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INFLUENCE OF AGEING ON THE EMC PERFORMANCE OF ELECTRONIC EQUIPMENT

Dissertation submitted in partial fulfillment for the degree of Master of Science in Electrical and Computer Engineering

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Influence of ageing on the EMC performance of electronic equipment

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Resumo

Dado o elevado número de aparelhos eletrónicos que estão em constante funcionamento nos dias que correm, a *Compatibilidade Eletromagnética* (CEM) é uma área fulcral para que seja possível utilizar de forma harmoniosa todos estes aparelhos electrónicos no dia-a-dia. A CEM é um ramo da engenharia que estuda a geração, receção e propagação de energia eletromagnética sendo que, este tem como objetivo o funcionamento, de forma satisfatória, de qualquer aparelho no seu ambiente eletromagnético sem causar distúrbios inaceitáveis nesse mesmo ambiente. As normas do *Comité Internacional Spécial des Perturbations Radioelectriques* (CISPR) regem os aparelhos fabricados com vista à comercialização na Europa, para que estes mesmos sejam testados no seu início do ciclo de vida e postos no mercado. Apesar de, em termos normativos, a CEM dos aparelhos dever ser garantida durante o seu tempo de vida útil, o comportamento destes engenhos ao longo do seu tempo de vida é desconhecido.

As Fontes de Alimentação Comutadas são aparelhos que devido ao seu design complexo geram alguma interferência eletromagnética. Assim, o foco desta dissertação será estudar o comportamento deste tipo de fontes ao nível do seu desempenho de CEM, mais especificamente em termos de emissões conduzidas, após o seu envelhecimento numa plataforma de envelhecimento. É também estudado o comportamento elétrico e térmico de alguns componentes de forma a tentar compreender de onde eventualmente poderão ser provenientes eventuais alterações de comportamento eletromagnético de emissões conduzidas.

Por forma a envelhecer as fontes de alimentação comutadas foram efectuados vários blocos de comutações, ligando e desligando as fontes com um período tempo definido. Este processo foi efectuado em dois conjuntos de fontes novas de duas marcas diferentes. Cada um destes conjuntos teve fontes envelhecidas em vazio bem como fontes envelhecidas enquanto ligadas a uma carga. Após cada conjunto de comutações foram efectuados os testes de conformidade de emissões conduzidas, para poder avaliar se o desempenho destas mesmas fontes sofreu alterações devido ao envelhecimento elétrico.

Alguns dos componentes destas fontes demonstraram comportamentos térmicos diferentes estando as fontes ligadas de forma continua ou sendo as fontes ligadas e desligadas ciclicamente.

As fontes de alimentação envelhecidas em vazio demonstraram poucas alterações a nível do seu comportamento em termos de emissões conduzidas, enquanto que as fontes envelhecidas ligadas a uma carga demonstraram uma notória alteração no seu comportamento, chegando mesmo a ultrapassar os limites padrão de CEM que devem ser respeitados a nível internacional.

O trabalho desenvolvido demonstrou que o envelhecimento dos equipamentos influenciou as medições de emissões conduzidas.

Keywords— Compatibilidade Electromagnética (CEM), Envelhecimento, Emissões conduzidas, EN 55032, Ensaios de CEM

Abstract

Considering the large number of electronic devices available nowadays in our surroundings, *Electromagnetic Compatibility* (EMC) is a very important area which allows a harmonious use of all these equipments on our daily lives. EMC is the engineering branch that studies generation, reception and propagation of electromagnetic energy. EMC's purpose is the sactisfactory functioning of any device in its electromagnetic environment without causing disturbances on that same environment. The *Comité Internacional Spécial des Perturbations Radioelectriques* (CISPR) regulates manufactured devices aimed to be commercialized in Europe. These same equipments are tested in the design and beginning phases of their life cycles to be sent to the marketplace. Although, in normative terms, the EMC performance of these devices must be guaranteed during their useful life cycle, the behavior of these devices throughout their continuous use is unknown.

Switch-Mode Power Supplies are devices that, due to its complex design, are propitious to generate a considerable amount of electromagnetic interference. This fact turns the focus of this dissertation to be the study of the EMC performance behavior, in terms of conducted emissions, of these power supplies after the use of an electrical ageing platform. The electrical and thermal behavior is studied in order to try to understand where and why any conducted emissions changes might come from.

In order to age a *Switch-Mode Power Supply* (SMPS), several blocks of "on-off" iterations have been performed with a predefined "on-off" time. This process was executed on two sets of new, off the box, power supplies of two different manufacturers. These two sets of units, were aged with load and without load. After each block of iterations, EMC compliance tests were carried out to find out if the EMC performance, in termos of conducted emissions, of these same power supplies changed because of the electrical ageing.

Some of the internal components of these SMPSs displayed different thermal behavior on power supplies that were continuously turned on with those switched on and off repeatedly.

Power supplies aged without a load have shown only small differences in their EMC conducted emissions performance while aged power supplies with a load exhibited significant changes in their EMC conducted emissions behavior, even exceeding the EMC standard limits for conducted emissions that must be met internationally.

The present work showed that the ageing of electronic devices afects their conducted emissions measurements.

Keywords— Electromagnetic Compatibility (EMC), Ageing, Conducted Emissions, EN 55032, EMC Tests

"The beautiful thing about learning is that nobody can take it away from you."

— Riley Ben King

Contents

Acronyms

ALT *Accelerated Life Testing*. 12, 13

CENELEC *Comité Européen de Normalisation Electrotechniques*. 3, 9

CISPR *Comité Internacional Spécial des Perturbations Radioelectriques*. ii, iv, 3, 9, 13, 15

DUT *Device Under Test*. xv, xvi, xvii, xviii, 13, 14, 15, 24, 32, 33, 37, 38, 39, 42, 43, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93

EM *Electromagnetic*. 6

EMC *Electromagnetic Compatibility*. iv, v, 1, 2, 3, 4, 5, 6, 9, 11, 12, 13, 14, 16, 32, 37, 39, 42, 44, 45

EMI *Electromagnetic Interference*. 2, 4, 5, 6, 7, 11, 15

EN *European Standard*. 9, 10, 16, 44

FCC *Federal Communications Commission*. 3, 9, 15

IEC International Electrotechnical Commission. 9

IR *Infra-Red*. 23, 27

LISN *Line Impedance Stabilization Network*. 14, 15

MTBF *Mean Time Before Failure*. 12

MTTF *Mean Time To Failure*. 12

PSU *Power Supply Unit*. xiv, 17, 21, 24, 26, 28, 30, 32, 34, 38, 39, 43

PWM *Pulse-Width Modulation*. 11

QP *Quasi-Peak*. 13, 14, 43

RFI *Radio Frequency Interference*. 11

SMPS *Switch-Mode Power Supply*. iv, xiv, 9, 11, 17, 21, 23, 24, 26, 28

SSR *Solid-State Relay*. xiv, 30, 31, 44, 45

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1 Introduction

1.1 Framework

It has been a long time since it is well known that electromagnetic waves can cause interference in electrical devices, particularly since the appearance of radio and telegraph communications. This kind of phenomena is studied by *Electromagnetic Compatibility* (EMC), the engineering field which concerns generation, transmission and reception of electromagnetic energy with respect to a certain equipment being able to work correctly in its electromagnetic environment, without causing unwanted disturbances in its environment. Nowadays, with the increased growth in numerous types of electrical equipment, EMC becomes more important each day, as the world becomes overpopulated with electronic devices.

EMC regards mainly three issues: Emission, Susceptibility/Immunity and Coupling. Emission, deliberate or accidental, is electromagnetic energy generated by all the devices into its environment. Susceptibility is the propensity of an electrical equipment to malfunction or breakdown with the existence of unwanted emissions while Immunity is the opposite of susceptibility, being the strength of an equipment to resist and function properly when being exposed to interference.

The problems associated with EMC can be divided into four subcategories, depicted in Figure 1.1:

- Radiated emissions
- Radiated susceptibility
- Conducted emissions
- Conducted susceptibility

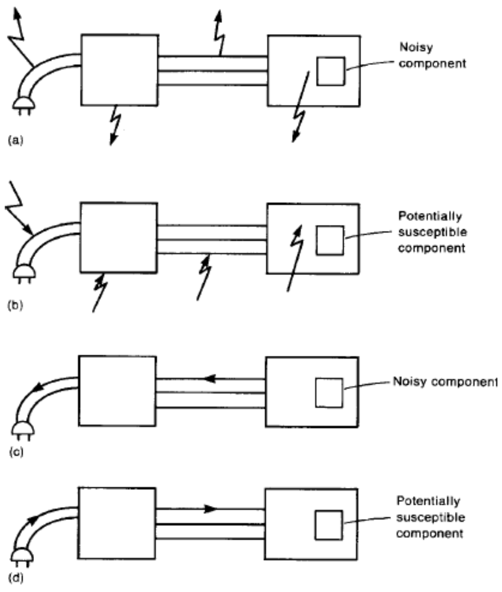

Figure 1.1: The four EMC subproblems: (a) radiated emissions; (b) radiated susceptibility; (c) conducted emissions; (d) conducted susceptibility[1]

Conducted emissions happen through physical contact along conductors (usually power cords) in the form of electrical current. This is problematic since devices are connected to the entire power distribution network. *Radiated emissions* are caused by induction in the form of electromagnetic energy propagated through air (without any contact) which have the potential to interfere with other devices. These two phenomenons are always related. In a very simple way, Faraday's Law explains that a varying magnetic field wil produce an electric current. According to *Lenz's* Law, this induced current wil produce a magnetic field that opposes to the original one. Electric current and magnetic fields are always interconnected meaning that radiated and conducted emissions influence each other constantly. This proves that both conducted and radiated emissions are dependent from one another.

Electromagnetic Interference (EMI) is the interference problem that causes the malfunction of an equipment and not the signal causing the problem. We can decompose EMI in three main elements:

- Emission/Source of a disturbance
- Coupling Path
- Equipment being interfered

Due to the over-population of electronic devices all around, rules had to be applied to guarantee harmony within technological devices. International organizations co-operated to standardize EMC around the globe. There are a few organisms around the world like the *Comité Internacional Spécial des Perturbations Radioelectriques* (CISPR), the european *Comité Européen de Normalisation Electrotechniques* (CENELEC) and the United States *Federal Communications Commission* (FCC) which produce the international commercial standards that must be met to ensure conformity of the equipments in terms of EMC. Conducted emissions are regulated from 150kHz to 30MHz while radiated emissions are regulated from 30MHz to 6GHz (CISPR) or 40GHz (FCC) [2] .

Compliance tests are made with new devices and there is no compliance control over the life cycle of those same devices. Materials age with time and electromagnetic compatibility issues may occur with the ageing of equipment which may be a problem to surrounding devices. It is well know that components wear out with use and time meaning important characteristics of the circuits may be at risk with ageing. The purpose of this work is to understand how ageing influences emissions on off the shelf certified equipment.

1.2 Document Structure

This introductory chapter is part of this five chapter dissertation. Chapter number 2 presents a succinct overview on important aspects concerning *Electromagnetic Compatibility*, essentialy main concepts and regulations. Every equipment, decisions and procedures regarding the present work are described in Chapter 3, while Chapter 4 reports all the significant results. Conclusions and future work concludes the document in Chapter 5.

2 Electromagnetic Compatibility and Electromagnetic Interference

2.1 Introduction

Electronic devices play a major role in our daily lives and technology has changed every aspect around the world.

EMC serves the purpose of making the technological world live in harmony with itself. When flying, passengers are asked to turn off all electronic devices during critical flight times like landing or takeoff. People that carry pace-makers often need special precautions. These are a couple examples on how EMC affects our world.

Electromagnetic Compatibility may be defined as the ability of an electronic device to function properly in its electromagnetic environment without interfering or disturbing nearby equipment and/or without suffering any interference problems by other equipment [3]. *Electromagnetic Interference* (EMI) is the malfunction of a system caused by an unwanted electromagnetic disturbance: *"Degradation in the performance of equipment or transmission channel or a system caused by an electromagnetic disturbance"*[4]. An electromagnetic disturbance is the *"electromagnetic phenomenon that can degrade the performance of a device, equipment or system, or adversely affect living or inert matter"*[4]. It is very important to note that the EMI is the interference problem and not the signal causing the problem. This phenomena is a tricky matter because a wanted signal for a device might be unwanted for another nearby device. In order to have an environment where all equipment can function properly, devices must have a combination of low susceptibility and high immunity, so they do not malfunction from undesirable signals, and have low emissions of electromagnetic energy, such they do not interfere with other apparatus. All of this has to be taken in account for the electromagnetic environment where the equipment is designed to function. When analyzing a product one must take considerations about five major aspects:

- The **frequency** spectrum in which the problem is observed.
- The **amplitude** i.e., the strength of the energy and its potential to cause harmful interference.
- **When** is the problem observed, being continuous or during only certain conditions.
- What is the **impedance** of the source, receptor and the transfer mechanism.
- What are the electrical **dimensions** of the circuits involved[5].

2.2 EMC accidents

It is very important to be aware that EMC problems can cause real and dangerous situations. There are several cases described in literature and some examples are listed below:

- Researchers from the University of Amsterdam have investigated 50 incidents of EMI related with cell phone usage in hospitals, and concluded that 75 % of them were significantly hazardous [6].
- Another study reports that EMI had the potential to cause critical care failure in medical devices[7].
- Two planes have crashed under the same electromagnetic environment at different times[8].
- A ferry crashed due to an interference in the propulsion pitch control system[9].
- NASA has a document reporting numerous EMC problems like a vacuum cleaner making a data transmission interface between the shuttle and the ground to stop working; early *Apache* helicopters were susceptible to commercial microwave, televisions, airport and missile radars; a heart monitor/defibrillator in an ambulance malfunctioned every time the radio transmitter was turned on[10].
- Pacemakers have been studied and proved to have abnormal functioning near some devices[11].

The list of proved interference is never-ending and all of these EMC problems mean people's lives might be in danger when this broad subject is not taken into account.

2.3 Immunity and Susceptibility

Immunity is the electromagnetic level surrounding a device that can be withstood while functioning properly, without degradation and with a certain amount of safety. *Susceptibility* is the contrary concept: the ineptitude of a system to behave without degradation in the presence of an electromagnetic disturbance.

These terms are complementary and have distinctive applications. There can always be found an *Electromagnetic* (EM) environment that can influence adversely a system, being it a specific characteristic - Susceptibility. Contrastingly, Immunity expresses the measurement of to what extent the EM environment can be hazardous preceding a system malfunction. It can be delicate to establish what is considered a device functioning properly. It is desirable to have a system with high immunity and low susceptibility.

2.4 Electromagnetic Interference

The EMI problem can be divided into the source of the disturbance(emitting electromagnetic energy), the device interfered with(susceptible to the disturbance) and the coupling path between the source and the victim.

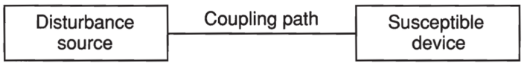

Figure 2.1: Abstract and basic view of the Electromagnetic Interference Problem[1]

The problem is usually very complex as sometimes a device might be both source and victim. When one of these three parts does not exist, the EMI problem is obviously solved. Although this might seem easy, it is certainly not.

We must take into account four levels in terms of EMC that can be interconnected:

- System level
- Equipment level
- Circuit-board level
- Component level

An example of this is if there is a AM broadcast transmitter is interfering with an electronic phone. If the handset is picked up, the person will hear the broadcast emission. This means that, at system level, the telephone system, the cables and the exchange itself are susceptible. The telephone line is a receiver for the unwanted transmitted signal, in this case. At the equipment level, stands the telephone set itself(the whole set) while at the circuit-board level is the audio amplifier. Depending on the circuit board design, more or less signal is picked up. At component level there is the integrated circuitry acquiring and demodulating the broadcast signal making it audible. The amount of signal that is made audible depends, ultimately, on the component design of the audio amplifier. Since in this situation the problem lies on the antenna emitting the signal, this particular problem should be solved by taking safety measures to block the coupling path between the antenna and the components of the telephone.

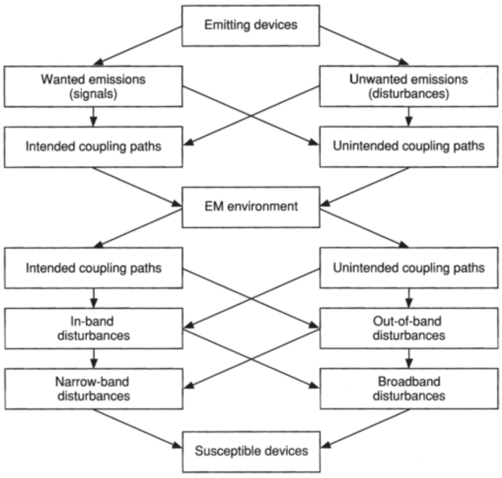

Figure 2.2: Approach on the Electromagnetic Interference Problem [3]

As it can be seen in Figure 2.2, the EMI problem is a multi-dimensional issue. All the paths above have to be analyzed to ensure that the problem is solved properly since these paths are not necessarily independent from one another and can lead an unwanted signal in several ways to a susceptible device.

2.4.1 Coupling Paths

As a victim is susceptible by an undesirable electromagnetic energy, this energy must be traveling along a path that may be one or more of the paths listed below:

- Conductive Coupling: Electric Current

- Radiated Coupling: Electromagnetic Field
- Capacitive Coupling: Electric Field
- Inductive Coupling: Magnetic Field

Conductive coupling happens when electric current from two or more circuits flow through the same impedance for example in a power supply and ground wires. The basic equation for electric current is the Ohm's Law

$$V = R \cdot i \tag{2.1}$$

This phenomena of interference can be divided into Common Mode and Differential Mode currents. Common Mode noise happens when current flows in the same direction thus making the noise be the sum of those currents. Differential Mode currents flow in a closed loop in different directions therefore subtracting each other.

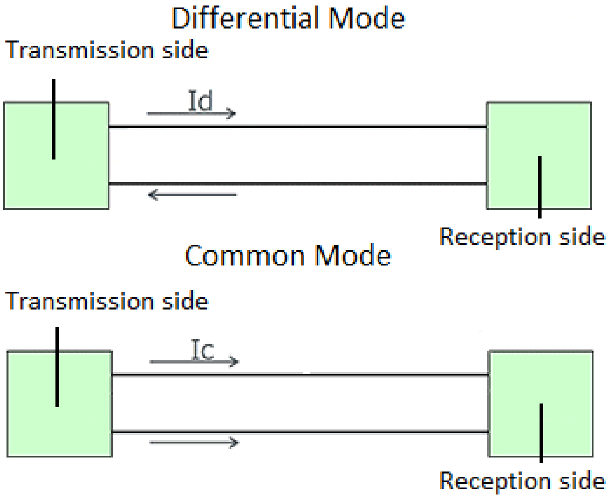

Figure 2.3: Differential Mode vs Common Mode[12]

Radiated coupling happens through electromagnetic field and can be distinguished between electric field and magnetic field. Electric field happens when a voltage is present and a magnetic field exists when a current flows.

A voltage difference between conductors (electric field coupling) may be modeled as a capacitor hence the designation **capacitive coupling**.

When a current flows in nearby conductors the magnetic field coupling mechanism may be modeled as a transformer thus it's denomination being **inductive coupling**.

All electromagnetic radiation involves electric and magnetic fields, which are dependent from each other. Any variation in the flux density of a magnetic field will turn out to an electric field variation and this electric field change makes the magnetic field fluctuate too (Faraday's Law). Consequently, a time-varying magnetic field will generate an electric field and a time-varying electric field will make a magnetic field.

2.5 EMC Regulations

Regulations help to keep the compatibility in the electromagnetic spectrum around the globe and there are several guidelines to follow worldwide. Since the goal of this work is to study the particular cases of a *Switch-Mode Power Supply* (SMPS), the focus will be regulations referring the category of these types of equipment only.

EN 55032 is one of the EMC standards to be met in Europe which is enforced by the International Special Committee on Radio Interference (CISPR). This standard defines measurement methods, equipment and limits for Information Technology and multimedia equipment.

Most used EMC standards in Europe are the CISPR 32 and EN 55032 (former CISPR 13, CISPR 22 and former EN 55013 and EN 55022, respectively). CISPR norms are under the International Electrotechnical Commission (IEC) and are optional since it is an international entity. In contrast, CENELEC's EN 55032 is imperative for all the IT and multimedia equipment in Europe. The equivalent for the United States of America is the FCC Part 15. All of these standards divide devices into two classes:

- Class A - products marketed for commercial or industrial use and not intended to be used in a home.
- Class B - products marketed for residential or home use.

Conducted and radiated emissions have several differences regarding these two classes.

The European standards require certification between 0.15 MHz and 30 MHz for conducted emissions and for radiated emissions from 30 MHz to 6.0 GHz although there are no specified limits for frequencies above 6.0 GHz. The CISPR limits are provided in dBμV while FCC limits are specified in μV meaning a conversion is needed although the equivalent limits are very similar.

The limits for conducted emissions that apply to the present work are the Class B EN 55032 standards which are the exact same limits as the former EN 55022:

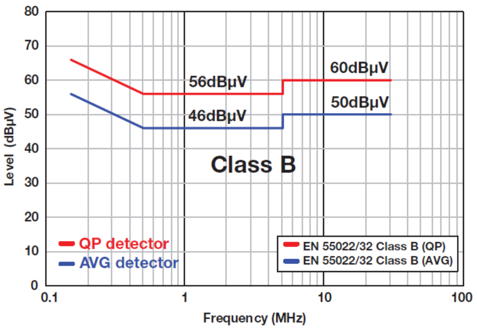

Figure 2.4: Class B EN 55022/32 Limits[2]

3 Experimental Procedures and Equipment

3.1 Switch Mode Power Supplies

In order to provide consistent power to its circuit, a *Switch-Mode Power Supply* plays a very important task so whatever is connected to the power supply has the power it needs. It also serves as insulation between the mains and the circuit, since the circuit that a SMPS is connected to, rarely operates at the grid's power characteristics. SMPSs are highly efficient and usually of small size and weight.

