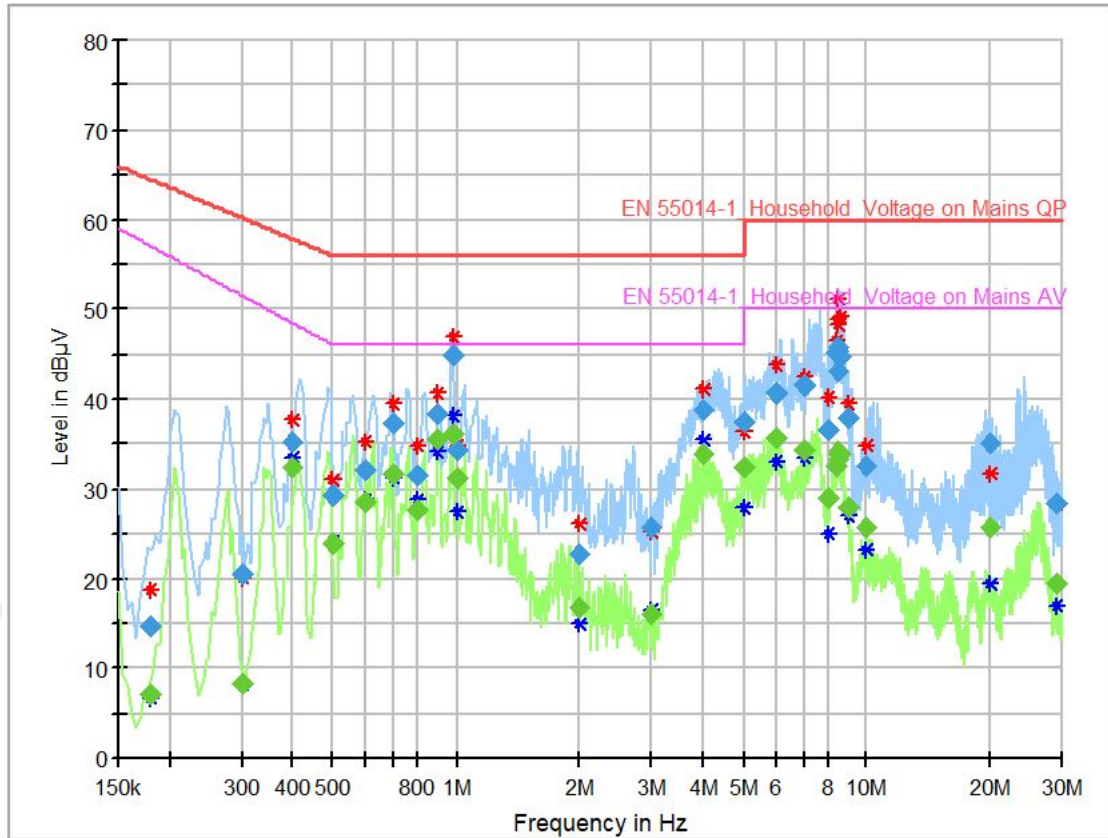


Figure 40: Ferrite core on DC cables - Phase line measurement graph

Table 16 shows the exact noise values of the phase line measurements on specific frequencies for the sample in which the ferrite core is located on DC carrying cables. It is seen from the table that the noise values are below the limits defined by the international standards. When it is checked from the table the closest value to the limits is 10.54 dB at 0.9 MHz at average measurement. The addition of ferrite core on DC cables improved the noise levels minimum of 4dB below 5 MHz frequency according to the noise levels of the unfiltered product. Above 5 MHz unfiltered product gave better results at some of the frequencies. When the test results are compared with the results of the product with ferrite core on AC cables, they are close to each other below 5 MHz, however, the addition of ferrite core on AC cables gave better results above 5 MHz frequency. When compared with the results of the product with an amorphous core on AC cables, the results are better below 4 MHz and worse above 4 MHz.