These types of power supplies operate with power transistors in both saturated and cutoff states at high switching frequencies allowing less magnetic components to be used but it intensifies the spectrum of EMI due to its active components and the power structure interaction. *Pulse-Width Modulation* (PWM) drives the switching components of the SMPSs using square waves. This signal activity may trigger a lot of *Radio Frequency Interference* (RFI) on its circuitry hence proper design should be taken into account. Precautions must be taken so that the RFI conducted into/out of the device or radiated away is minimized, making less pollution to the electromagnetic environment around it. Abrupt changes in current or voltage of power semiconductors generate high frequency harmonics meaning that the parts of the circuit that make high variations of voltage or current are the most problematic. All these facts make the use of Switched-Mode Power Supplies a good option to analyze their EMC conducted emissions performance after ageing.

It is very important to note that throughout this work, two sets of new SMPS manufacturers were analyzed. These two different manufacturers are denominated throughout this document "Batch A" and "Batch B". Batch A's power supplies are from *LC POWER* and the model is *LC420H-12*; Batch B's power supplies are from *MS-Tech* and the model is *MPS-400*.

3.2 Accelerated Life Testing

The growth and evolution of technological devices nowadays is extraordinary and some of those devices have an estimated lifetime of 10 years or more. If manufacturers had to test these devices for such a long period of time, they would most likely be wasting time examining an outdated product, thus *Accelerated Life Testing* (ALT) is used to examine devices. ALT is a method of testing products in a short period of time in order to analyze data on their operating characteristics, providing valuable information about the tested equipment.

Usually, *Mean Time To Failure* (MTTF) and *Mean Time Before Failure* (MTBF) are a couple of data indicators collected that might expose potential faulty designs. MTBF and MTTF are two commonly used indicators of a product's reliability. They represent the measure of time for which a certain system is expected to perform without any failures.

Finding product weaknesses, making predictions about service life/maintenance intervals and making changes accordingly earlier in the design process can reduce development costs and shorten the time to market. When ALT is used after a product is already in the market it serves to examine product reliability caused by changes in components, manufacturing process or suppliers. In other words, ALT can be used to age devices so that, in this case, its EMC performance is examined.

Depending on the kind of device and the objective of the testing in question, some common conditions for ALT might be [13]:

- High level of temperature
- Pressure
- Voltage
- Load
- Vibration

In this case, ALT is used not to expose failures or a better design purpose but to emulate the lifespan of the equipment and uncover possible EMC degradation issues.

3.3 Ageing Platform

The Ageing Platform used to perform ALT in the present work, built and designed by Joaquim Alcafache, induces electrical stress via "on-off" switching.

This device has an *Arduino Mega 2560* that controls 8 relays. Time OFF and Time ON will be the main settings controlled by the Arduino for our ageing process purpose. The Platform is connected to the computer via USB and has a *LabVIEW GUI* that controls the *Arduino MEGA*. It has 8 power strips with 3 sockets each that are connected via two 16A circuit breakers, to 8 mechanical relays [14].

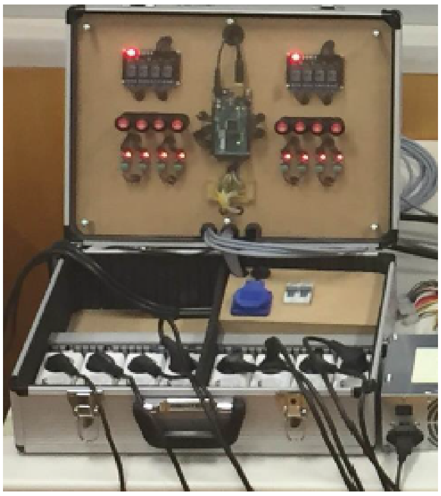

Figure 3.1: Ageing Platform Image [14]

3.4 Quasi-Peak, Average and Peak Detection

Emissions testing focuses on unwanted signals that are generated by a *Device Under Test* (DUT). For EMC testing, CISPR uses Peak, Average, C-Average, RMS, RMS-Average, and *Quasi-Peak* (QP) detectors. The relevant ones for the present work are Average, Peak and QP detectors.

Historically, QP was supposed to emulate human response to noise. Humans have a slowly increasing level of annoyance to a persistent disturbance meaning that it is a subjective response.

A QP detector is a dynamic peak detector with an integrator and has a built-in attack and release rate to weight the signal measured. The signal level is weighted accordingly to its repetition, meaning the result of a QP measurement will depend on the repetition rate of this signal: high repetition, higher measurement. The result of a QP measurement for a series of impulses is higher when the pulse repetition rate is higher.

The spectrum analyzer does a full scan over the frequency spectrum and is very slow when working on QP mode because of the charge and discharge constants involved.

Peak detection is more frequently used in early stages of development because of its fast scanning. If a DUT's peak measurement stays below the quasi-peak limit, quasi-peak measurements have a security margin because QP always has a lower reading than peak.

Average and peak measurements will be used throughout this work only because QP scanning would be too much time-consuming.

3.5 Line Impedance Stabilization Network

With respect to having trustworthy measurements around the world, there is a piece of equipment that is crucial: a *Line Impedance Stabilization Network* (LISN). One of the main functions of this equipment is to make repeatable measurements presenting a constant impedance, since the impedance seen by the DUT to the power source varies from site to site and across the frequency spectrum. It also serves as an insolator preventing incoming noise to the system being tested. It usually serves as connection to a measurement device, typically a spectrum analyzer. One understated goal is that the LISN needs to supply the power required to the DUT, commonly at the 50Hz frequency. All these objectives are supposed to prevail and work between the frequency range of the EMC conducted tests, from 150 kHz to 30 MHz. A schematic of a typical LISN is shown in Figure 3.2.

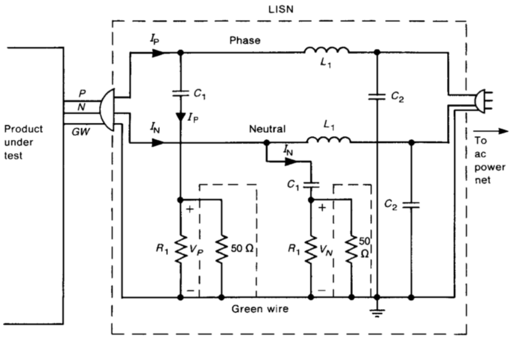

Figure 3.2: Class B EN 55022 Limits[2]

The inductors L1 block noise, and capacitors C2 divert noise thus preventing external disturbances from contaminating measurements, while passing the power required to operate the DUT, which are two objectives of a LISN. These two components make an open circuit looking into the distribution system, accomplishing the impedance seen by the product between phase/ground and between neutral/ground to be 50 Ω. The capacitors C1 prevent any DC component from overloading the DUT whilst R1 serve as a discharge path in the event of the disconnection of the 50 Ω resistor.

The *EMI Receiver PMM 7010* will be the equipment used being both LISN and spectral analyzer for the present work.

3.5.1 EMI Receiver 7010

With the ability to measure conducted and radiated interference from 150kHz to 1 GHz, the *PMM 7010* is an EMI receiver that helps make precompliance measurements in consonance with CISPR, International Electrotechnical Commission (IEC), European Standards (EN) and FCC standards. It has an integrated LISN, being a perfect whole package equipment to measure emissions. In this case, only conducted emissions will be measured.

This device has a software designated "PMM Emission Suite" that helps get data in an easy and accurate way when set-up properly.

A few parameters need to be set when using this device's software. After choosing the Ancillary "L2 7010" , the parameters to be set for CISPR 22/32 standards, are [15]:

- Frequency Range: 150kHz - 30MHz
- Resolution Bandwidth: 9kHz
- Step: 2.5 kHz
- Detector : P(Peak), A(Average)
- Pre Amp: Off
- Pre Sel: Off
- Ancillary: L1, L2
- Min Att: 10

3.6 EMC Conducted Emissions Test Setup

In order to ensure proper quality on conducted emissions testing, a few standard procedures must be done. A fixed distance of 400 mm to a non conductive table needs to be ensured. At least 800 mm of clearance from all other conducting surfaces must be assured. Usually all test setups have a 800 mm high table on which a DUT must be located 400 mm away from the vertical ground plane. Great care must be taken in account with all the cables: if a cable extra length is coiled or it is laid on the ground plane, it will introduce more inductance and capacitance to the system. This can be controlled by bundling the cables as shown in the figure beneath. An example of a conducted emissions test setup derived from the EN 55022 is presented below in Figure 3.3.

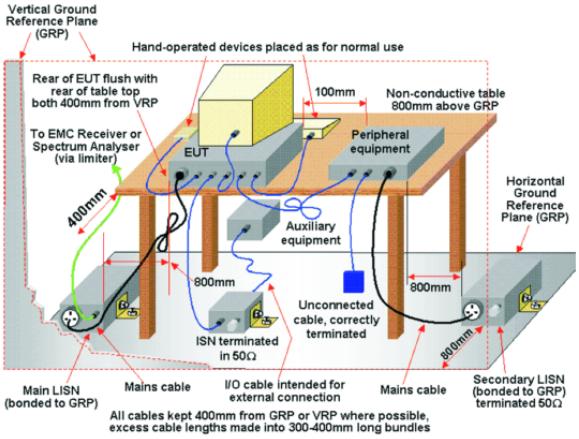

Figure 3.3: Conducted emissions test setup in a screened room [16]

With all of this taken into account, Figure 3.4 shows the real test setup used to make all EMC conducted emissions testing in the present work

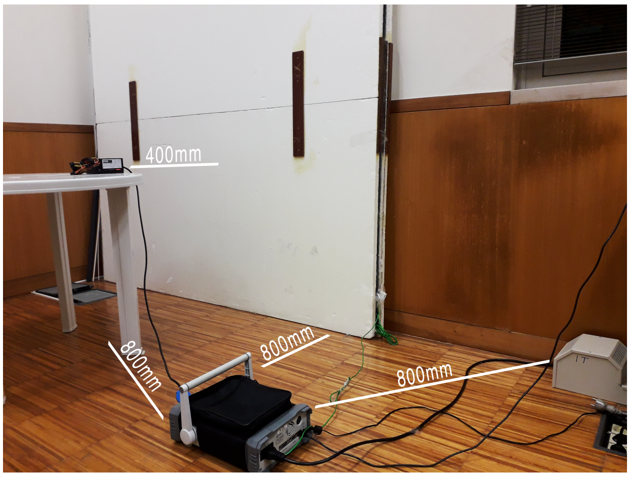

Figure 3.4: Conducted emissions test setup

3.7 Switching Time Analysis

In order to decide which on and off times would be best to age a SMPS, electrical analysis was conducted.

Voltage values, while switching a PSU on and off, were inspected in both the output pins and a couple of randomly chosen capacitors. Using an oscilloscope, the charge and discharge behavior of the 12 V, 5 V buses and 2200 μF, 470 μF capacitors(from the PSU) were inspected.

The following images show the process of switching a *Power Supply Unit* (PSU) on.

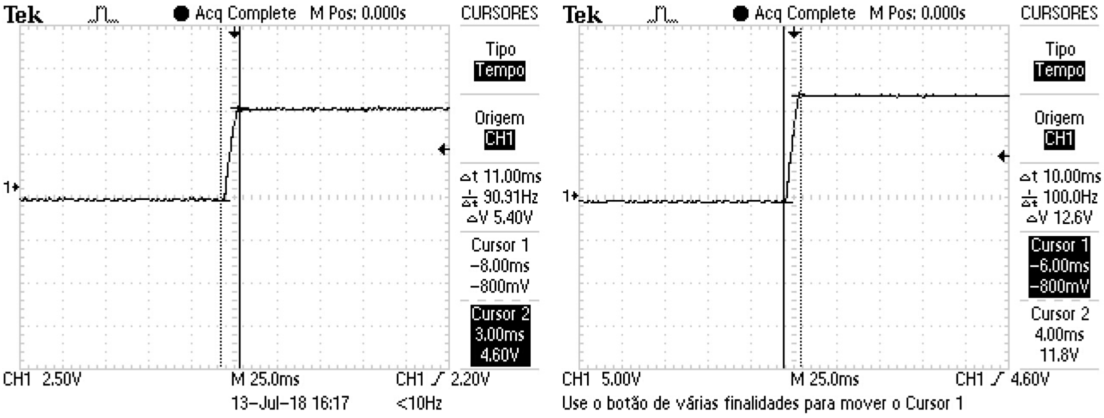

Figure 3.5: Charging time of the 5 V and 12 V output pins respectively

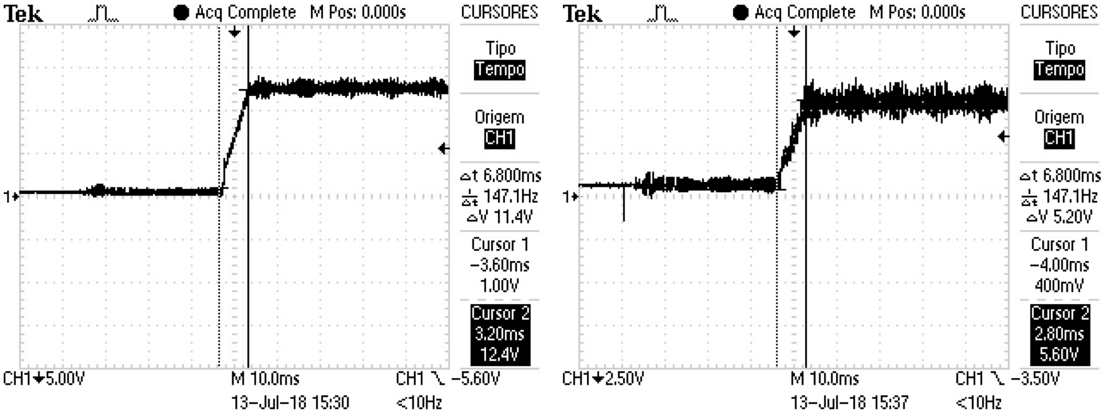

Figure 3.6: Charging curve for 2200 μF capacitor on the left and 470 μF capacitor on the right

After analyzing Figures 3.5 and 3.6, the turning on process of a SMPS is almost instantaneous with capacitors charging in less than 7 ms and the output reaching its normal output voltage level in around 10 ms.

The turning off of the SMPS had the behavior in the images below.

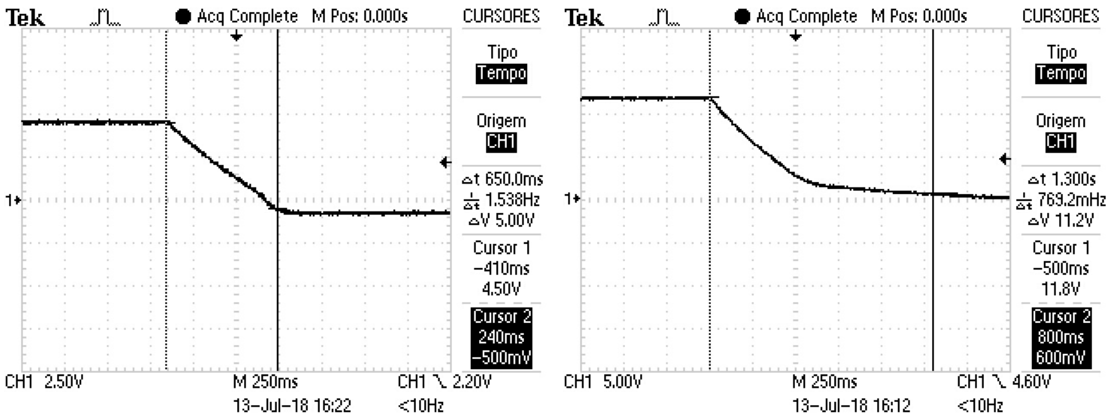

Figure 3.7: Discharge time of the 5 V and 12 V output pins

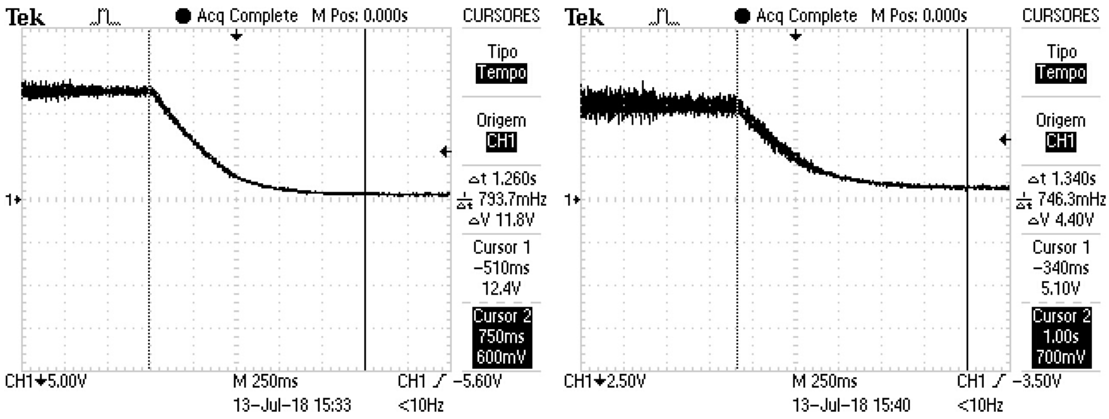

Figure 3.8: Discharge curve for the 2200 μF capacitor first and for the 470 μF capacitor

As it can be observed, the discharge time of the system is considerably longer than its charge time. Capacitors and the 12 V output take around 1.3 seconds to discharge (Figure 3.8) while the 5 V output discharges at around 0.6 seconds (Figure 3.7).

3.8 Thermal Inspection

3.8.1 NEC TH7700 Infrared Camera

With a flip-up LCD and manual focus, this device is a hand-held camera used for thermal inspection. It only takes pictures and it is able to transfer images via USB. The images need to be converted to a more common image format using a software called "Viewer Program".

Figure 3.9: NEC TH7700 Infrared Camera [17]

3.8.2 Optris PI400

The small sized camera used for thermal inspection has a fixed focus point and can record video and pictures. It needs to be connected to the computer via USB and it must be used with the "Optris PIX Connect" software.

Figure 3.10: Optris PI400 Camera [18]

3.8.3 Heat Sink

In order to prevent resistor damage throughout the ageing process, the IR camera was used to understand the type of heat dissipation the loads would make on a dissipating metal sheet. The following image(Figure 3.11) shows 40W through the resistor.

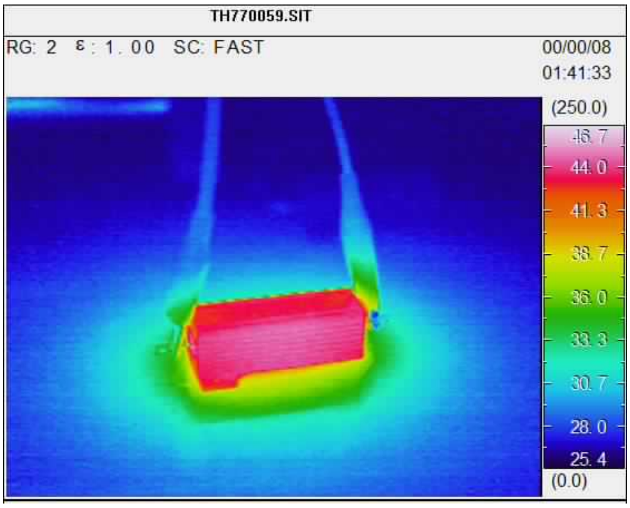

Figure 3.11: Power resistor supporting 40W out of its 50W maximum after aproximatly 5 minutes

From the available metal sheets, the aluminum was the chosen material, as it is one of the metals with best heat conductivity coefficient. Aluminum is also one of the most common heat dissipation metals used because of it's high coefficient and low price compared to, for example, copper. Copper has a higher coefficient than aluminum but has a significant higher price meaning copper is usually used for high efficiency and more critical systems.

In Figure 3.12 is presented an image of the heat sink with all the power resistors and wire connections.

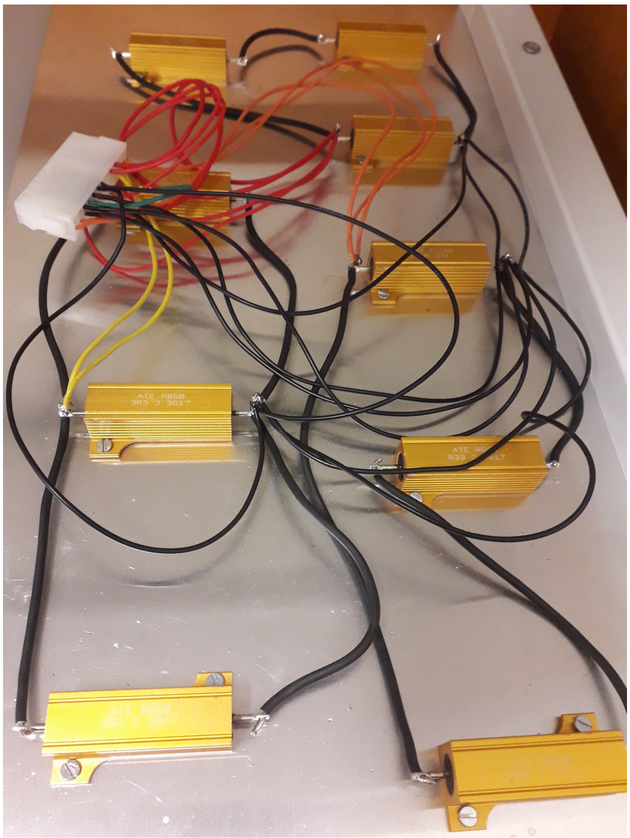

Figure 3.12: Power Resistors on its heat sink with the 24pin connection for the PSUs

3.9 Power Resistors as Loads

The ageing process is accelerated by having the SMPS under power delivery. Power resistors were chosen to be connected to the power supplies voltage buses as loads.

The power supplies main output buses are 12 V, 5 V and 3.3 V. For the present work, two different manufacturers of SMPS were considered, identified as *Batch A* and *Batch B*. Because of this, there were two different SMPS output specifications and therefore two load setups were determined.

With the available resistors on the market and considering Ohm's Law and Jule's Law, a combination of power resistors was calculated to ensure a power consumption of the SMPSs within their limits. All the power resistors used in this work can hold up to a maximum of 50W of power through them and the chosen values were 0.39 Ω, 0.47 Ω, 1 Ω and 3.3 Ω.

The power supplies of *Batch A* were connected to the power resistors according to Table 3.1. In this table is also presented the corresponding power consumption.

The batch of power supplies in Table 3.1 will be aged at 72,34% of their three buses total power capacity.

Power resistors chosen for *Batch B* and the power specifications for the SMPS are pre-

Bus	**Load**	**Current Drained**	**Max Current**	**Power Drained**
12 V	3.3//3.3//3.3 Ω	10.9 A	15 A	130.8 W
5 V	1//1 Ω	10 A	16 A	50 W
3.3 V	0.47//0.47 Ω	13.75 A	16 A	45.34 W

Table 3.1: Power resistors used and power consumption for *Batch A*

sented in Table 3.2. This batch will be aged at 77.3% of the 12 V, 5 V and 3.3 V total power capacity:

Bus	**Load**	**Current Drained**	**Max Current**	**Power Drained**
12 V	3.3//3.3//3.3 Ω	10.9 A	14 A	130.8 W
5 V	(1+0.47)//1 Ω	8.3 A	10 A	41 W
3.3 V	(0.39+0.39)//0.47 Ω	11.37 A	16 A	37 W

Table 3.2: Power resistors used and power consumption for *Batch B*

3.10 Ageing Process Guide

3.10.1 Ageing Process Guide

In the present work, thirty-six new SMPS units were tested, half of them from one manufacturer and the other half from another. This splits the power supplies into *Batch A* and *Batch B*.

Two units of each batch were kept as part of a control group and remained untouched meaning they had no inflicted ageing. Half of the remaining SMPSs were aged with a load while the other half were aged with no load. There was an *Infra-Red* (IR) camera to inspect two SMPSs, one unit inspected while being connected to no load and one unit inspected while having a load connected to it. The diagram in Figure 3.13 displays the description above in a more understandable and simplistic fashion.

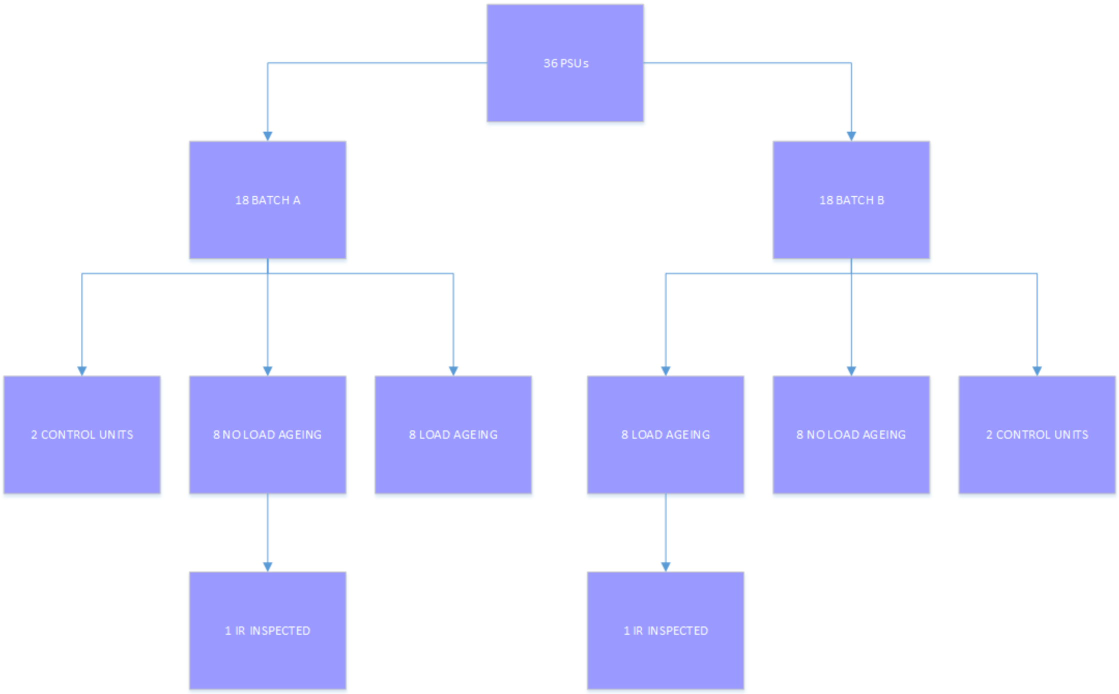

Figure 3.13: SMPS ageing description

All of these SMPS were labeled as follows:

- #1 and #2 - Control Units of *Batch A*
- #11 and #12 - Control Units of *Batch B*
- #13 to #28 - Devices Under Test of *Batch B*
- #3 to #10, #31 to #38 - Devices Under Test *Batch A*

DUTs 3 to 10 and 13 to 20 were aged without being ever connected to a load while DUT 21 to 28 and 31 to 38 were aged only connected to a load. It is relevant to point out that, in this document, an "Iteration" is considered to be the process of switching on and off a SMPS once. The ageing process is divided into 6 blocks of iterations and they are performed in the their cardinal order. Every time one block of iterations is finished, conducted emissions of all the DUT involved are measured. After that, the iterations counter is reset. The amount of iterations considered for each block is described in Table 3.3. One iteration for all blocks presented in the table below consist of a DUT turned on for 1 second and turned off for 2 seconds. This value was chosen taking in account the charge and discharge times measured in Seccion 3.7. It is worth mentioning that after all these 6 blocks, 144 000 cycles of 1 second on and 2 seconds off were performed.

3.10.2 Extra Ageing

After the ageing process done above it was decided to have another two ageing procedures done on a few SMPSs. A random "on-off" time ageing was applied to PSUs number 32, 33, 34 and 35 while still having a control batch of the same iterations but with the normal fixed "on-off" time for the rest of the PSUs from the group of PSUs labeled from 31 to 38. The random "on-off" iterations consisted of both on and off time randomly being chosen between 0.5 seconds and 8 seconds. After this extra ageing procedure DUTs 31 to 38 will have completed 224 000 "on-off" iterations.

Ageing Test Number	**DUT Number**	**Load**	**Number of Iterations**	**Switching Time (On - Off)**
1	3 to 10 13 to 20	No	1 000	1s - 2s
	21 to 28 31 to 38	Yes		
2	3 to 10 13 to 20	No	3 000	1s - 2s
	21 to 28 31 to 38	Yes		
3	3 to 10 13 to 20	No	10 000	1s - 2s
	21 to 28 31 to 38	Yes		
4	3 to 10 13 to 20	No	20 000	1s - 2s
	21 to 28 31 to 38	Yes		
5	3 to 10 13 to 20	No	45 000	1s - 2s
	21 to 28 31 to 38	Yes		
6	3 to 10 13 to 20	No	65 000	1s - 2s
	21 to 28 31 to 38	Yes		

Table 3.3: Ageing Process general guidelines

4 Experimental Results

4.1 Thermal Inspection Results

Using the Optris PI400 it was possible to determine that the main heating components of a PSU take 2 to 3 seconds to heat up with simple video analysis(Figure 4.1).

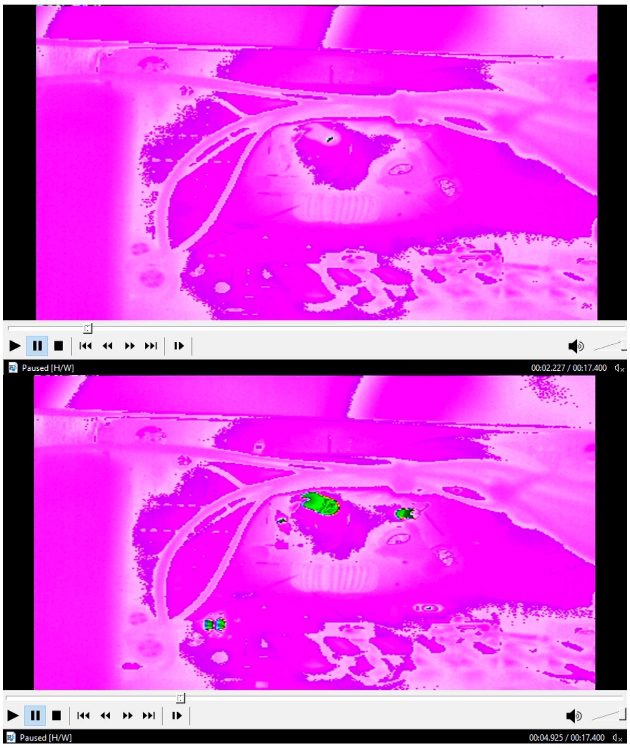

Figure 4.1: First screenshot shows a cold resistor at 2.2 s and the image on the bottom shows the same component's increased temperature at 4.9 s

As the Optris PI400 camera had a fixed-focus lens, it was a very limiting device because it only focused on a fixed distance. Using the NEC TH7700 camera, it was noticeable that the closed SMPS's components with no load seemed to reach a temperature of around 40ºC. Outside of the enclosure remains at around 27ºC except for a small area that reaches around 32 ºC (Figure 4.2).

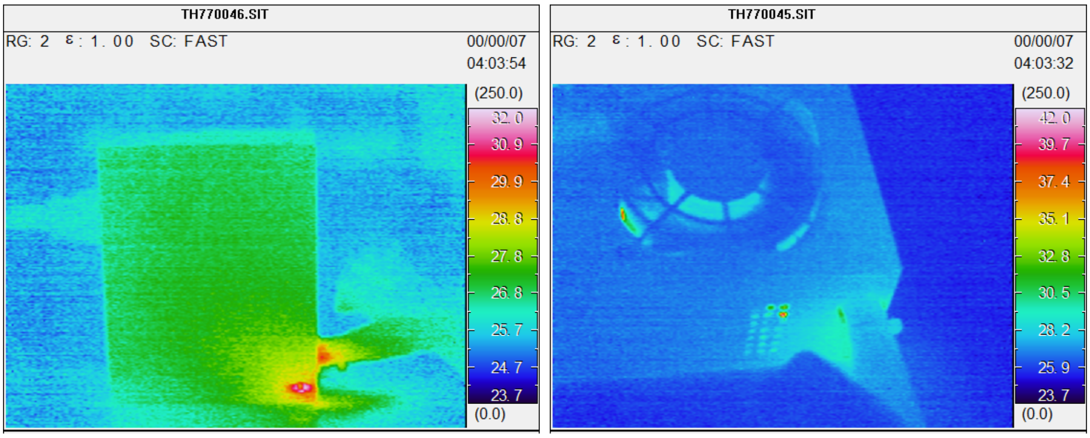

Figure 4.2: Thermal Inspection with closed SMPS's with no load: On the left, the outside at a maximum of 32 ºC; on the right, the components inside at 42 ºC

Inspecting further on the area with the highest temperature it can be observed that there is a component reaching very high temperatures. Without the closed armature and without ventilation, this component reaches 130 ºC (Figure 4.3). It is not possible to determine exactly this component's temperature with the enclosure fully closed due to the lack of a line of sight for the IR camera.

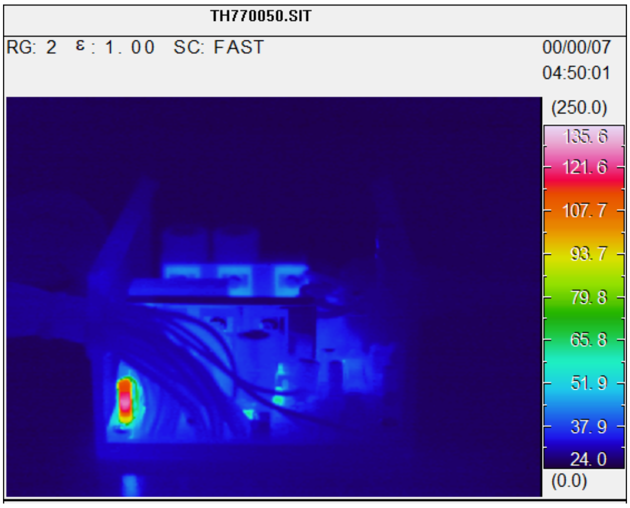

Figure 4.3: Highest temperature component at 135 ºC

When switching on and off continuously there is another component, a thermistor, that heats up to a considerably high temperature. When turned on permanently, this component remains cold (30 ºC), oppositely from when the power supply is turned on and off(53 ºC). Figure 4.4 compares this two situations side-be-side.

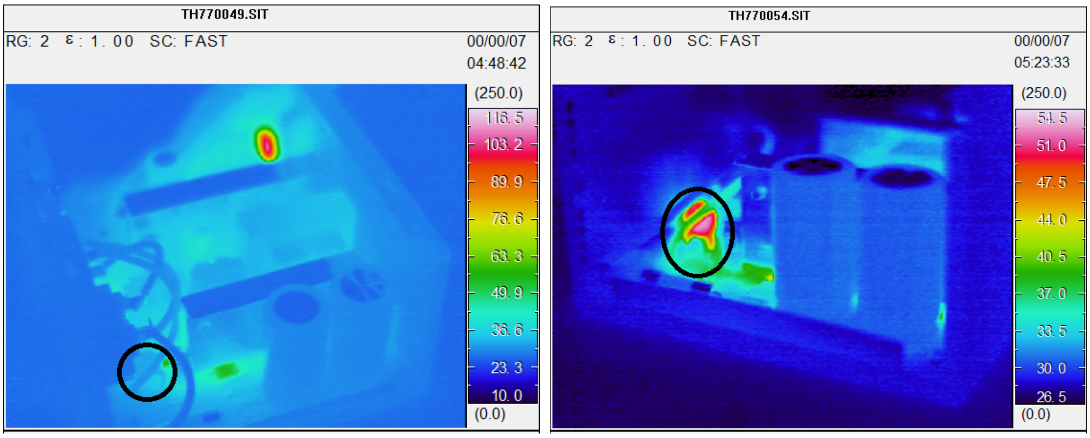

Figure 4.4: Thermistor when the SMPS with no load is turned on for a couple of minutes (left) and the same component under switching action (right)

4.2 Ageing Platform Troubleshooting

A problem was encountered during the ageing process that froze the work-flow until the problem was solved. The mechanical relays implemented in the Ageing Platform started to fail when the devices under testing were aged connected to a load. Future work of Joaquim Alcafache stated that the mechanical relays of the platform should be replaced with another type of relays [14] because they could possibly be a problem in future usages.

4.2.1 Relay Analysis

The platform's mechanical relays started to fail within an unreasonable amount of cycles during the ageing process under load. To explore the reasons behind such phenomena, the problem was inspected with an oscilloscope.

Upon voltage inspection at one of the mechanical relay's terminals while connected to a PSU nothing out of ordinary was observed.

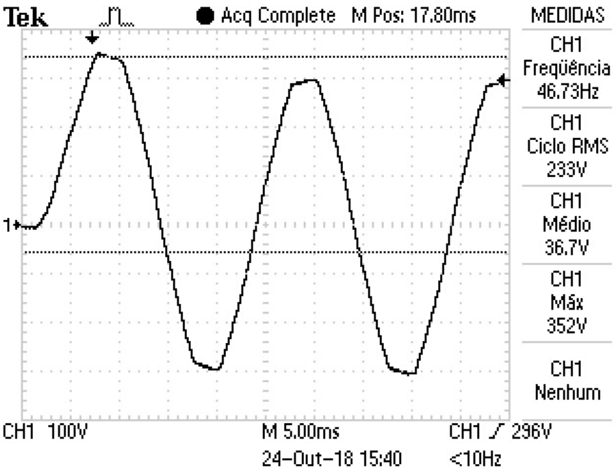

Figure 4.5: Voltage at the Mechanical Relay's terminals

The HK3FF-DC5 V-SHG relays used in the platform were labeled 10 A at 250 V RMS meaning they could withstand around 350 V peak.

As Figure 4.5 shows, this value didn't seem abnormal so further inspection on the current flowing through the relays was done.

The next few graphics read voltage through a 1Ω resistor in series with the relay meaning 1 Volt read in the graphics is, in fact, 1 Amp.

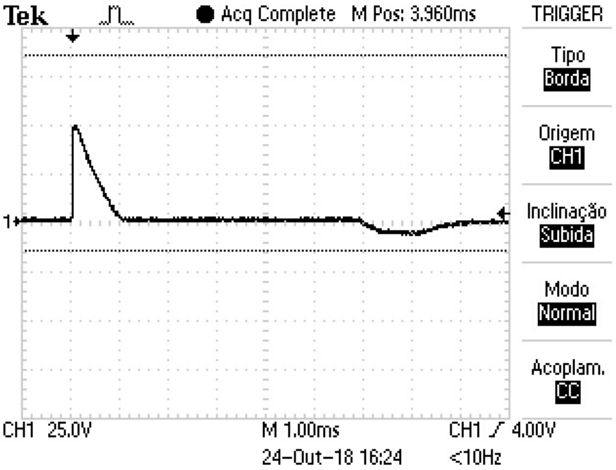

Figure 4.6: Voltage at a 1Ω resistor through the Mechanical Relay with no load

In Figure 4.6, the mechanical relay without a load is exposed during 1ms to a 50 A current. This current is very high for its specifications although it is with a PSU under load that an even greater value is observed.

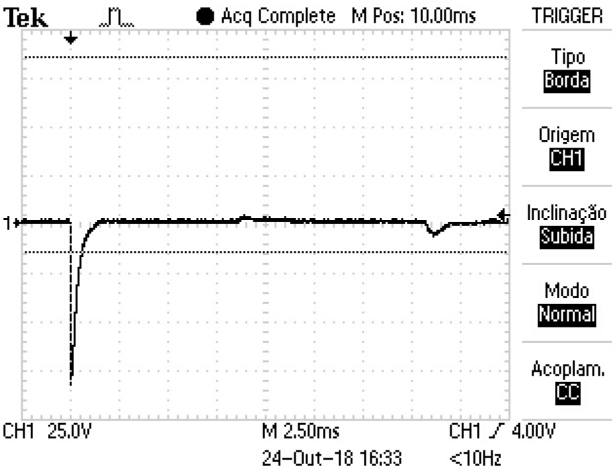

Figure 4.7: Voltage at a 1Ω resistor through the Mechanical Relay under load

Figure 4.7 clearly shows a current of around 80A passing through the mechanical relays, which was destroying them. Despite the fact that these are very short time current peaks, the relays were having their life cycles reduced greatly.

The use of a *Solid-State Relay* (SSR) was taken into consideration as a solution for this problem. A similar inspection was conducted to ensure that this was, in fact, a safe solution. The SSR has a built in Zero-Crossing Circuit making the circuit switch ON or OFF only when the sine wave is at 0 V preventing troublesome behaviors associated with switching activity on random points of the AC sine wave.

The behavior of the SSR relay is very constant having a 9V peak, on the 1 Ω resistor, for about 4 ms, meaning 9 A through the SSR relay regardless of the PSU connected to it having a load or not. This SSR model, the *SSR-25 DA*, is labeled at 25 A maximum current and its behavior can be seen below, on Figure 4.8

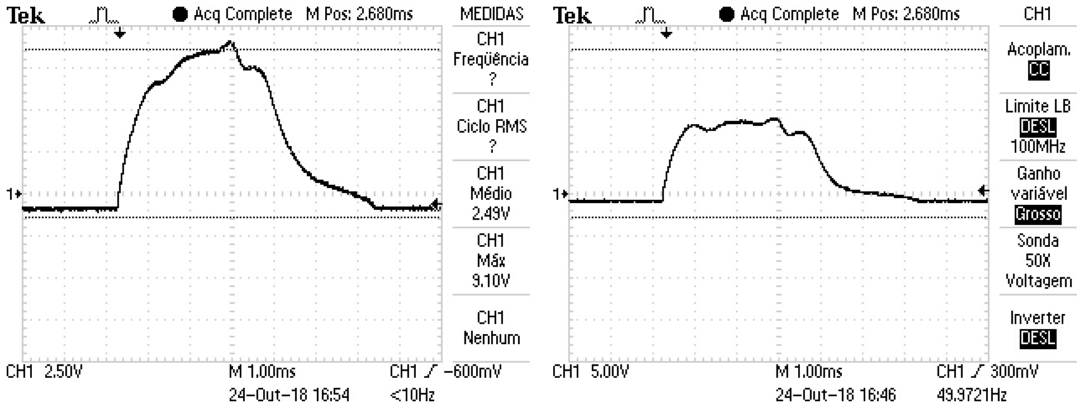

Figure 4.8: Voltage at a 1Ω resistor through the SSR connected to a PSU with no load(left) and with load(right)

4.2.2 Ageing Platform Fix

After investigating the reasons behind the failure of the ageing platform's relays and verifying that the *Solid-State Relay* was a feasible solution, a simple and quick fix was implemented in order to ensure the work could be continued as soon as possible. The Arduino Mega was programmed from scratch to make it easier and quicker than debugging the existing code. This way, 8 independent relays ceased to exist and only one controllable relay was used to do the rest of the ageing process.

A simple code was implemented to operate the SSR activating and deactivating the *Arduino*'s digital output with delays in-between. The number of iterations and on/off times are programmable only via the *.c* file, included in Appendix B, in which there are appropriate comments on where and how to edit such parameters.

4.3 Conducted Emissions EMC Test Results

It is important to say that all controllable variables in every test measurement were handled properly, meaning that only the DUT was changed in every test setup measurement. It is also relevant to say that, in this section, there will only be presented significant cases. All graphic colors go from a lighter to a darker color meaning lighter color measurements are done previous to the darker colored ones.

4.3.1 Failing EMC Test DUT

Right at the beginning of the present work, it was found that one of the batches did not pass the EMC conducted emissions standard tests. While all the *Batch A* passed all the EMC tests, none of the units from *Batch B* passed any conducted emissions test.

With no iterations done, with new, out of the shelf power supplies, all of these *Batch B* PSU, did not meet the conducted emissions standard requirements. DUT number 11, one of the control units, is an example of this and it is shown further on the next section. It is worth mentioning that these were the cheapest manufactured PSU.