Table 16: Ferrite core on DC cables - Phase line measurement results

<i>Frequency</i> (MHz)	<i>QuasiPeak</i> (dBV)	<i>Average</i> (dBV)	<i>Limit</i> (dBV)	<i>Margin</i> (dB)
0.18	—	7.11	57.03	49.92
0.18	14.82	—	64.49	49.67
0.3	—	8.26	51.52	43.26
0.3	20.52	—	60.24	39.72
0.4	—	32.3	48.41	16.11
0.4	35.31	—	57.85	22.54
0.5	—	23.83	46	22.17
0.5	29.33	—	56	26.67
0.6	—	28.64	46	17.36
0.6	32.21	—	56	23.79
0.7	—	31.77	46	14.23
0.7	37.32	—	56	18.68
0.8	—	27.78	46	18.22
0.8	31.5	—	56	24.5
0.9	—	35.46	46	10.54
0.9	38.43	—	56	17.57
1	—	31.32	46	14.68
1	34.43	—	56	21.57
2	—	16.7	46	29.3
2	22.71	—	56	33.29
3	—	16.11	46	29.89
3	25.62	—	56	30.38
4	—	33.88	46	12.12
4	38.85	—	56	17.15
5	—	32.5	46	13.5
5	37.61	—	56	18.39
6	—	35.71	50	14.29
6	40.58	—	60	19.42
7	—	34.49	50	15.51
7	41.46	—	60	18.54
8	—	28.99	50	21.01
8	36.72	—	60	23.28
9	—	27.92	50	22.08
9	37.93	—	60	22.07
10	—	25.72	50	24.28
10	32.63	—	60	27.37
20	—	25.73	50	24.27
20	34.99	—	60	25.01
29	—	19.52	50	30.48
29	28.44	—	60	31.56

Figure 41 shows the neutral line measurement graph. Since the plots of the measurements are below the average and quasi-peak limit lines the product passes the according to the international standards.