4.3.2 Control Group Power Supply Units

During the process, the control units conducted emissions were measured at random, separated days and hours of the day but always keeping track of the order that measurements were performed. The overall measurements of the control units are stable throughout the extent of the work meaning all changes that possibly could be observed on other DUT would be from the ageing process carried on the power supplies.

It is vital to remark that no iterations were made on any of the control group PSUs. Figure 4.9, represents, average measurements of the control unit PSU #2 across the course of all the ageing process. The legend's measurement numbers are only indicative of the chronological order that the control units were measured. The average normative limit is always represented by the red line in the graphics, except in Section 4.3.8.

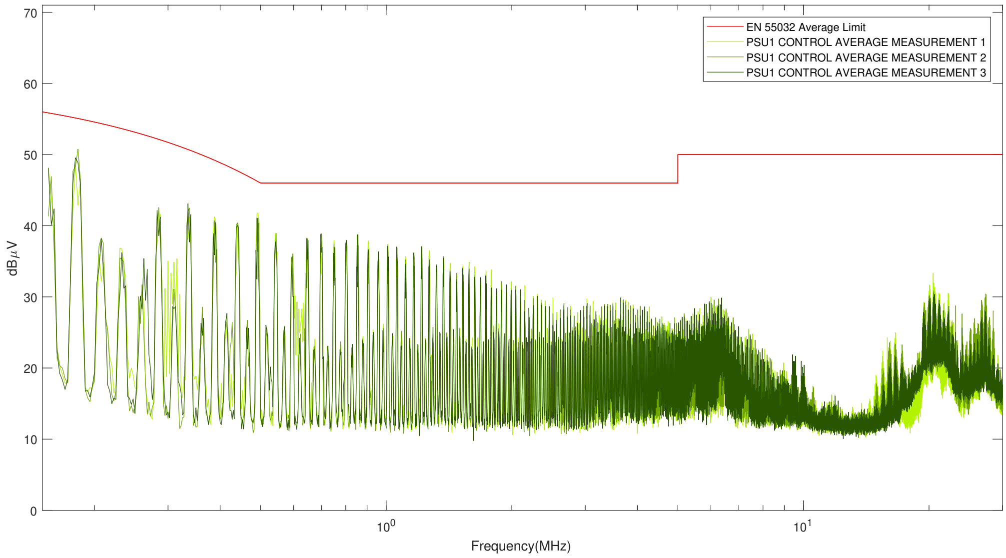

Figure 4.9: Average Measurements of the PSU #2

Maximum average values and their corresponding frequency in the spectrum remain fairly the same on all different measurements, on different dates, from the beginning to the end of the ageing process occurring on the other DUT. This is a desirable control behavior for the control units since we should expect no ageing and no significant changes in the conducted emissions test performance.

Despite the fact that none of the *Batch B*'s PSUs did not pass the conducted emissions standard tests, these units still have a desirable control group behavior as it can be seen in Figure 4.10

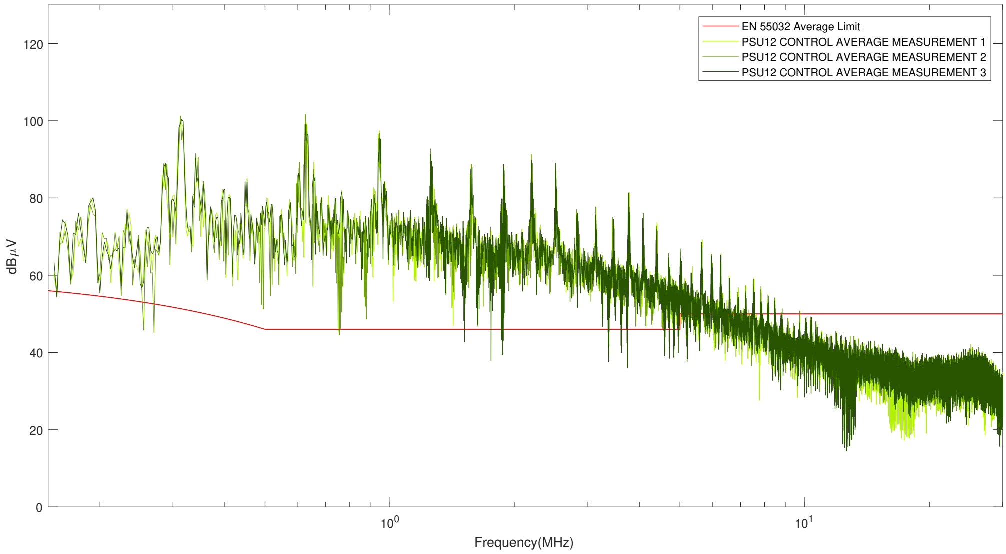

Figure 4.10: Average Measurements of the PSU #12

Peak measurements of the control units #1 and #11 in Figures 4.11 and 4.12, respectively, are desirable measurements as there are no changes in conducted emissions throughout time. These measurements happened in different days at different times of the day since the start, to the end of the present work.

The graphics presented so far, represent the behavior of all the control group's DUTs and represent the expected non-variable behavior after the course of the ageing process done on all of the other power supplies.

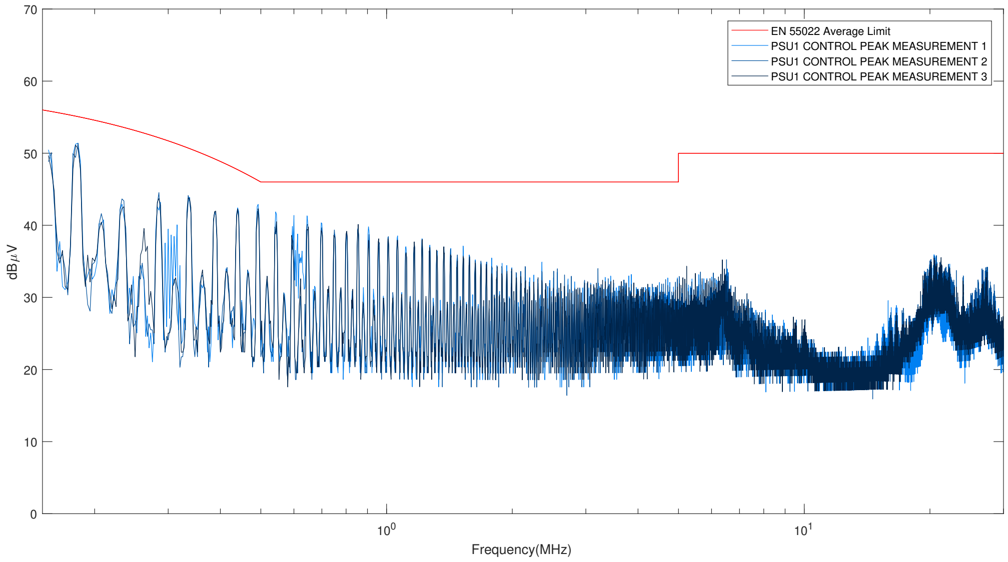

Figure 4.11: Peak Measurements of the PSU #1

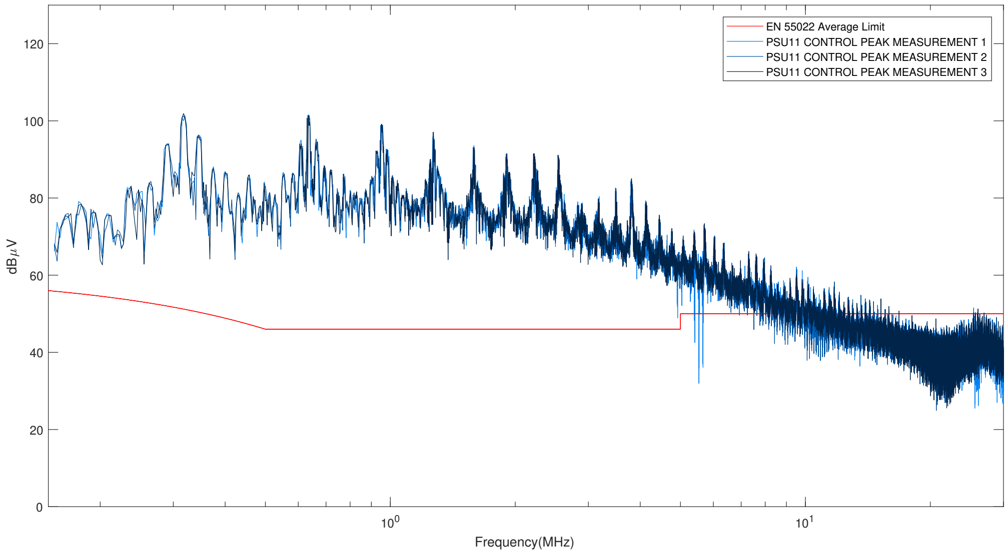

Figure 4.12: Peak Measurements of the PSU #11

4.3.3 No Load Ageing

Ageing without a load was found out to be lightly influential on the equipment's conducted emissions testing performance. During the next sections, the graphics and the cases exposed are representative of the behavior of most of the PSUs belonging to each group aged under the same conditions. Worst and best cases are described beneath.

DUTs Number 3 to 10 (No Load)

DUT Number 3 is representative of the bundle of SMPSs numbered from 3 to 10 and have average values that stay reasonably the same until the end of the ageing procedure.

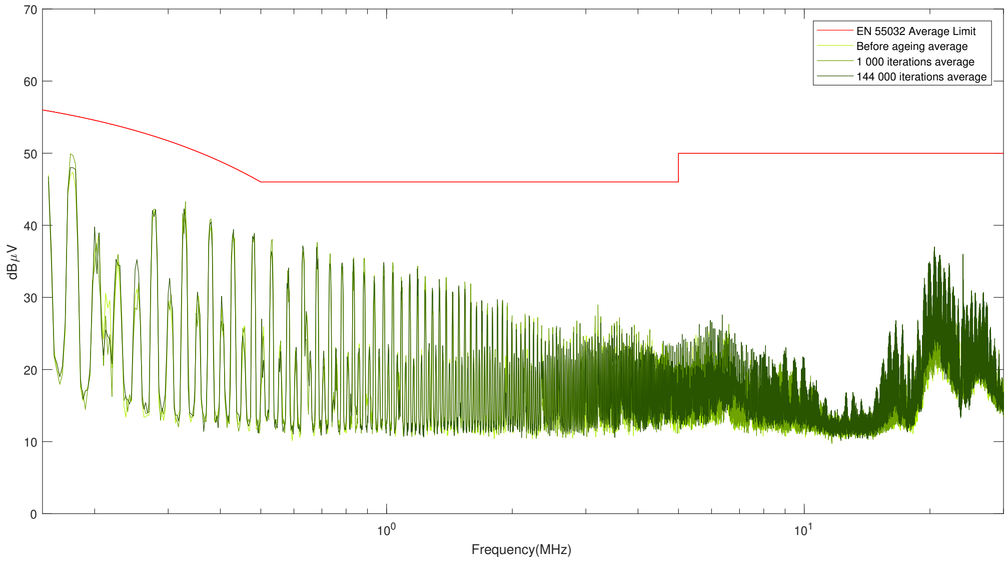

Figure 4.13: Average Measurements of the PSU #3

Maximum average values do not quite change although the bottom of the curve seems to rise across all frequency spectrum as it can be observed in Figure 4.13. The lighter colored measurements stay below the darker colored ones: the bottom of the curve of the last measurements(after ageing) has increased.

Contrary to average values, there are two units of this group that have a significant change in peak values. Maximum measured peak values increase while still observing(in 4.14) a similar small increase in the bottom of the curve as the average graphic above (Figure 4.13).

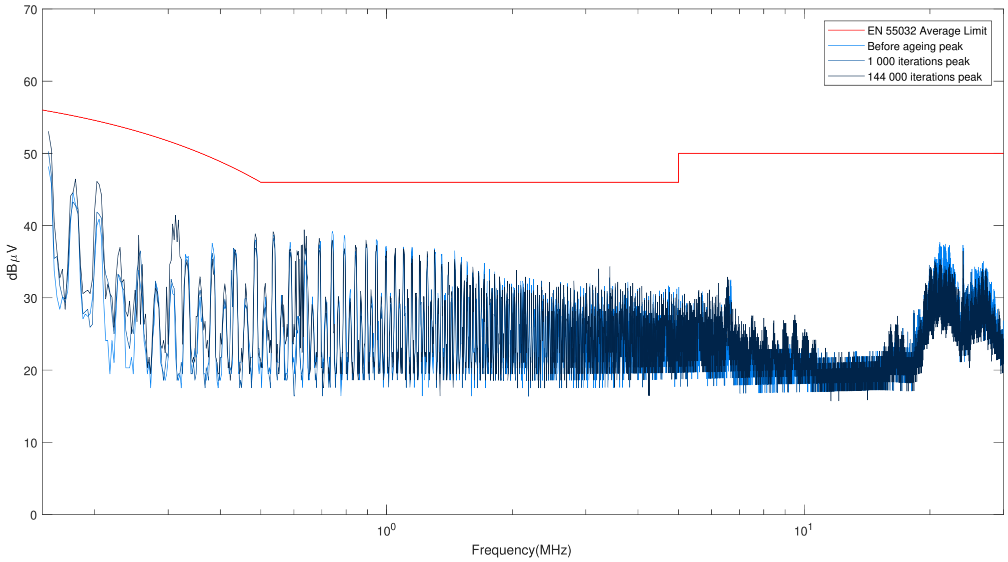

Figure 4.14: Peak Measurements of the PSU #5

DUTs Number 13 to 20 (No Load)

DUTs number 13 to 20 were aged as the guidelines in section 3.10.1 and as it can be seen in Figure 4.15, although being part of the more noisy batch of DUTs, there is no significant variation on PSU #14 nor any other DUTs after the ageing process. Once again, just like the previous section, the bottom of the measurements increases.

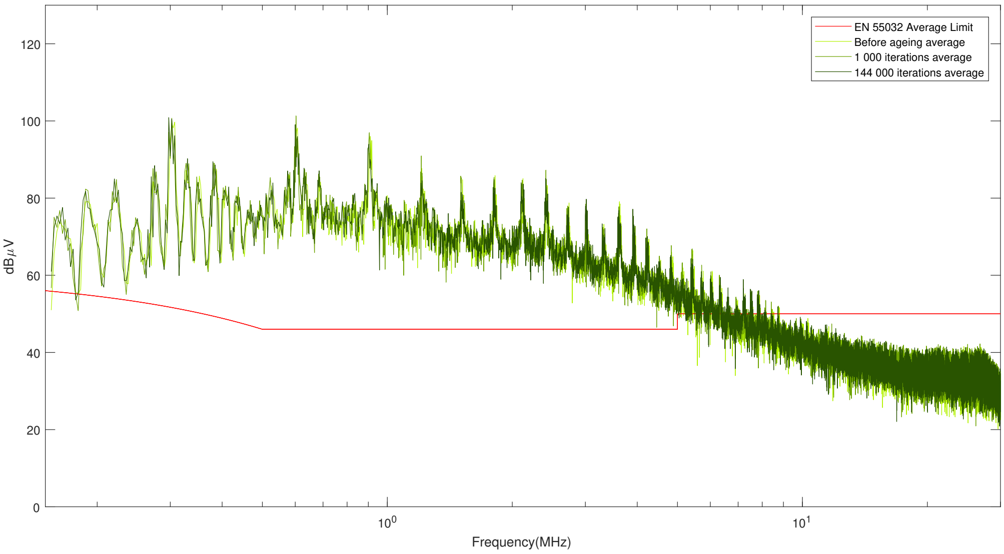

Figure 4.15: Average Measurements of the PSU #14

Peak measurements in this group of power supplies stay fairly the same throughout all the ageing process and only two of them show a slight increase in the minimum measured values. While maintaining the top measurements, Figure 4.16 represents this slight change.

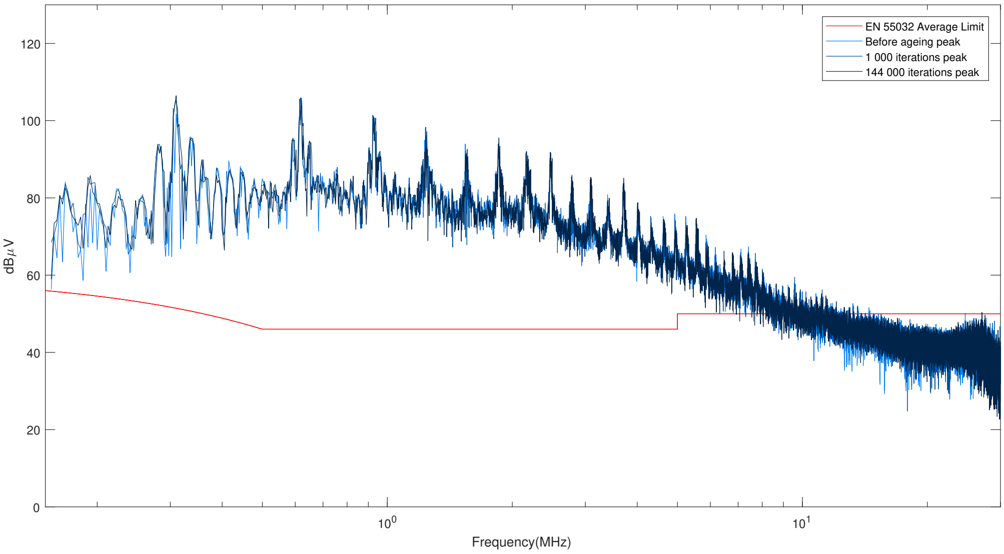

Figure 4.16: Peak Measurements of the PSU #17

4.3.4 Load Ageing

Significant changes in EMC conducted emissions performance were found to be happening after ageing a device under a load. Frequency and global measurements can be seen to have clear variations in this section.

DUTs Number 21 to 28 (Load)

Once again, although being part of *Batch B* (not passing conducted emissions standards batch), every tested unit from this group had a shift to the right (in terms of frequency) in the measured conducted emissions average values. There was no significant increase in the maximum measured values although some of the DUTs show some variations in the minimum values.

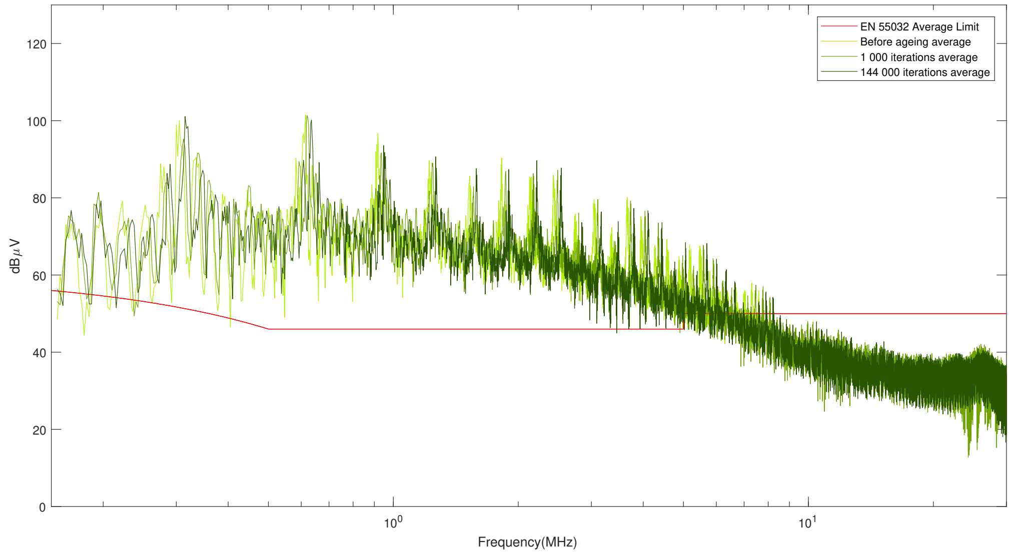

Figure 4.17: Average Measurements of the PSU #21

All the average measurement changes described above are very clear in Figure 4.17 while the same frequency deviation can be observed in peak values on another PSU in 4.18.

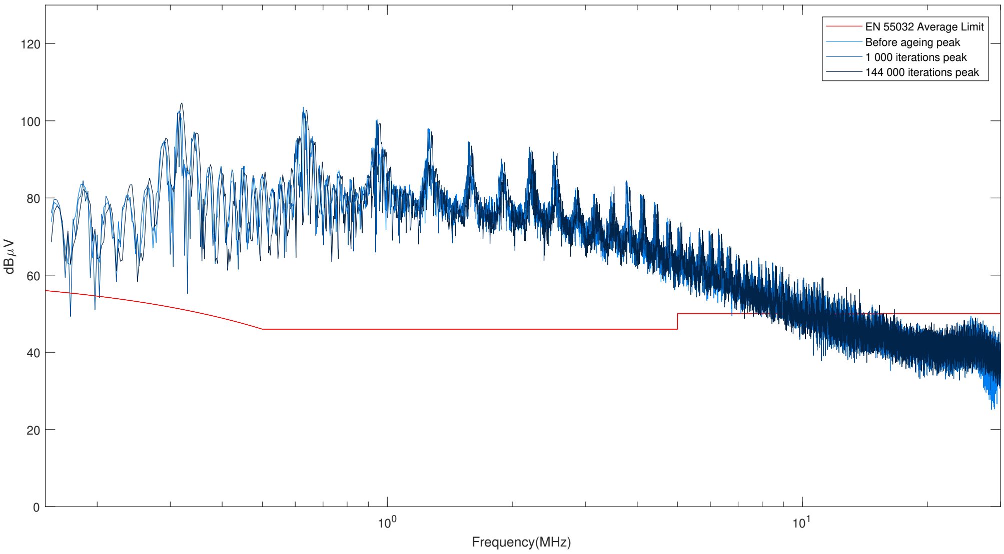

Figure 4.18: Peak Measurements of the PSU #26

This frequency transformation can only be found in the power supplies of *Batch B*, being them aged while connected to a load.

DUTs Number 31 to 38 (Load)

The most significant changes were observed in a few of these SMPS. Despite the fact that there are no frequency shift in these tested units, it was observed a great increase in the maximum measured values. PSU numbered from 31 to 38 were passing conducted emissions test standards before ageing but in this section there are some of them exceeding these same limits after the ageing process under a load.

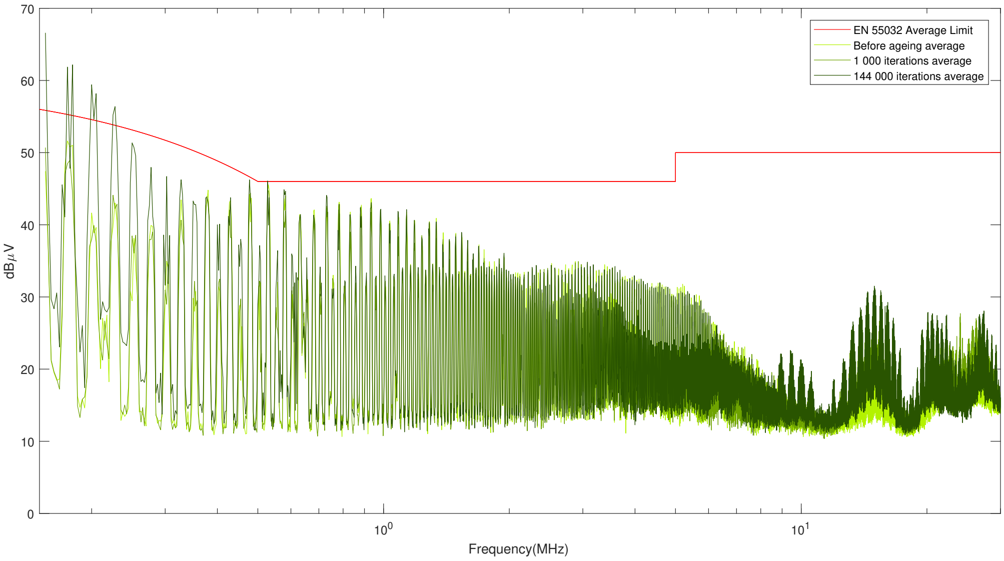

Figure 4.19: Average Measurements of the PSU #35

Before any ageing was done, DUT #35, like all other units, was passing the EMC conducted emission standard tests. As result of the ageing process, a few of these SMPSs did not pass conducted emissions standards anymore. As it can be observed in figure 4.19, measured values for DUT #35 go above the limits 10dBs after the ageing process.

DUT #33 has showed the same behavior as #35. Regarding peak measurements, it can be noticed the same enormous increase in the Figure 4.20.

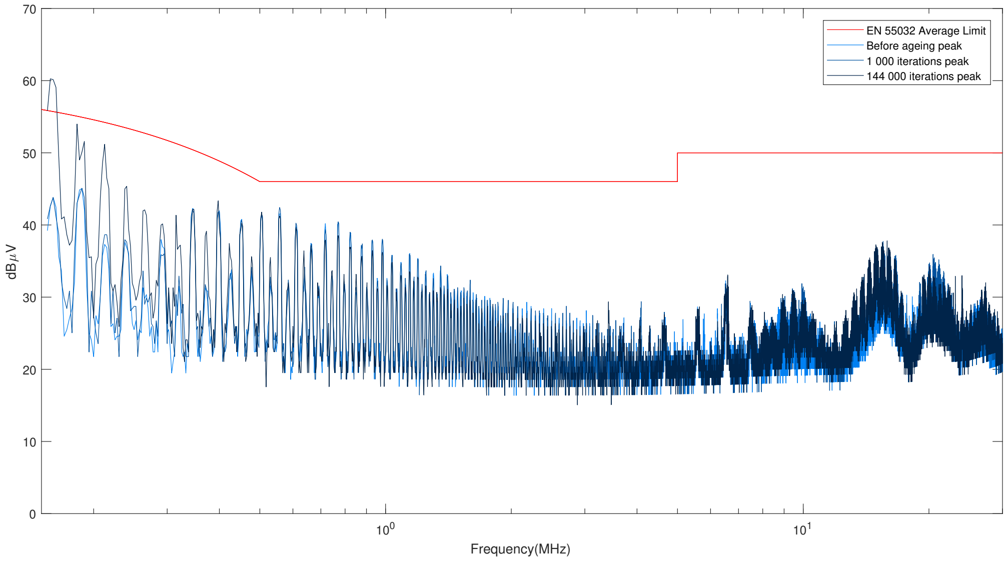

Figure 4.20: Peak Measurements of the PSU #33

4.3.5 Ultimate Random Ageing

After the ageing plan was finished, it was decided to perform an additional set of 80 000 iterations with both random on and off switching times. This means that a DUT is randomly turned on and off for a time between 0.5 s and 8 s during this set. DUT number 32, 33, 34 and 35 were chosen to this random ageing procedure. These PSU were chosen because they showed the biggest changes and the objective was to trigger an even bigger change in their EMC conducted emissions measurements. This last block of iterations made the ageing process have a total of 244 000 "on-off" switching cycles.

On the lower and higher parts of the frequency spectrum, it can be observed, in Figure 4.21, an increase in measured average values across a bigger number of harmonics. This variation on the top of the curve was more substantial after this ultimate random ageing process than all of the previous iterations.

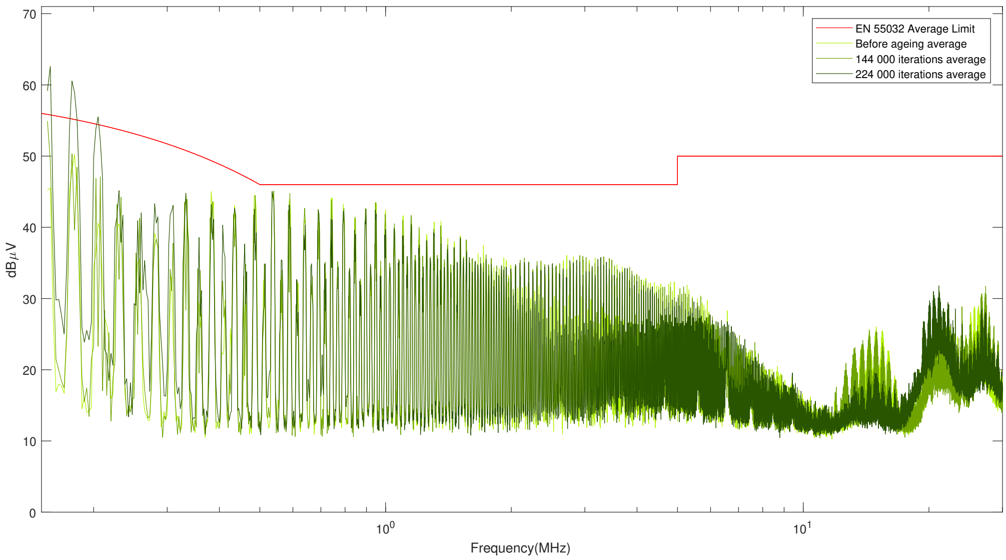

Figure 4.21: Average Measurements of the PSU #34 after the ultimate random ageing

Peak measurements also have a considerable increase in both maximum and minimum values (Figure 4.22) across all the frequencies in several DUTs, similarly to average measurements.

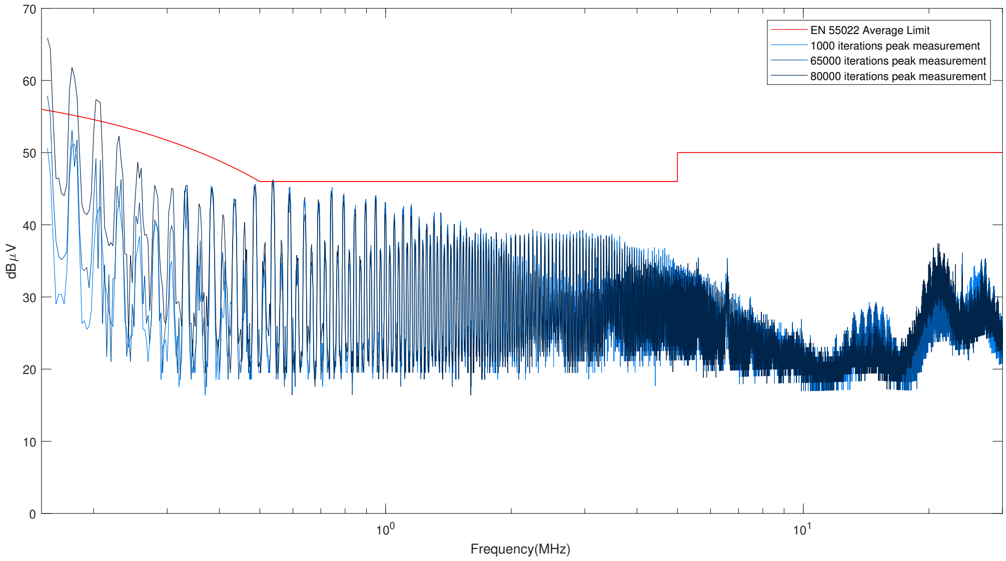

Figure 4.22: Peak Measurements of the PSU #34 after the ultimate random ageing

4.3.6 Ultimate Normal Ageing

To understand on what extent the random values influenced these variations, the remaining PSUs were aged with another 80 000 iterations but this time with the normal fixed on and off time values. DUTs number 31, 36, 37 and 38 were aged by these 80 000 iterations with fix 1s-2s "on-off" time(respectively) and it is explicit in all of them that there were no major changes compared with the random time 80 000 iterations.

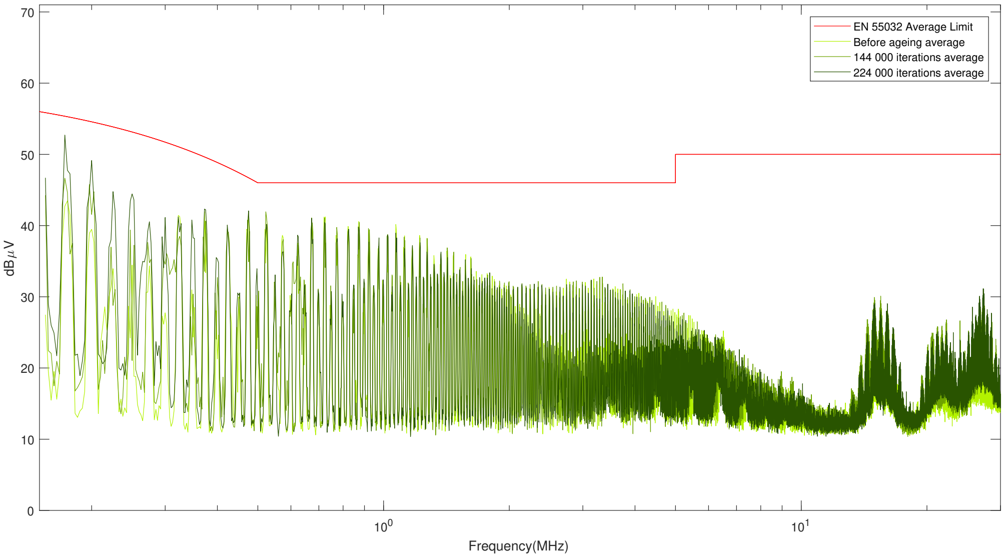

Figure 4.23: Average Measurements of the PSU #36 after the ultimate random ageing

PSU #36 was the DUT that showed greater variation in the measured average values having a slight increase in the lower and higher frequencies. Coincidentally, it is the only PSU that showed an abrupt increase in the measured peak values(Figure 4.24).

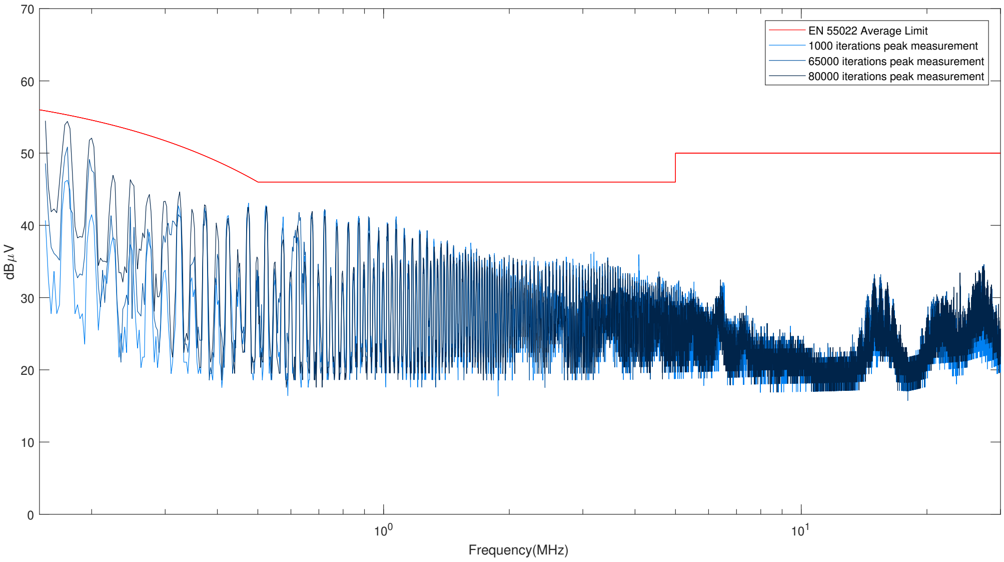

Figure 4.24: Peak Measurements of the PSU #36 after the ultimate random ageing

4.3.7 Thermal Inspection under Ultimate Ageing

So that conclusions could be taken about whether the consequences of normal time ageing and random time ageing were about temperature or not it was decided to examine the DUTs with the NEC TH7700 IR camera.

Two PSUs of the same manufacturer with similar EMC behaviour were selected to be inspected. The process used to take the IR photos was the following:

1. Take the cold (off for a long time) selected DUTs from the shelf.
2. Age one DUT for 30 minutes with the normal time ageing iterations and the other DUT with the random time iterations.
3. Take IR pictures.

Two sets of pictures were taken that clearly show that the random time iterations influence directly the temperature at which the DUTs work.

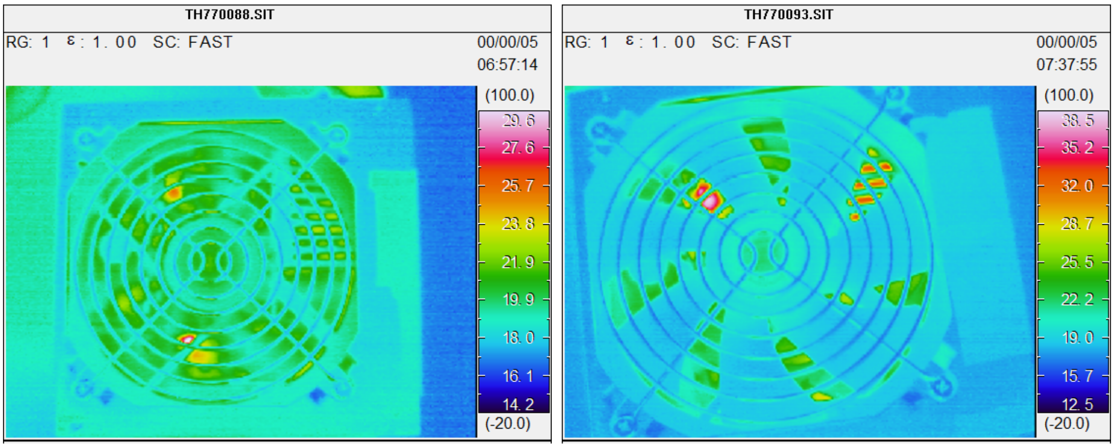

Figure 4.25: On the left, an image of a DUT after 30 minutes of normal time iterations and, on the right, a DUT after the random time iterations

The first pictures (Figure 4.25) show that the within the same duration (30 minutes) the devices show a difference of around 10^{o}C on internal components. An identical 10^{o}C difference is verifiable on the second set of pictures on another perspective that shows the inside of the PSUs(Figure 4.26).

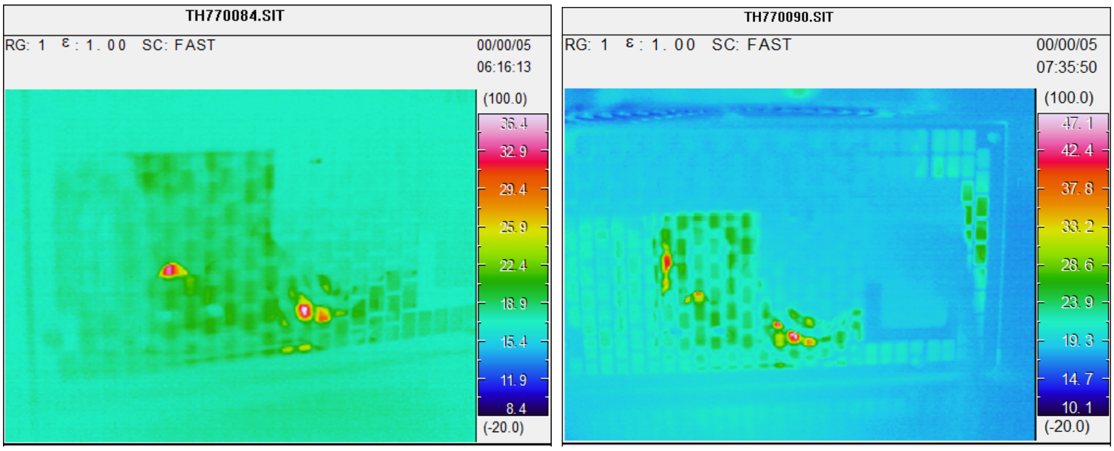

Figure 4.26: Thermal image of the DUT after 30 minutes of normal time iterations and the other DUT after the random time iterations, respectively

4.3.8 Quasi-Peak Measurements

At the end of the work it was decided to take three DUTs from *Batch A* and examine conducted emissions QP measurements. As expected, the control unit(DUT #1), was the PSU with less conducted emission measurements.

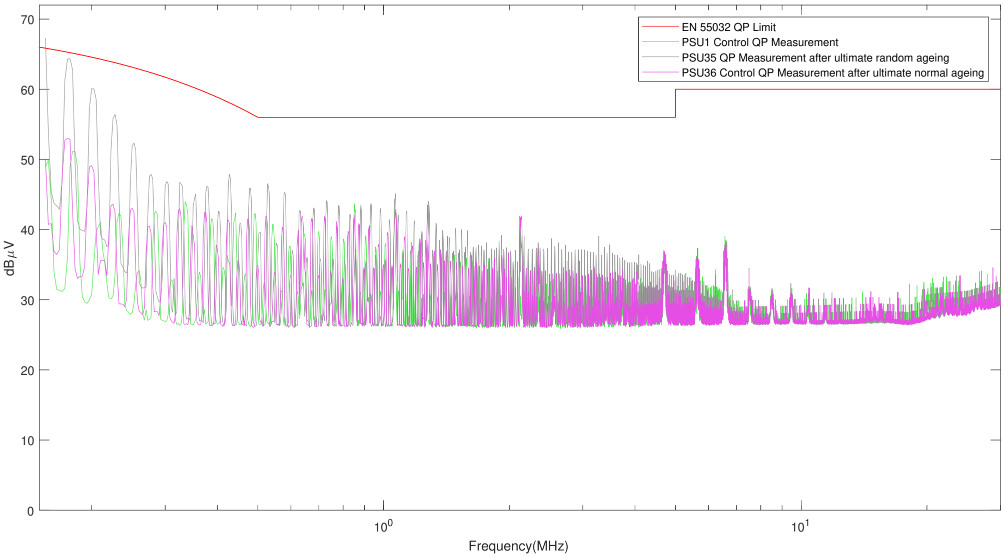

Figure 4.27: Quasi-Peak Measurements of DUT #1, #35, #36

Having 144 000 normal iterations plus 80 000 random iterations performed, DUT #35 exceeded the QP standard conducted emissions European limit. Although there was also an increase in QP measurements, after 244 000 normal iterations, DUT #36 did not exceed the QP limits.

5 Conclusions

5.1 Conclusion

From the beginning of the present work, the main focus was to find out if ageing influenced conducted emissions tests and if those same ageing alterations could possibly make a device exceed the regulated conducted emissions limits.

The ageing procedure consisted of different sets of on-off switching cycles. In order to make the appropriate choice for the switching times, charge and discharge of components was examined. After implementing a last random time iterations, these last results might indicate that time choices for switching might possibly be examined and improved further.

The mechanical relays of the platform started to fail and a solution with a *Solid-State Relay* was implemented. An indicator that *Electromagnetic Compatibility* might not be taken into serious account by manufacturers is that a batch of manufacturer new power supplies from a specific manufacturer, the cheapest one used in this work, did not meet the *Electromagnetic Compatibility* EN 55032 conducted emissions limits.

Thermal imaging analyses was performed with the objective of better understanding some specific components' behavior. The approach used for this matter might have been short-handed because the equipment used might have been limiting. Despite this fact, some clear conclusions were taken since it was found that a thermistor abruptly increased its temperature when the power supply was switched on and off continuously. While ageing with a random 0.5s-8s switching time and after 30 minutes of switching, a difference of 10ºC was found to exist in the power supplies internal components when compared to 1s-2s fixed switching after the same amount of time. As it is well-known, temperature plays a big role in the ageing of devices and the results explained in this paragraph might indicate that, perhaps, temperature can be as important as the switching times chosen.

Even though a batch of power supplies exceeded conducted emissions normative limits, these same devices showed a shift in terms of frequency and increase in measured conducted emissions, being this fact more noticeable when aged while connected to a load. This frequency shift was not observed in the other batch of tested devices but an increase in the conducted emissions measurements was very clear.

Due to the ageing process, it is evident that some of these power supplies did not meet the European conducted emissions standards anymore even though they were within these limits before the ageing process began.

5.2 Future Work

Since one of the main devices, the ageing platform, broke down mid-work, it needs deeper and better modifications. The use of more than one independent *Solid-State Relay* could possibily be a major implementation. A different *GUI* could also be implement instead of the present *LabView GUI.* When doing random time switching, these random generated intervals could be saved so they could possibly be investigated. A small display could also be implemented so that important information can be shown without a physical connection to a computer.