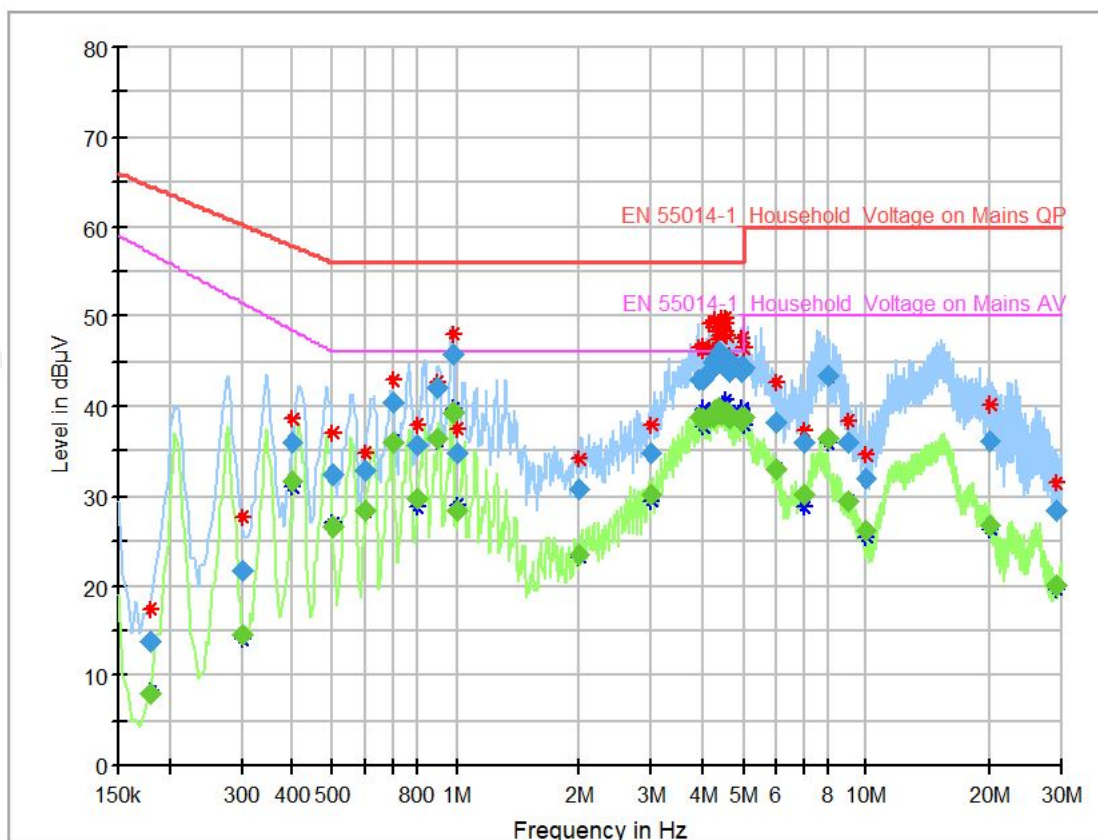


Figure 41: Ferrite core on DC cables - Neutral line measurement graph

Table 17 shows the exact values of the neutral line measurements for the sample in which the ferrite core is located on DC carrying cables. When the noise values are checked from the table the closest value to the limits is 7.12 dB at 5 MHz at average measurement. When compared with the neutral line measurements of the product without a ferrite filter, the ferrite core on the DC cables improved the noise level by around 2.5 dB at 5 MHz which both products have the worst noise value at this frequency.

Table 17: Ferrite core on DC cables - Neutral line measurement results

<i>Frequency</i> (MHz)	<i>QuasiPeak</i> (dBV)	<i>Average</i> (dBV)	<i>Limit</i> (dBV)	<i>Margin</i> (dB)
0.18	—	8.11	57.03	48.92
0.18	13.96	—	64.49	50.53
0.3	—	14.46	51.52	37.06
0.3	21.66	—	60.24	38.58
0.4	—	31.67	48.41	16.74
0.4	35.99	—	57.85	21.86
0.5	—	26.55	46	19.45
0.5	32.37	—	56	23.63
0.6	—	28.41	46	17.59
0.6	32.88	—	56	23.12
0.7	—	35.94	46	10.06
0.7	40.46	—	56	15.54
0.8	—	29.68	46	16.32
0.8	35.67	—	56	20.33
0.9	—	36.47	46	9.53
0.9	41.98	—	56	14.02
1	—	28.41	46	17.59
1	34.84	—	56	21.16
2	—	23.57	46	22.43
2	30.8	—	56	25.2
3	—	30.07	46	15.93
3	34.9	—	56	21.1
4	—	38.36	46	7.64
4	42.83	—	56	13.17
5	—	38.88	46	7.12
5	44.22	—	56	11.78
6	—	33.13	50	16.87
6	38.16	—	60	21.84
7	—	30.09	50	19.91
7	36.02	—	60	23.98
8	—	36.45	50	13.55
8	43.4	—	60	16.6
9	—	29.53	50	20.47
9	35.91	—	60	24.09
10	—	26.23	50	23.77
10	32.05	—	60	27.95
20	—	26.71	50	23.29
20	36.11	—	60	23.89
29	—	20.09	50	29.91
29	28.46	—	60	31.54

4.2.4 Amorphous Core on DC Cables

Figure 42 shows the position of the amorphous core on DC carrying cables. Cables are passed through the middle of the ferrite core and wrapped around it for 2 turns. No filtering was applied to the other cables. The filtered cable group includes the receiver and transmitter cables for the communication between the control board and the display board, ground cable, and +12 V supply cable.



Figure 42: Amorphous core on DC cables

Figure 43 shows the phase line measurement graph of the sample in which the amorphous core is located on DC cables. It can be seen from the graph that filtering the DC cables decreased the overall noise values significantly according to the without filter option.