Power supplies are very complex systems and should be investigated down further into smaller, less complex components or parts. It might be interesting to find out where these ageing changes come from and try to model these same critical components. This would allow manufacturers to be able to modulate their products in terms of ageing and *Electromagnetic Compatibility*.

6 Bibliography

[1] C. R. Paul, *Introduction to electromagnetic compatibility*, vol. 184. John Wiley & Sons, 2006.

[2] T. Hegarty, "An overview of conducted EMI specifications for power supplies," 2018.

[3] J. Scott and C. V. Zyl, "15 Introduction to EMC," pp. 5–24, 1997.

[4] "International Electrotechinal Comiision - Electromagnetic Compatibility / Basic Concepts." `http://www.electropedia.org/iev/iev.nsf/display?openform&ievref=161-01-06`, Sep 2018.

[5] E. M. Montrose M. I. Nakauchi, *TESTING FOR EMC COMPLIANCE Approaches and Techniques*. 2004.

[6] R. Staff, "Mobile phone use in hospitals poses danger: study." `https://www.reuters.com/article/us-mobilephones-hospitals/mobile-phone-use-in-hospitals-poses-danger-study-idUSL0685683920070906`, September 2007. last checked: 30.04.2018.

[7] "Electromagnetic interference from some identification devices may pose hazards to medical equipment." `http://esciencenews.com/articles/2008/06/24/electromagnetic.interference.some.identification.devices.may.pose.hazards.medical.equipment/`, June 2008. last checked: 30.04.2018.

[8] E. Scarry, "Swissair 111, TWA 800, and Electromagnetic Interference." `http://www.nybooks.com/articles/2000/09/21/swissair-111-twa-800-electromagnetic-interference/`, September 2000. last checked: 30.04.2018.

[9] I. Media, "EMI Named as Cause in Ferry Crash Lawsuit." `https:`

//interferencetechnology.com/ferry-crash-emi/, Dec 2013. last checked: 30.04.2018.

[10] R. D. Leach and M. B. Alexander, "Electronic systems failures and anomalies attributed to electromagnetic interference," no. July, pp. 1–22, 1995.

[11] L. Rapaport, "Pacemakers may malfunction near certain appliances or tools." https://www.reuters.com/article/us-health-pacemakers-appliances-idUSKBN1662EX, Feb 2017. last checked: 30.04.2018.

[12] "Differential (normal) mode noise and common mode noise | basic knowledge," 2018.

[13] T. Lee, "Accelerated Life Testing," vol. 47, no. 2, pp. 135–141, 1998.

[14] J. Alcafache, "Ageing Platform for EMC Testing," Master's thesis, DEEC-UC, 2016.

[15] Acer, "EMI TEST REPORT CISPR 22 Class B," tech. rep., 2001.

[16] K. Armstrong, "A Practical Guide for EN55022 and EN55011,"

[17] "Thermo Tracer TH7700." http://www.infrared.avio.co.jp/en/products/ir-thermo/lineup/th7700/index.html.

[18] "Infrared camera optris PI 400 / PI 450." https://www.optris.global/thermal-imager-optris-pi400-pi450.

Appendices

A EMC Conducted Emissions Test Graphics

Control DUT 1

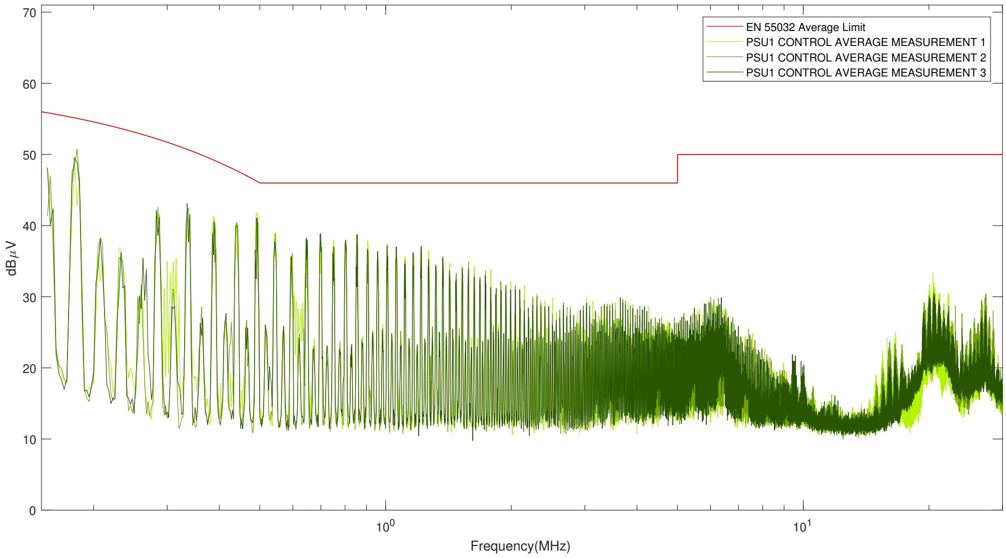

Figure A.1: Average Measurements of DUT #1

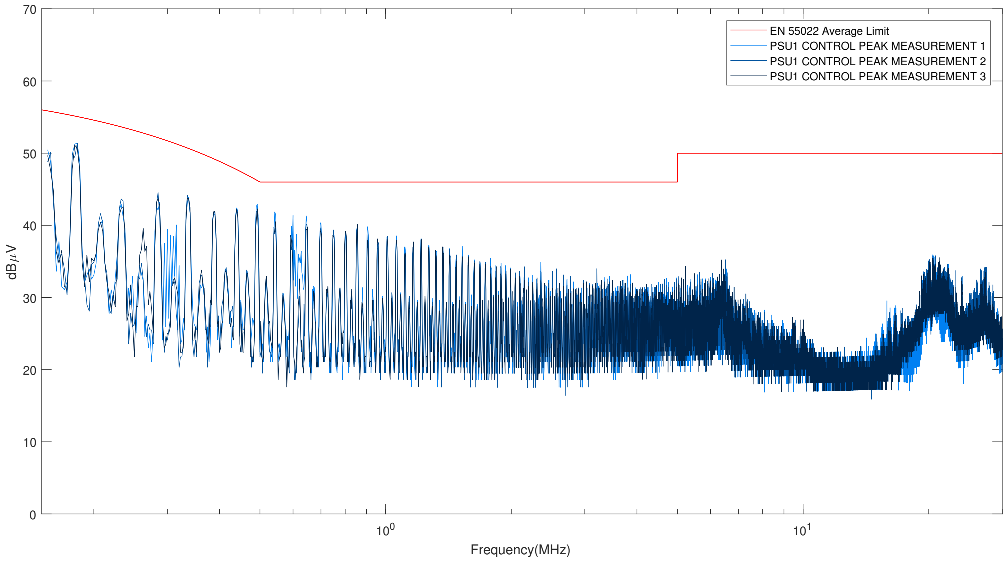

Figure A.2: Peak Measurements of DUT #1

Control DUT 2

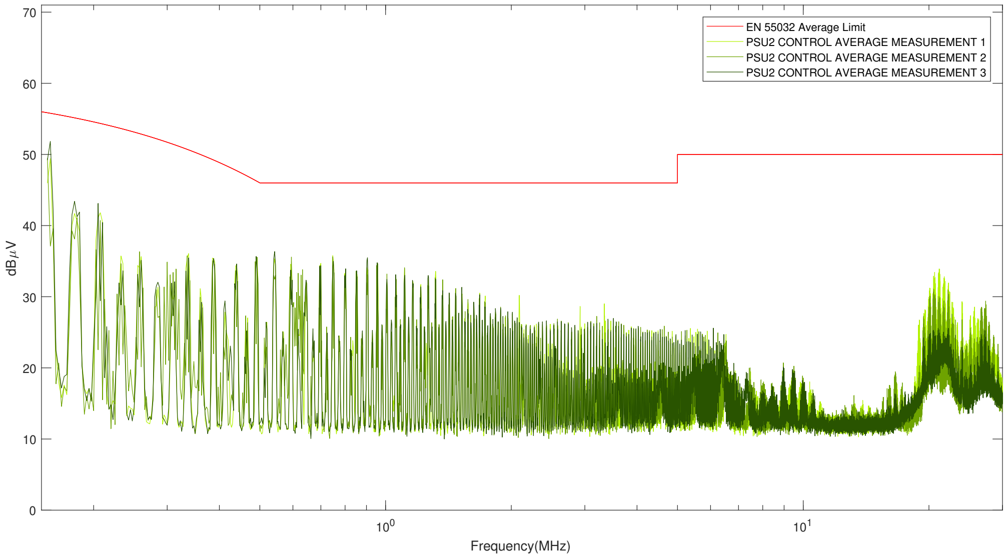

Figure A.3: Average Measurements of DUT #2

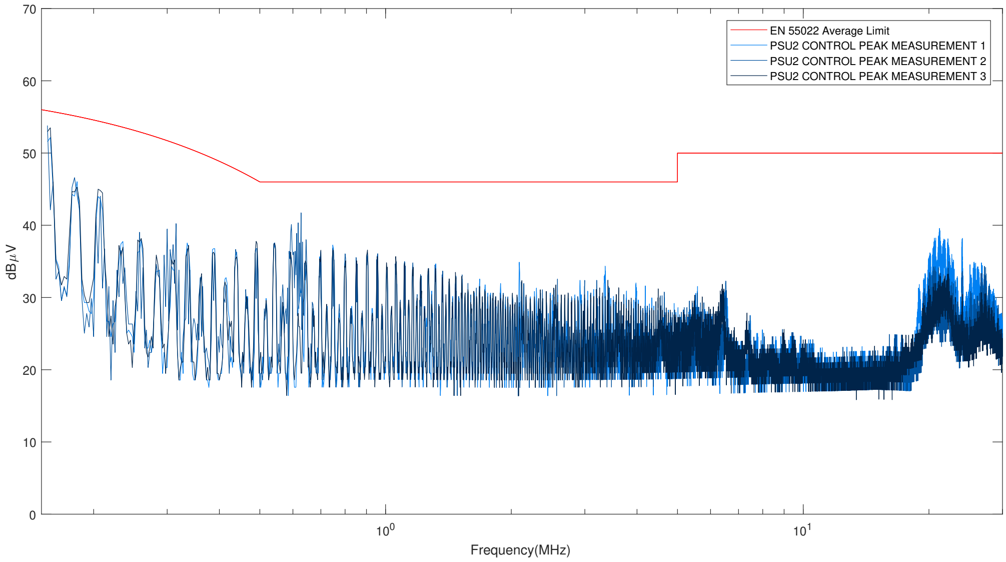

Figure A.4: Peak Measurements of DUT #2

DUT 3

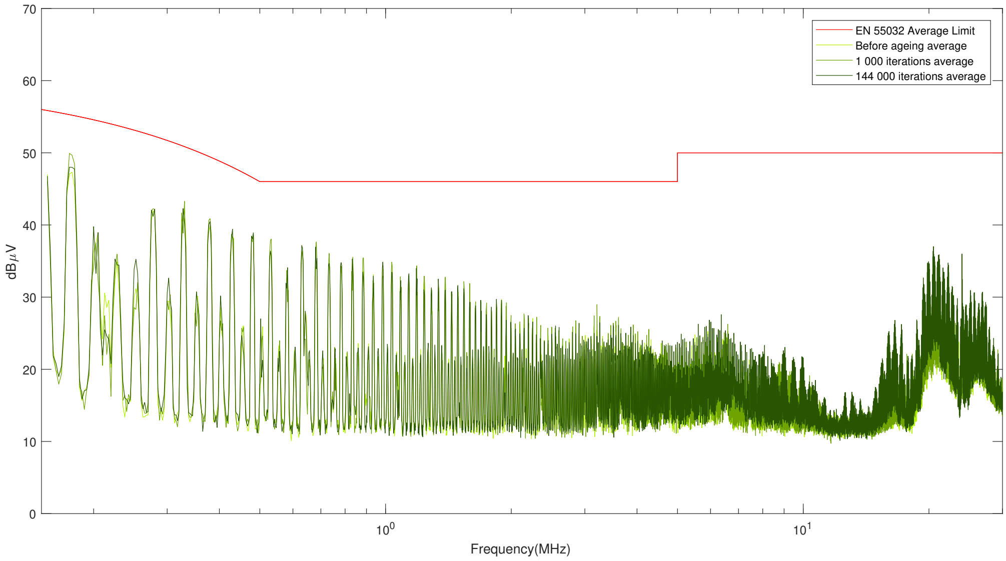

Figure A.5: Average Measurements of DUT #3

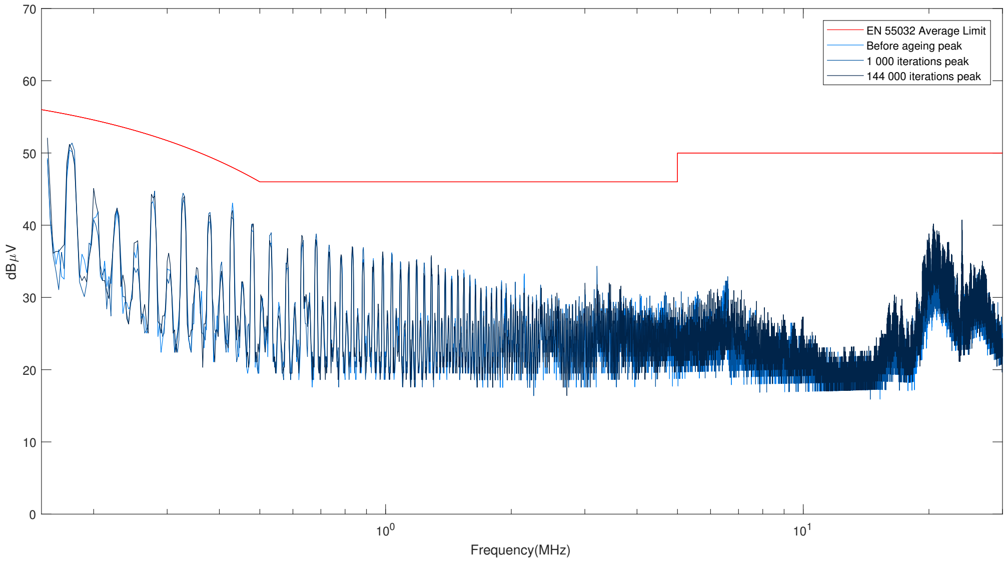

Figure A.6: Peak Measurements of DUT #3

DUT 4

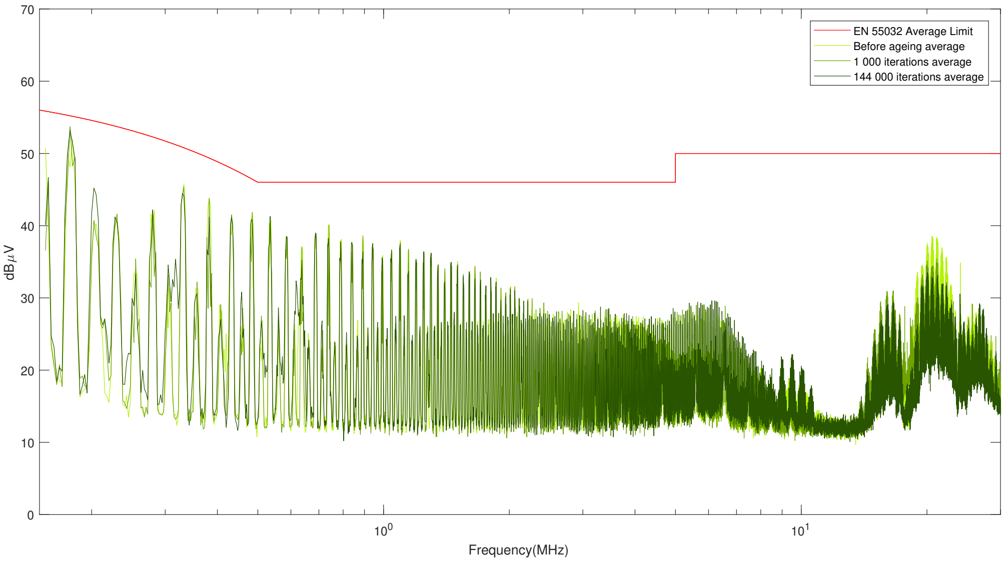

Figure A.7: Average Measurements of DUT #4

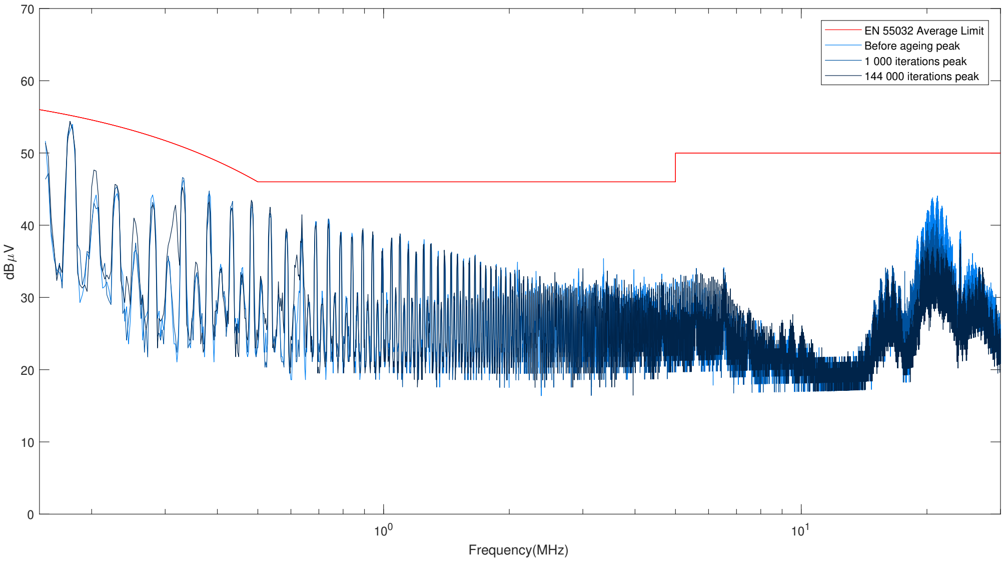

Figure A.8: Peak Measurements of DUT #4

DUT 5

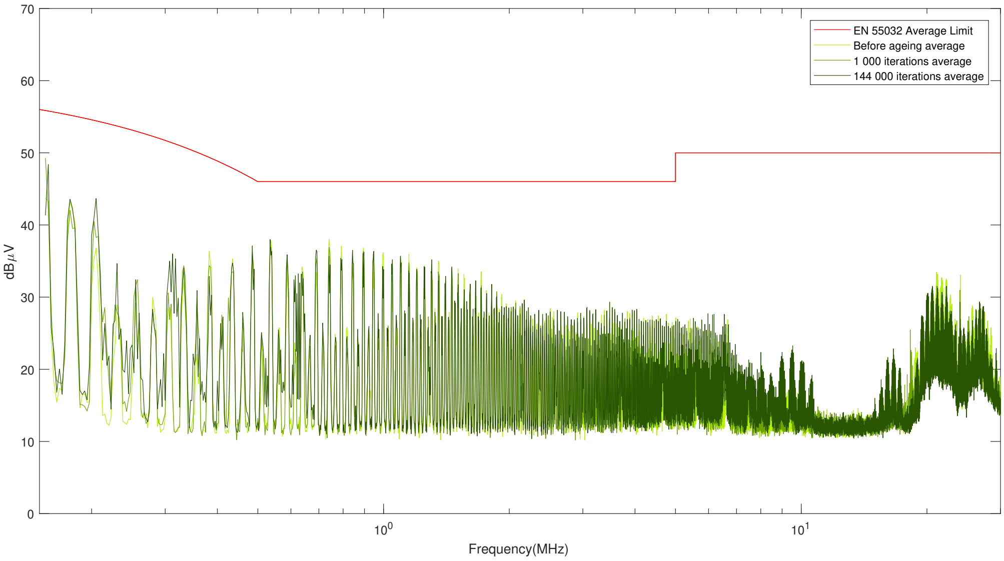

Figure A.9: Average Measurements of DUT #5

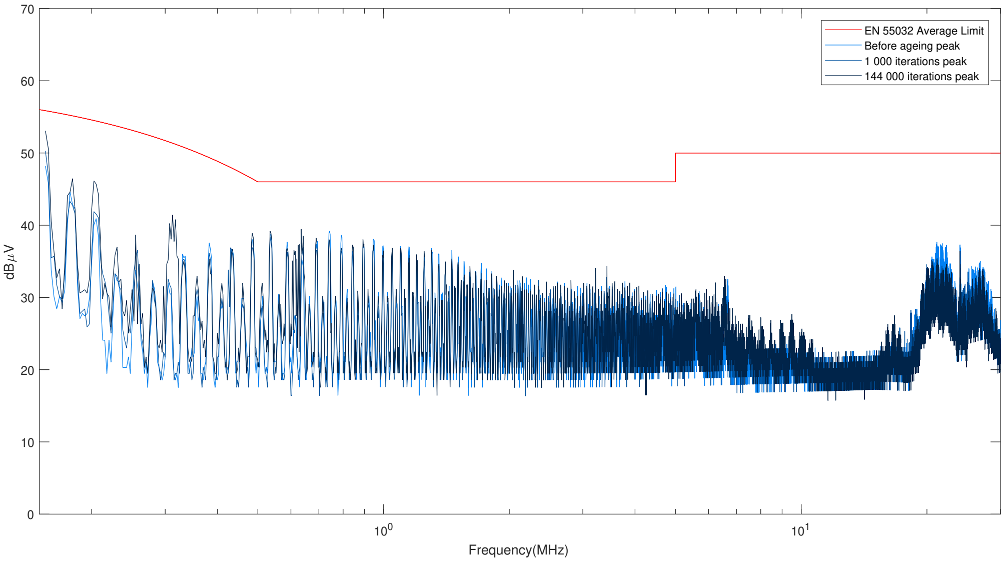

Figure A.10: Peak Measurements of DUT #5

DUT 6

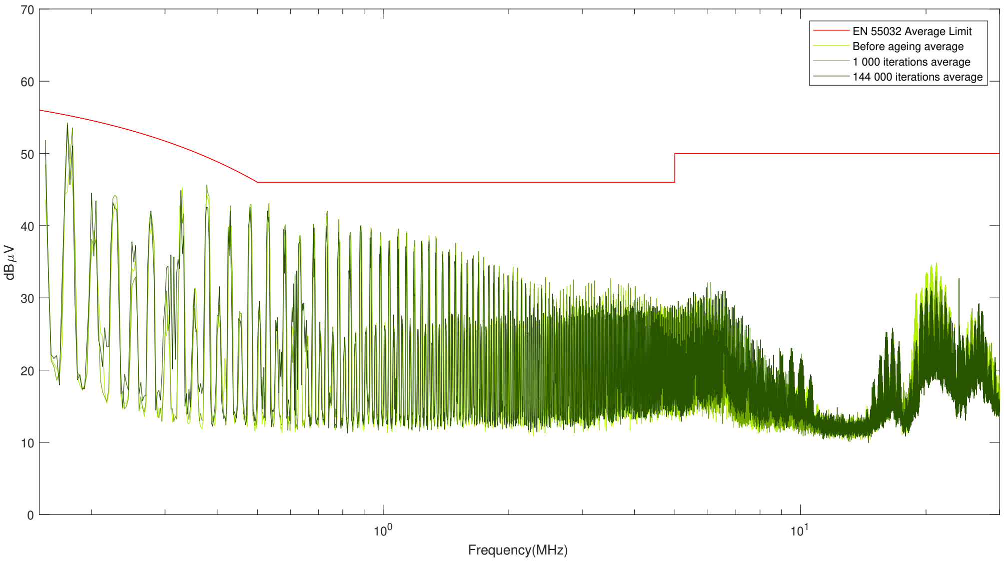

Figure A.11: Average Measurements of DUT #6

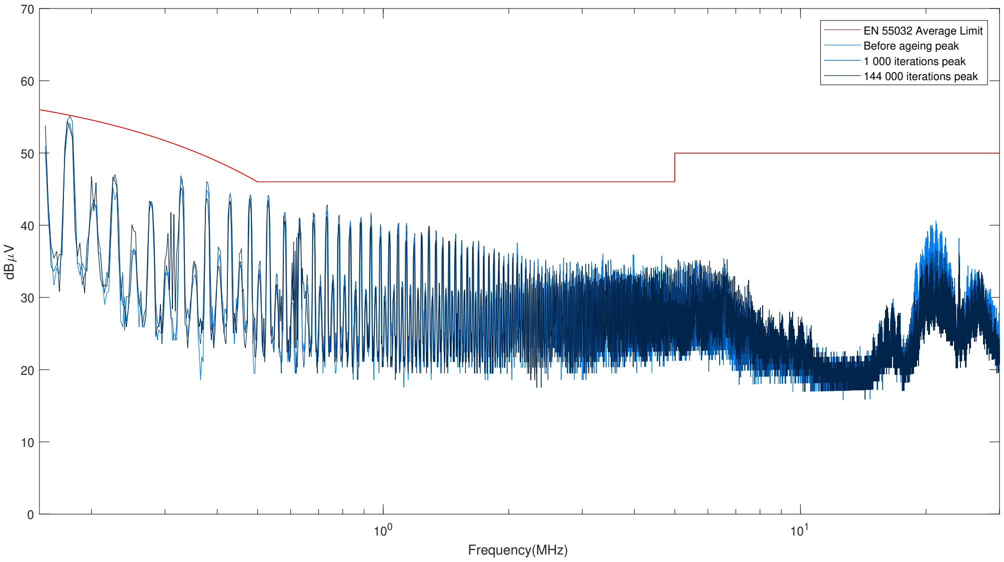

Figure A.12: Peak Measurements of DUT #6

DUT 7

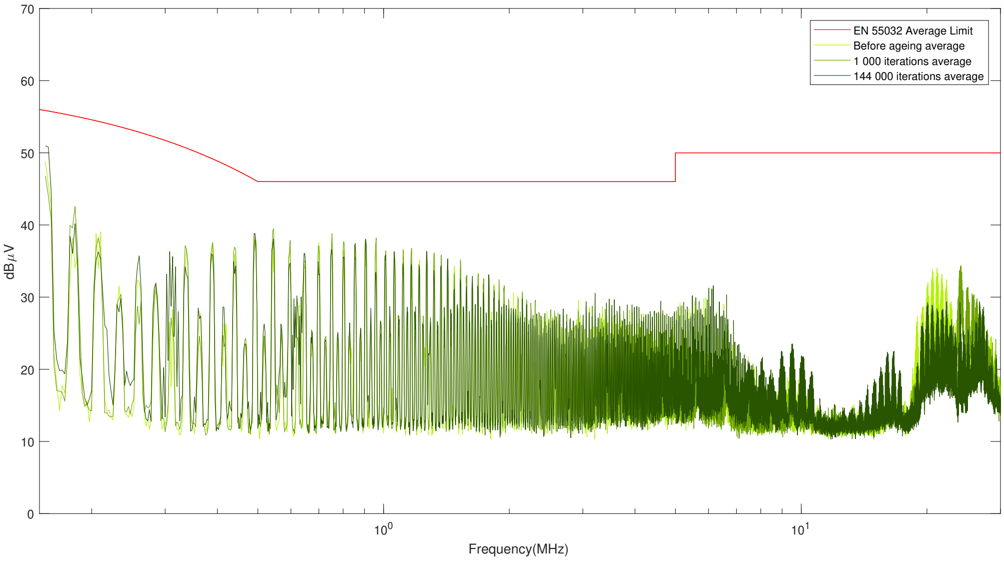

Figure A.13: Average Measurements of DUT #7

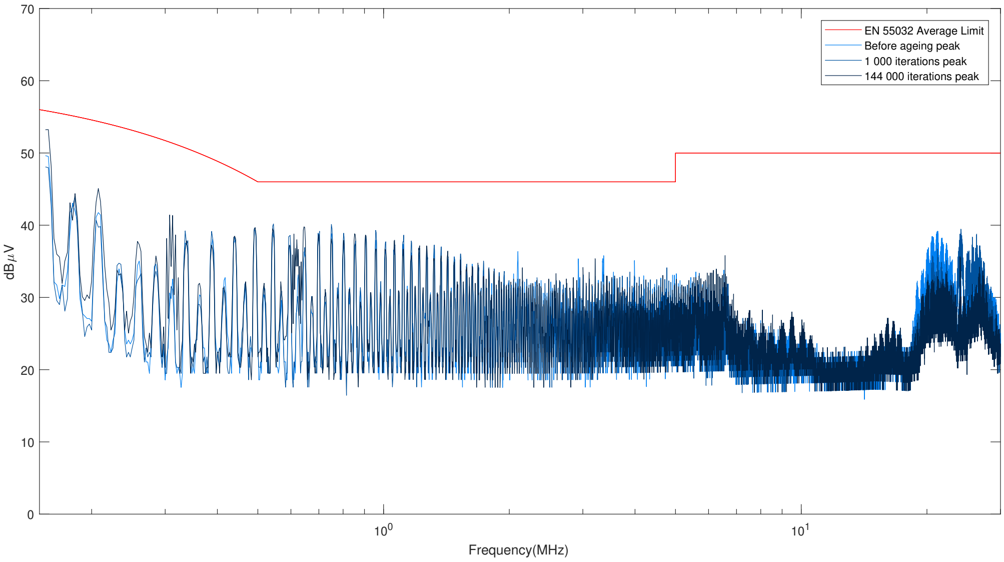

Figure A.14: Peak Measurements of DUT #7

DUT 8

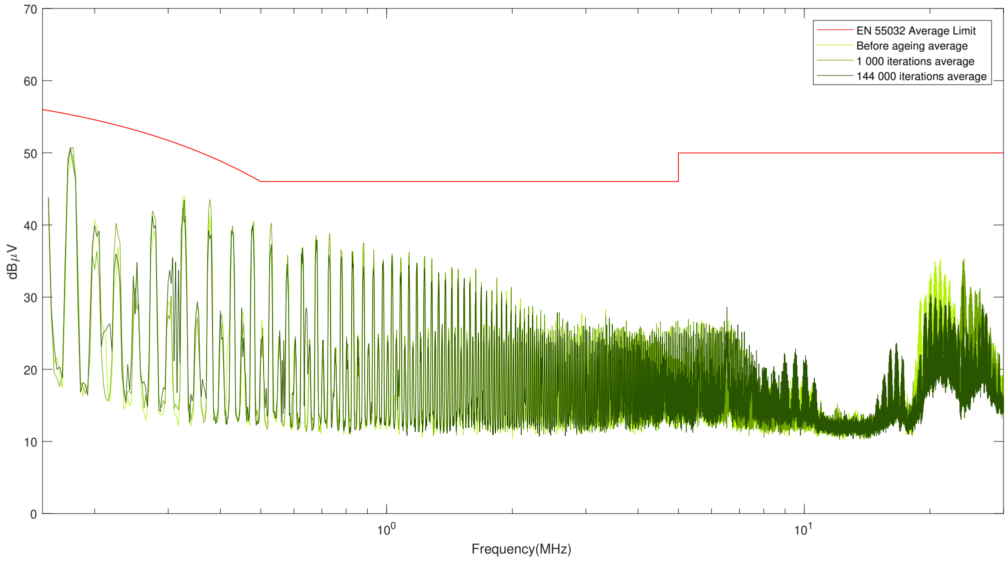

Figure A.15: Average Measurements of DUT #8

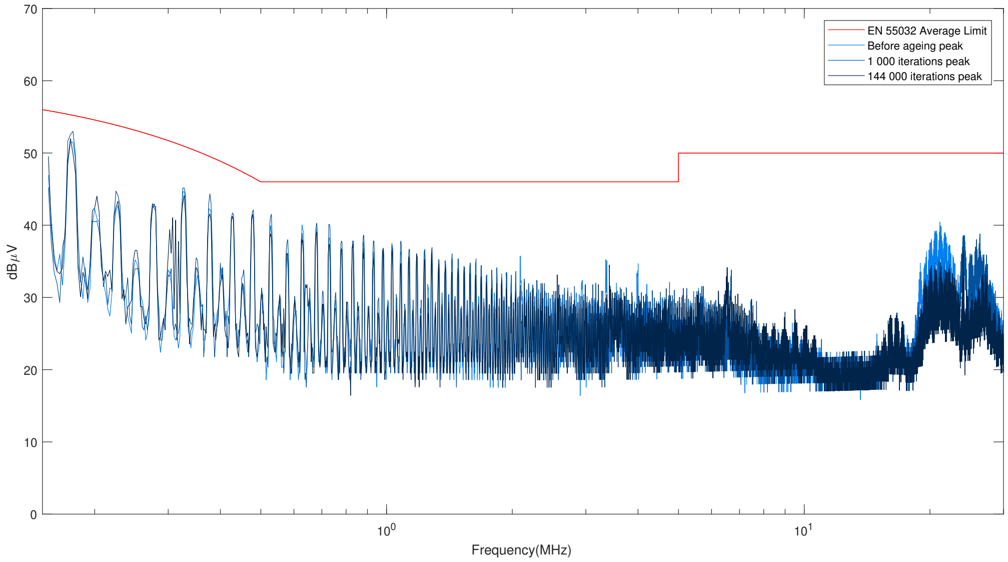

Figure A.16: Peak Measurements of DUT #8

DUT 9

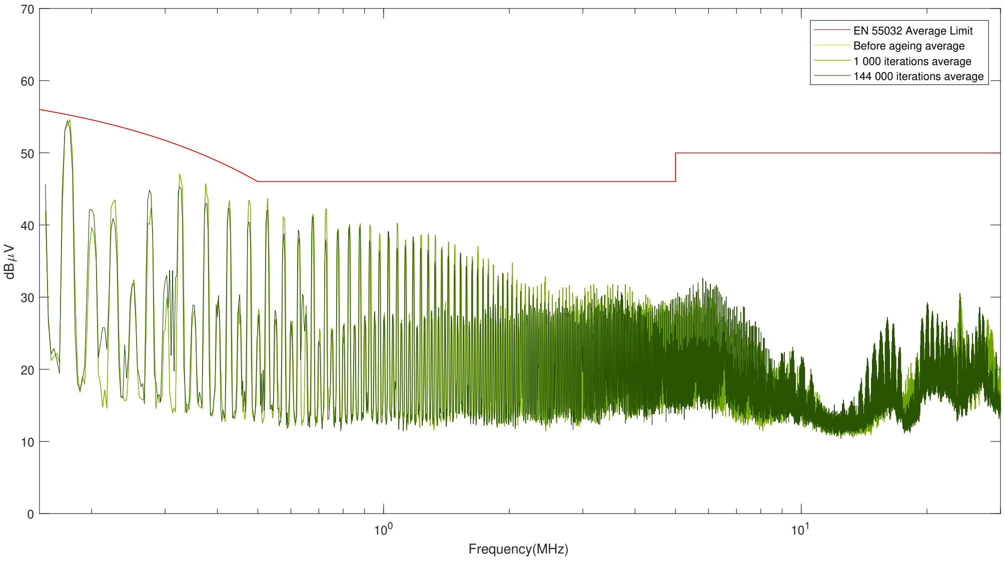

Figure A.17: Average Measurements of DUT #9