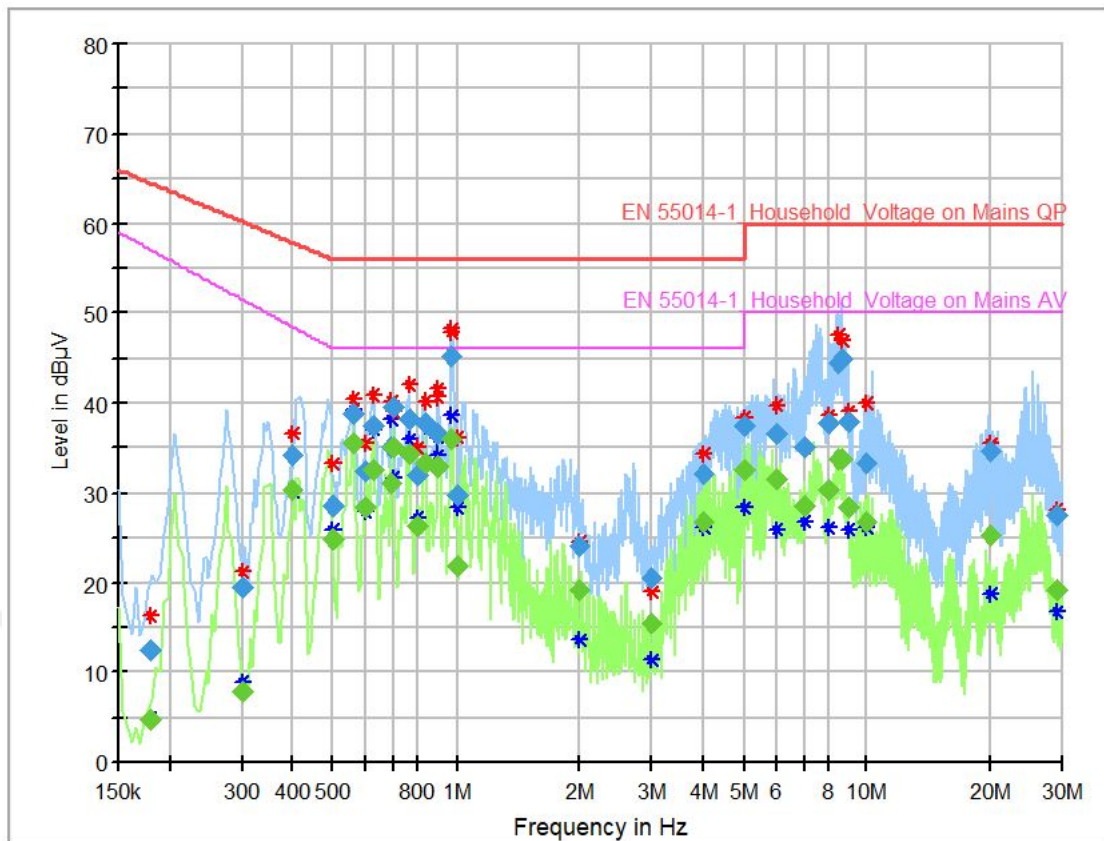


Figure 43: Amorphous core on DC cables - Phase line measurement graph

Table 18 shows the exact noise values of the phase line measurements on specific frequencies for the sample in which the amorphous core is located on DC carrying cables. All the results are far from the limit values and the product passes the test according to the international standards. When it is checked from the table the closest value to the limits is 10.85 dB at 0.7 MHz at average measurement. This value is the highest margin value among the worst noise values obtained in all tests. Amorphous core on DC cables improved the noise values at most of the frequencies according to the product that has no ferrite filter. It even improved the worst noise value of the unfiltered product from 6.9 dB to 19.08 dB at 4 MHz. It is seen from the table that the best overall noise values below 5 MHz are taken from this measurement when compared with other tests performed with ferrite filters. Above 5 MHz using the tests with ferrite filters on AC cables gave better results.

Table 18: Amorphous core on DC cables - Phase line measurement results

<i>Frequency</i> (MHz)	<i>QuasiPeak</i> (dBV)	<i>Average</i> (dBV)	<i>Limit</i> (dBV)	<i>Margin</i> (dB)
0.18	—	4.61	57.03	52.42
0.18	12.41	—	64.49	52.08
0.3	—	7.87	51.52	43.65
0.3	19.53	—	60.24	40.71
0.4	—	30.44	48.41	17.97
0.4	34.21	—	57.85	23.64
0.5	—	24.86	46	21.14
0.5	28.7	—	56	27.3
0.6	—	28.32	46	17.68
0.6	32.32	—	56	23.68
0.7	—	35.15	46	10.85
0.7	39.5	—	56	16.5
0.8	—	26.33	46	19.67
0.8	31.94	—	56	24.06
0.9	—	32.94	46	13.06
0.9	36.66	—	56	19.34
1	—	21.88	46	24.12
1	29.67	—	56	26.33
2	—	19.25	46	26.75
2	24.13	—	56	31.87
3	—	15.31	46	30.69
3	20.62	—	56	35.38
4	—	26.92	46	19.08
4	32.11	—	56	23.89
5	—	32.73	46	13.27
5	37.52	—	56	18.48
6	—	31.43	50	18.57
6	36.68	—	60	23.32
7	—	28.61	50	21.39
7	35.05	—	60	24.95
8	—	30.49	50	19.51
8	37.73	—	60	22.27
9	—	28.33	50	21.67
9	37.93	—	60	22.07
10	—	26.78	50	23.22
10	33.29	—	60	26.71
20	—	25.18	50	24.82
20	34.72	—	60	25.28
29	—	19.18	50	30.82
29	27.56	—	60	32.44

Figure 44 shows the neutral line measurement graph of the sample in which the amorphous core is located on DC cables. Average and quasi-peak measurement graphs are below the average and quasi-peak limit lines therefore the product passes the according to the international standards.

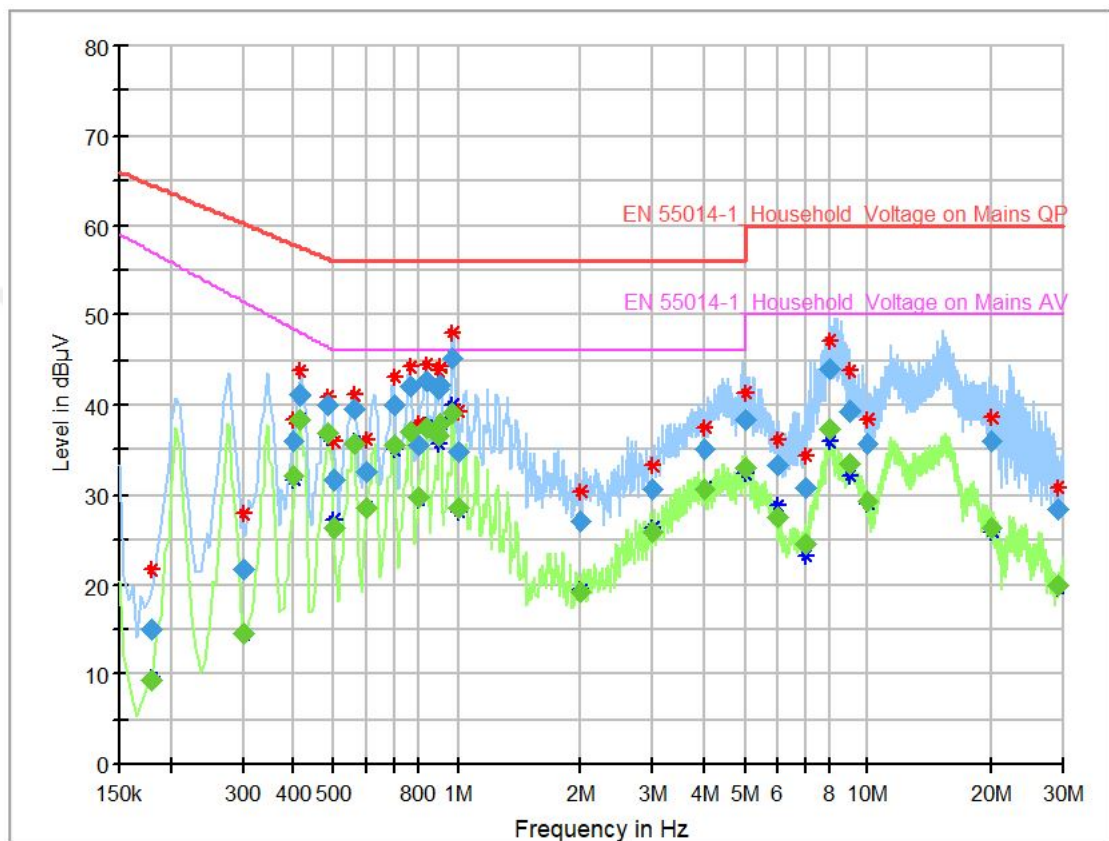


Figure 44: Amorphous core on DC cables - Neutral line measurement graph

Table 19 shows the exact values of the neutral line measurements for the sample in which the amorphous core is located on DC carrying cables. Test results show that the product passes the test. When the noise values are checked from the table the closest value to the limits is 9.34 dB at 0.9 MHz at average measurement. When compared with the neutral line measurements of the product without a ferrite filter, the amorphous core on the DC cables improved the noise level below 9 MHz. When compared with the other products with filters the results of the products with filters on the AC cables are better.

Table 19: Amorphous core on DC cables - Neutral line measurement results

<i>Frequency (MHz)</i>	<i>QuasiPeak (dBV)</i>	<i>Average (dBV)</i>	<i>Limit (dBV)</i>	<i>Margin (dB)</i>
0.18	—	8.11	57.03	48.92
0.18	—	9.38	57.03	47.65
0.18	15.07	—	64.49	49.42
0.3	—	14.48	51.52	37.04
0.3	21.71	—	60.24	38.53
0.4	—	32.09	48.41	16.32
0.4	35.98	—	57.85	21.87
0.5	—	26.31	46	19.69
0.5	31.79	—	56	24.21
0.6	—	28.59	46	17.41
0.6	32.73	—	56	23.27
0.7	—	35.49	46	10.51
0.7	40.05	—	56	15.95
0.8	—	29.76	46	16.24
0.8	35.48	—	56	20.52
0.9	—	36.66	46	9.34
0.9	41.78	—	56	14.22
1	—	28.68	46	17.32
1	34.81	—	56	21.19
2	—	19.16	46	26.84
2	27.08	—	56	28.92
3	—	25.95	46	20.05
3	30.52	—	56	25.48
4	—	30.54	46	15.46
4	35.1	—	56	20.9
5	—	33.08	46	12.92
5	38.45	—	56	17.55
6	—	27.48	50	22.52
6	33.26	—	60	26.74
7	—	24.55	50	25.45
7	30.84	—	60	29.16
8	—	37.39	50	12.61
8	44.07	—	60	15.93
9	—	33.63	50	16.37
9	39.37	—	60	20.63
10	—	29.35	50	20.65
10	35.8	—	60	24.2
20	—	26.41	50	23.59
20	35.91	—	60	24.09
29	—	19.94	50	30.06
29	28.32	—	60	31.68

4.2.5 Comparison of the Results

The results obtained from the tests with different ferrite filters on different cable groups are compiled in Table 20 for phase line measurements and Table 21 for neutral line measurements. Among the abbreviations in the tables, FA represents the results of the product with ferrite core on AC cables, AA represents the results of the product with amorphous core on AC cables, FE represents the results of the product with completely entangled cables, FD represents the results of the product with ferrite core on DC cables, and AD represents the results of the product with amorphous core on DC cables. The table contains the margin values therefore the larger the value, the better the result. When the best margin values are compared it is seen that the use of ferrite filters has a positive effect on the conducted emission tests. Whether the filter used is ferrite or amorphous, the location of the filter is AC or DC cables, the results are better than the product without a ferrite filter. When filters are placed in AC cables, the ferrite core is more effective in the 150 kHz-1 MHz and 7 MHz-30 MHz range, while the amorphous core is more effective in the 1 MHz-7 MHz frequency range. When the filters were placed on DC cables, the amorphous filter provided the best results at almost all frequencies according to the ferrite core. In terms of positioning ferrite filters on AC cables and DC cables, there is no significant difference when the test results are examined. The value of 6.48 dB at 0.9 MHz and 6.9 dB at 4 MHz at average measurements are the worst margin values measured in the tests of the product with entangled cable, which is determined as the reference product. When the results at these frequencies are checked, all the ferrite filter solutions improved the worst noise values of the reference product which has fully entangled cables.

Table 20: Comparison of the tests - Phase line measurement results

	<i>FA</i>	<i>AA</i>	<i>FE</i>	<i>FD</i>	<i>AD</i>
<i>Frequency</i> (<i>MHz</i>)	<i>Margin</i> (<i>dB</i>)	<i>Margin</i> (<i>dB</i>)	<i>Margin</i> (<i>dB</i>)	<i>Margin</i> (<i>dB</i>)	<i>Margin</i> (<i>dB</i>)
0.18	50.01	46.3	40.69	49.92	52.42
0.18	52.38	48.51	42.64	49.67	52.08
0.3	39.04	36.45	31.11	43.26	43.65
0.3	40.66	37.92	31.94	39.72	40.71
0.4	16.05	15.05	11.39	16.11	17.97
0.4	21.82	19.73	16.68	22.54	23.64
0.5	18.95	18.18	13.44	22.17	21.14
0.5	23.76	22.59	19.44	26.67	27.3
0.6	17.3	16.58	12.82	17.36	17.68
0.6	22.65	21.38	19.16	23.79	23.68
0.7	12.34	9.39	9.06	14.23	10.85
0.7	16.28	14.05	11.08	18.68	16.5
0.8	16.62	15.22	14.66	18.22	19.67
0.8	22	19.83	19.57	24.5	24.06
0.9	8.11	7.77	6.48	10.54	13.06
0.9	14.28	13.21	10.59	17.57	19.34
1	14.14	15.49	10.43	14.68	24.12
1	20.69	19.58	15.08	21.57	26.33
2	27.25	28.11	15.26	29.3	26.75
2	31.06	32.01	19.41	33.29	31.87
3	16.39	26.12	15.95	29.89	30.69
3	22.04	30.8	21.59	30.38	35.38
4	11.2	18.11	6.9	12.12	19.08
4	17.63	23.68	12.93	17.15	23.89
5	19.2	26.85	16.15	13.5	13.27
5	21.2	30.56	20.67	18.39	18.48
6	17.65	26.09	21.22	14.29	18.57
6	23.55	27.48	23.8	19.42	23.32
7	23.12	21.6	20.49	15.51	21.39
7	26.64	23.79	24.2	18.54	24.95
8	20.27	18.25	14.6	21.01	19.51
8	23.96	21.52	17.15	23.28	22.27
9	24.15	25.31	18.47	22.08	21.67
9	26.06	25.55	22.22	22.07	22.07
10	34.33	31.44	30.4	24.28	23.22
10	36.31	32.54	35.21	27.37	26.71
20	31.54	29.83	19.55	24.27	24.82
20	33.84	32.08	23.03	25.01	25.28
29	39.19	37.71	25.07	30.48	30.82
29	42.43	40.6	28.84	31.56	32.44

Table 21: Comparison of the tests - Neutral line measurement results

	<i>FA</i>	<i>AA</i>	<i>FE</i>	<i>FD</i>	<i>AD</i>
<i>Frequency</i> (<i>MHz</i>)	<i>Margin</i> (<i>dB</i>)	<i>Margin</i> (<i>dB</i>)	<i>Margin</i> (<i>dB</i>)	<i>Margin</i> (<i>dB</i>)	<i>Margin</i> (<i>dB</i>)
0.18	48.67	47.67	52.09	48.92	47.65
0.18	49.71	49.34	46.46	50.53	49.42
0.3	36.37	36.92	38.05	37.06	37.04
0.3	38.11	37.92	40.15	38.58	38.53
0.4	19.24	13.68	12.28	16.74	16.32
0.4	25.14	19.65	18.07	21.86	21.87
0.5	18.83	18.34	14.93	19.45	19.69
0.5	22.89	23.07	21.23	23.63	24.21
0.6	17.84	15.6	12.12	17.59	17.41
0.6	23.85	21.21	19.6	23.12	23.27
0.7	8.72	8.89	8.95	10.06	10.51
0.7	14.87	13.69	11.78	15.54	15.95
0.8	17.59	13.92	14.65	16.32	16.24
0.8	24.13	18.93	18.49	20.33	20.52
0.9	11.92	6.79	5.32	9.53	9.34
0.9	17.38	12.27	10.23	14.02	14.22
1	22.38	15.67	10.72	17.59	17.32
1	24.11	20.26	15.47	21.16	21.19
2	24.33	30.62	17.72	22.43	26.84
2	28.74	32.98	21.92	25.2	28.92
3	16.27	20.2	20.3	15.93	20.05
3	21.72	25.67	24.08	21.1	25.48
4	12.61	15.96	8.75	7.64	15.46
4	18.4	21.66	14.16	13.17	20.9
5	21.4	16.32	4.87	7.12	12.92
5	24.48	20.87	10.07	11.78	17.55
6	28.48	24.48	13.36	16.87	22.52
6	32.38	28.85	16.6	21.84	26.74
7	24.38	24.63	13.85	19.91	25.45
7	28.37	27.85	17.81	23.98	29.16
8	21.66	12.24	11.35	13.55	12.61
8	25.22	14.78	15.2	16.6	15.93
9	26.67	20.44	25.97	20.47	16.37
9	30.9	24.15	29.65	24.09	20.63
10	28.59	27.99	28.14	23.77	20.65
10	34.31	31.89	31.42	27.95	24.2
20	29.14	29.95	29.56	23.29	23.59
20	32.15	31.63	32.68	23.89	24.09
29	40.95	34.09	24.78	29.91	30.06
29	44.42	38.44	28.54	31.54	31.68

CHAPTER V

CONCLUSION

This research aimed to examine experimentally the impact of changes in the components of a refrigerator on the conducted emission results in which the electromagnetic noise values are measured at frequencies between 150 kHz and 30 MHz. The first group of tests has been performed by changing the cable distributions. Since the impact of electromagnetic energy attenuates with distance, better results are expected when AC and DC cables are separated from each other. Besides, the risk of unintentional coupling of the cables would have been minimized. It worked for the refrigerator where the cables are completely separated. This refrigerator gave the best results in terms of conducted emission. However, the refrigerator in which the cables are only separated inside the control box gave worse results than the refrigerator that has completely entangled cables. Cables that enter the control box from separate points may be touching an undesirable point on the control board. On the other hand, the entanglement of cables may be creating a magnetic field and suppress electromagnetic energy at certain frequencies. That means separation of AC and DC cables is an effective way to suppress the electromagnetic noise, but not in all cases. Therefore the designers cannot only count on the separation of AC and DC cables for their products to pass the conducted emission test. Determination of the source or using other solutions may be a good way to suppress the EMI. The second group of tests has been performed to check the impact of the ferrite filters on the suppression of conducted emission at its source. Two different types of ferrite filters, ferrite core, and amorphous core are located on AC and DC cables in the control box of the product which has fully entangled cables. It has been seen that adding a ferrite filter, regardless of position on the AC or DC cable, has significantly improved the noise levels.

There are three points to consider when evaluating test results. The first is to evaluate how much the solution improves the noise value closest to the limit because if one frequency has a noise value above the limit, it doesn't matter how far the noise values at other frequencies are from the limit. Second, when the solution improves the result at one frequency it shouldn't fail at other frequencies. Third, the phase and neutral test results for a test sample should be evaluated together. All the solutions except for the separation of AC and DC cables just before they enter the control box improved the worst noise value of the reference product which has the fully entangled cables. Changing the cable distributions and using ferrite filters are the cheapest and easiest to apply EMI suppression techniques in complex products without changing the design and these solutions are frequently used in the industry. One of the main purposes of this study was to support and compare these solutions, which are made somewhat conventionally, with tests.

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