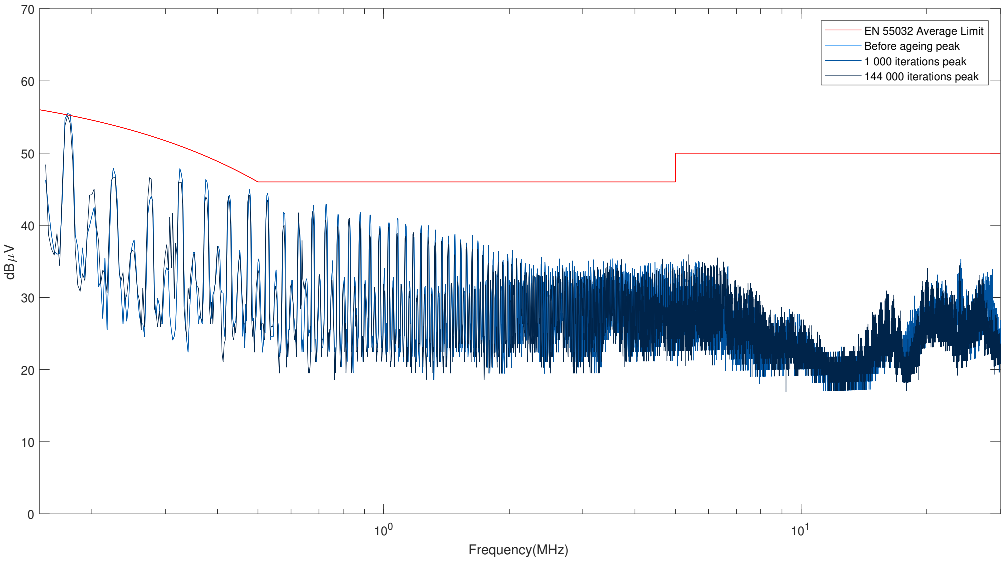

Figure A.18: Peak Measurements of DUT #9

DUT 10

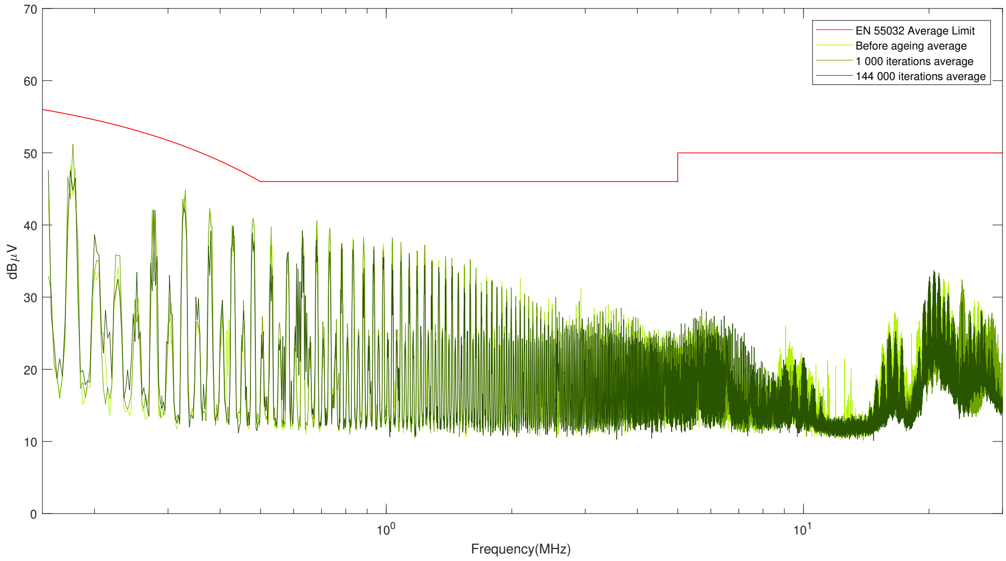

Figure A.19: Average Measurements of DUT #10

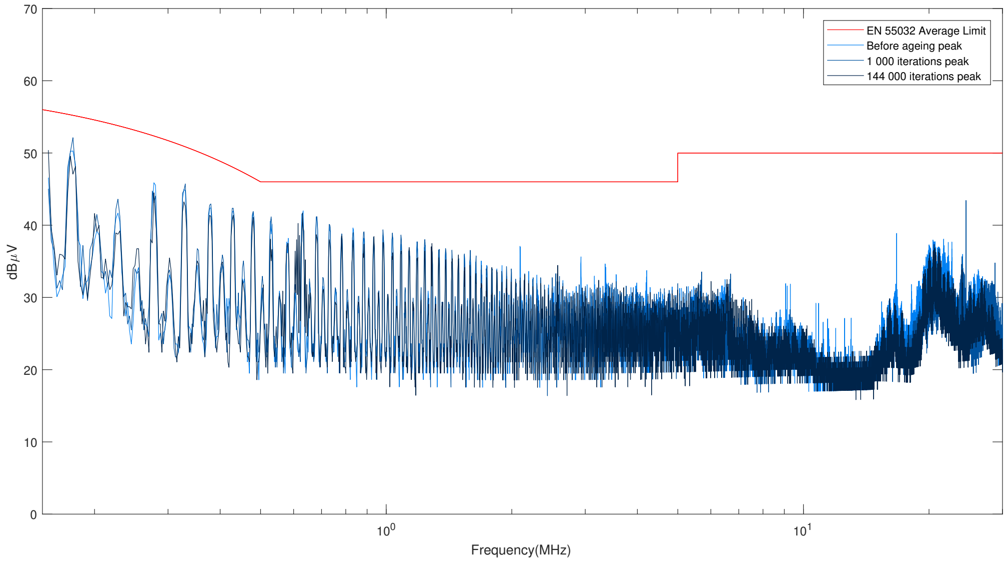

Figure A.20: Peak Measurements of DUT #10

Control DUT 11

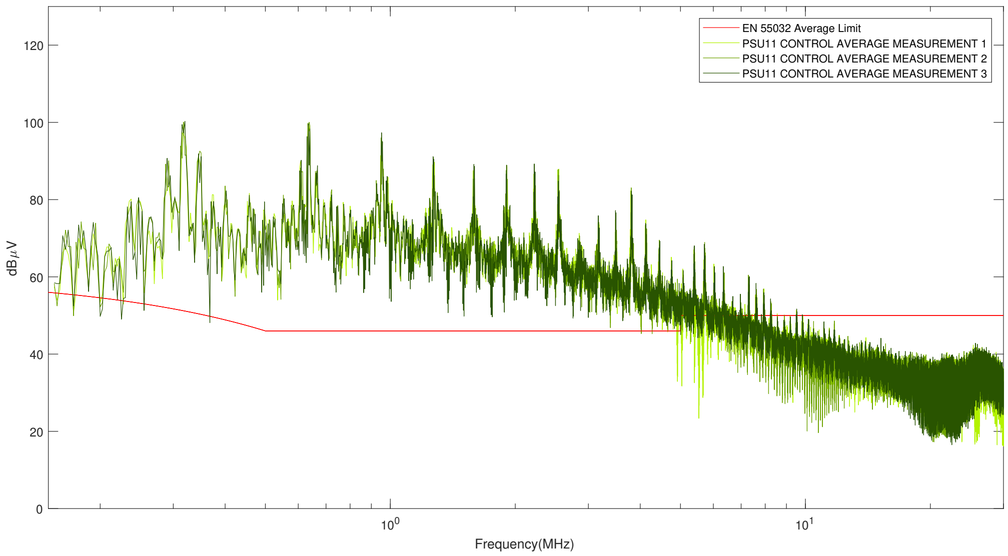

Figure A.21: Average Measurements of DUT #11

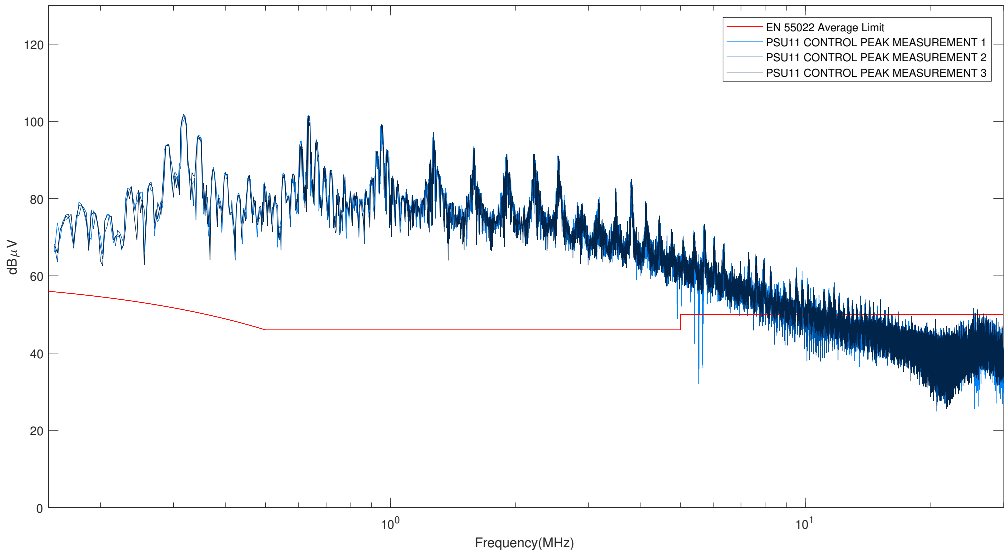

Figure A.22: Peak Measurements of DUT #11

Control DUT 12

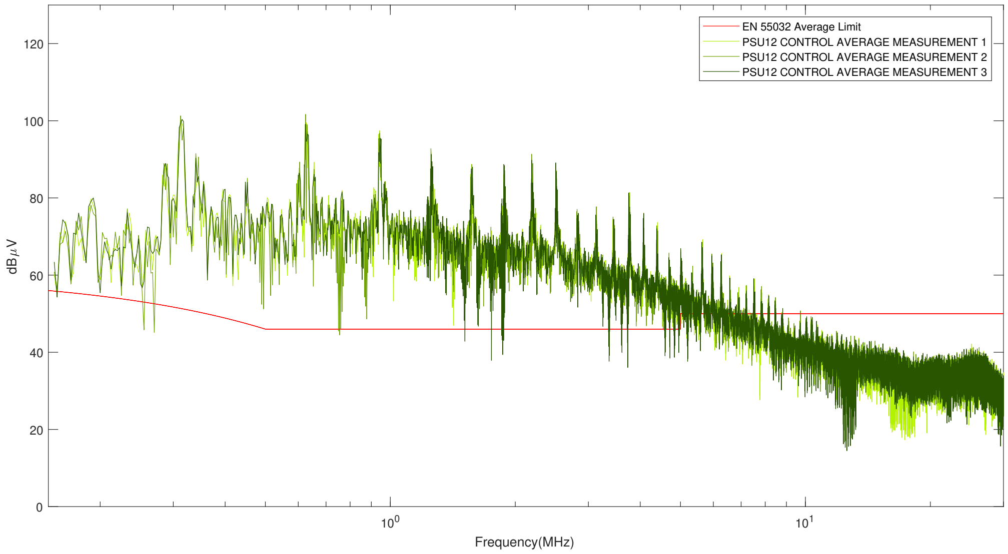

Figure A.23: Average Measurements of DUT #12

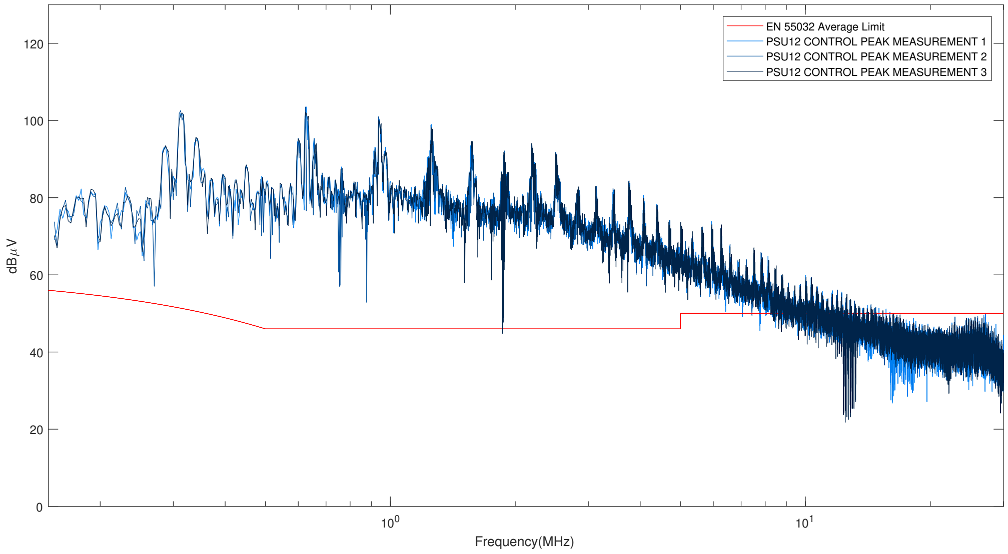

Figure A.24: Peak Measurements of DUT #12

DUT 13

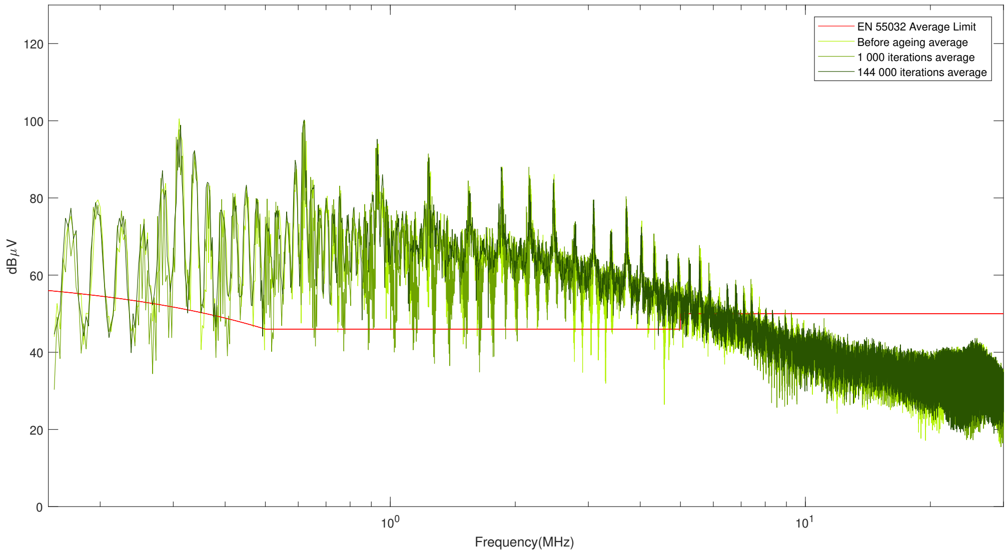

Figure A.25: Average Measurements of DUT #13

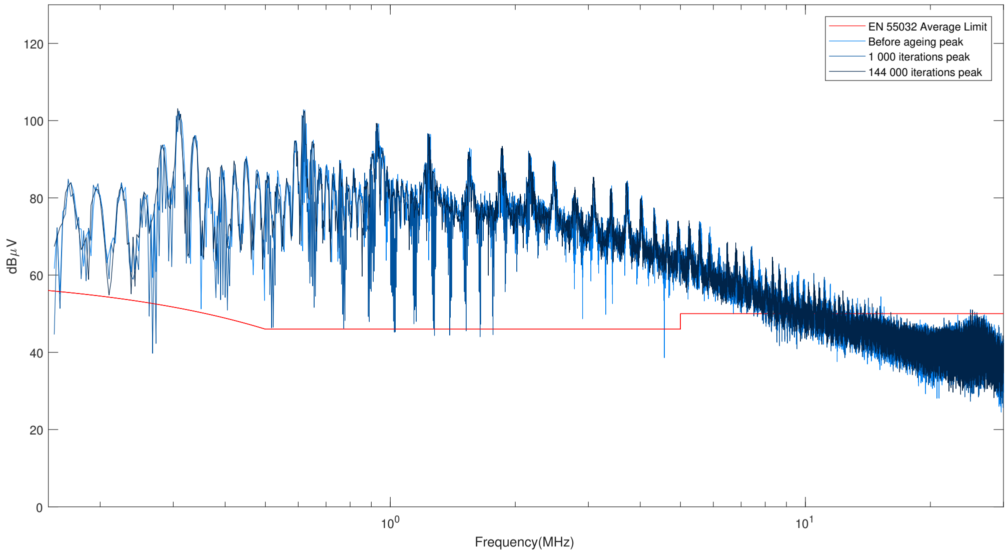

Figure A.26: Peak Measurements of DUT #13

DUT 14

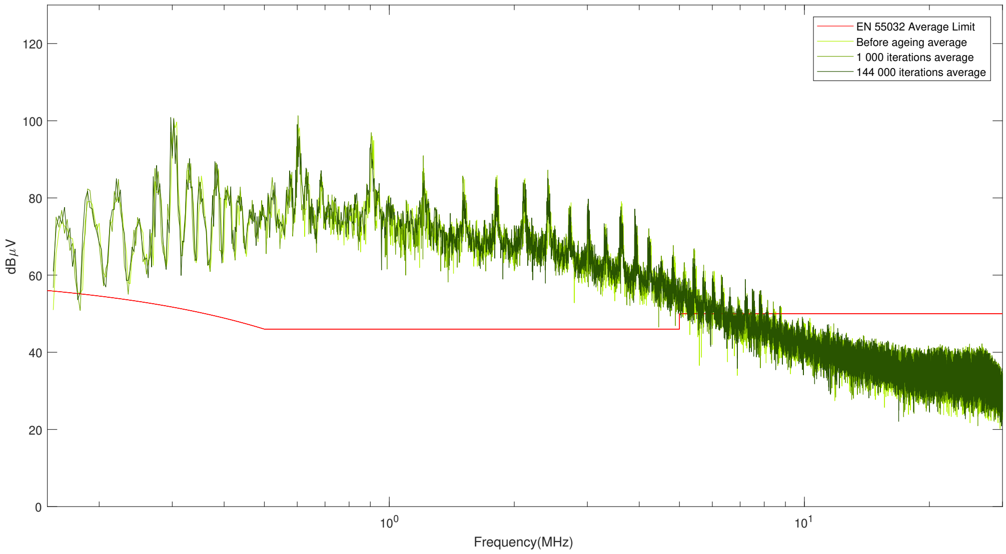

Figure A.27: Average Measurements of DUT #14

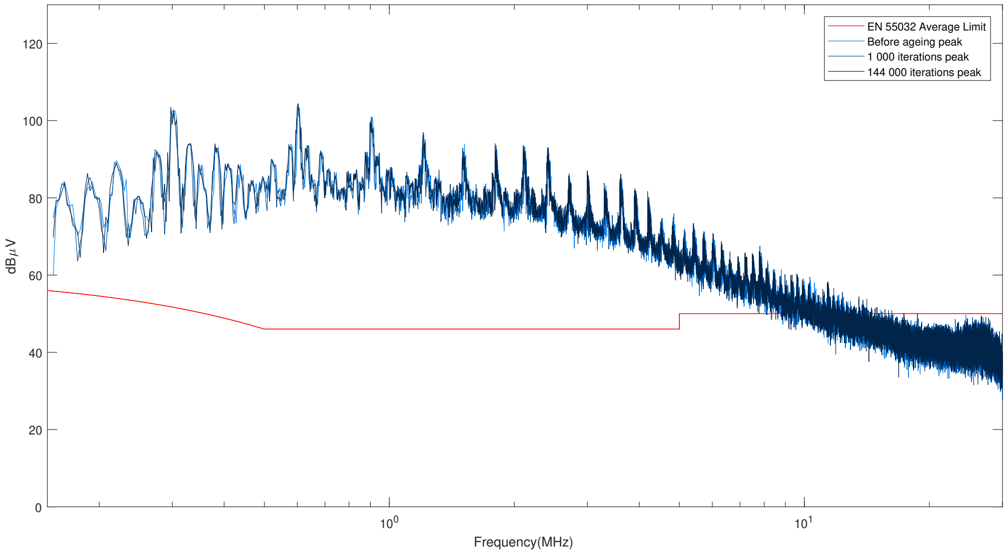

Figure A.28: Peak Measurements of DUT #14

DUT 15

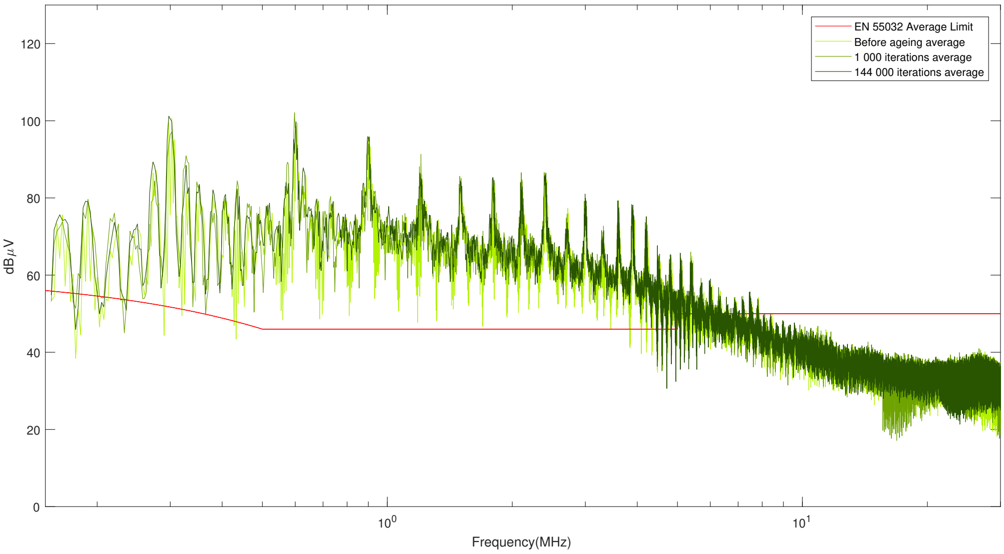

Figure A.29: Average Measurements of DUT #15

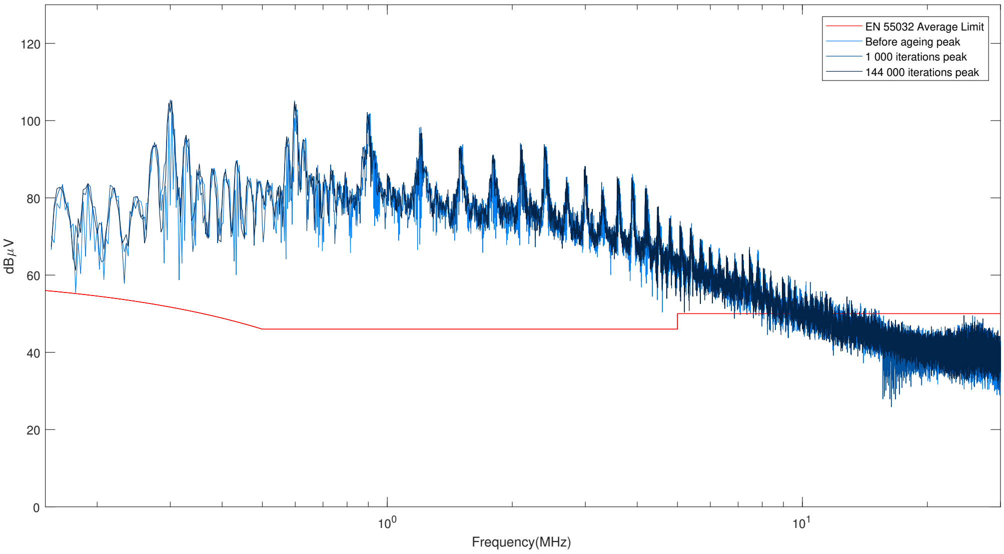

Figure A.30: Peak Measurements of DUT #15

DUT 16

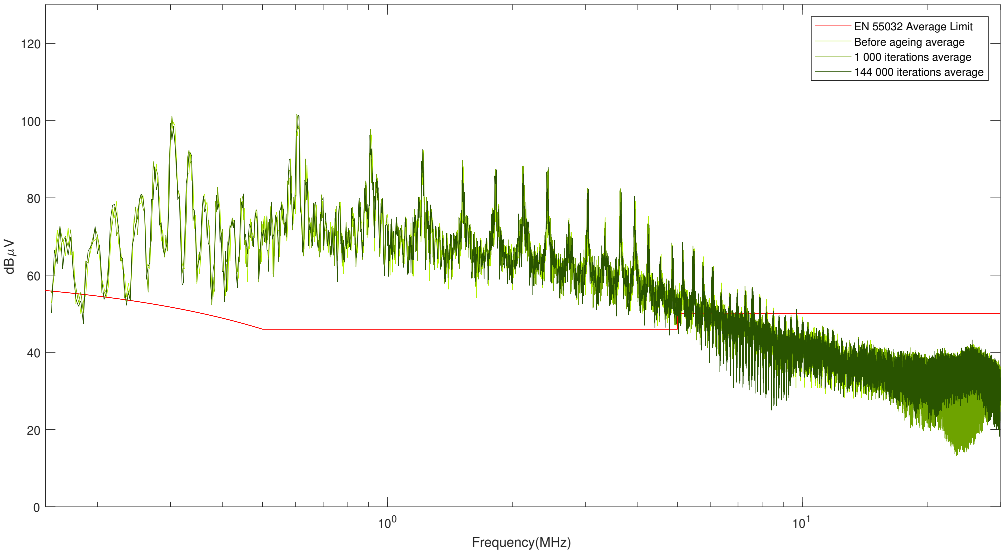

Figure A.31: Average Measurements of DUT #16

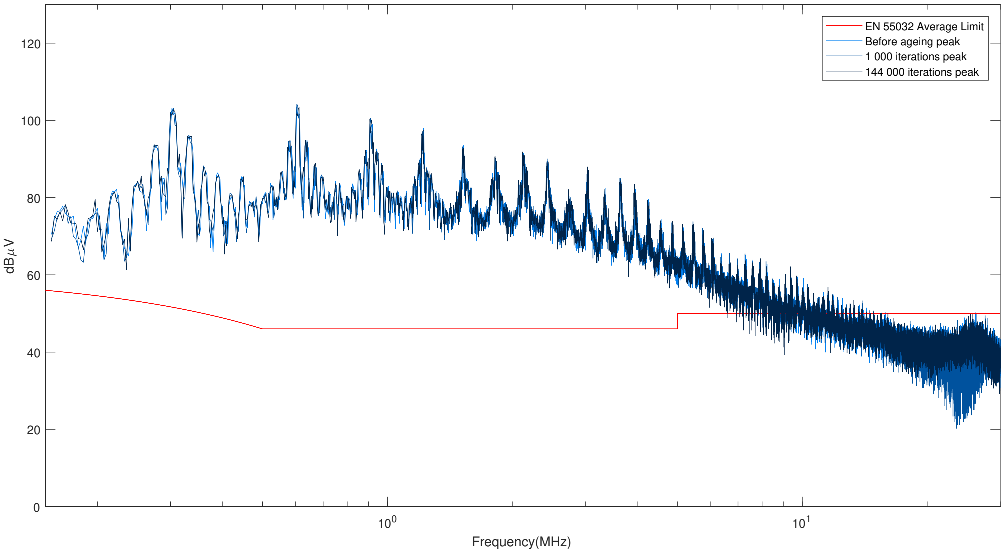

Figure A.32: Peak Measurements of DUT #16

DUT 17

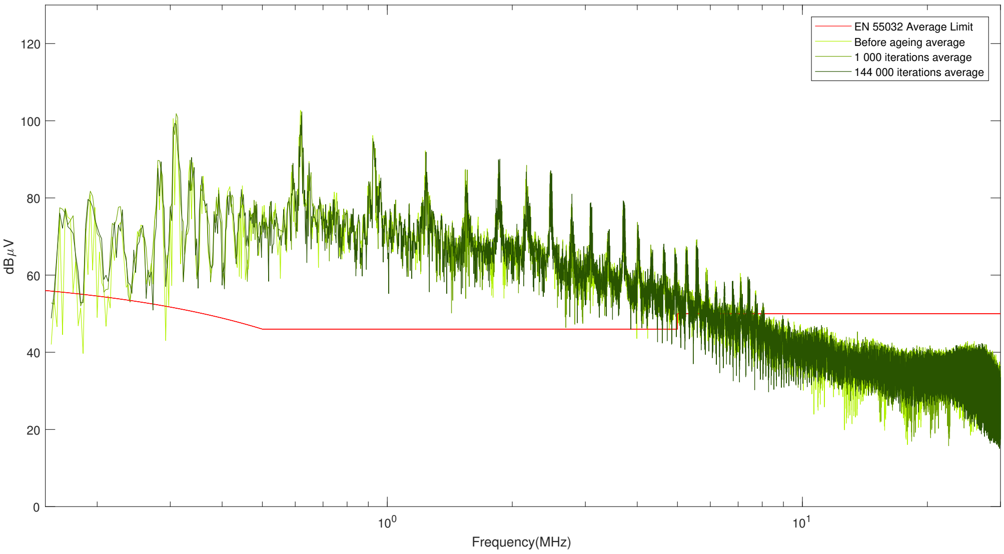

Figure A.33: Average Measurements of DUT #17

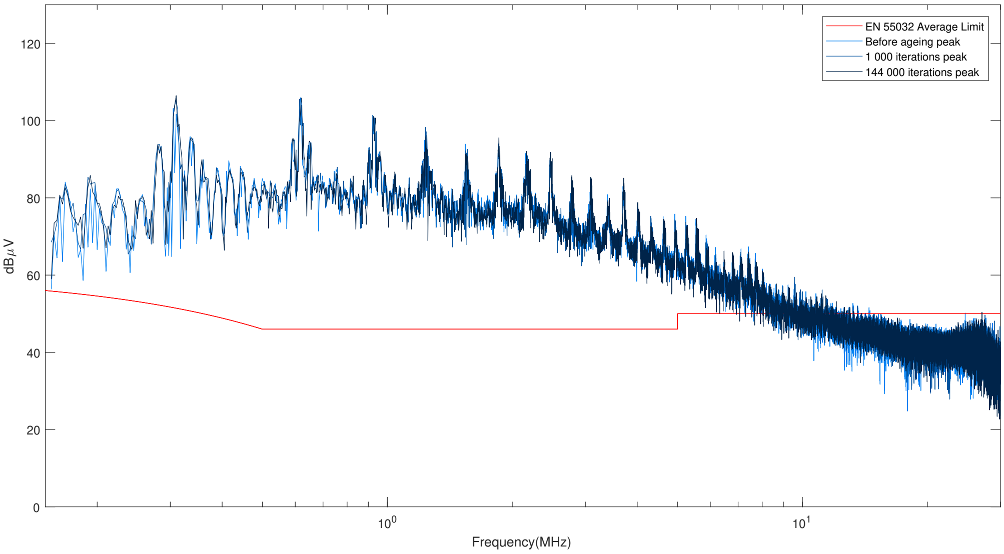

Figure A.34: Peak Measurements of DUT #17

DUT 18

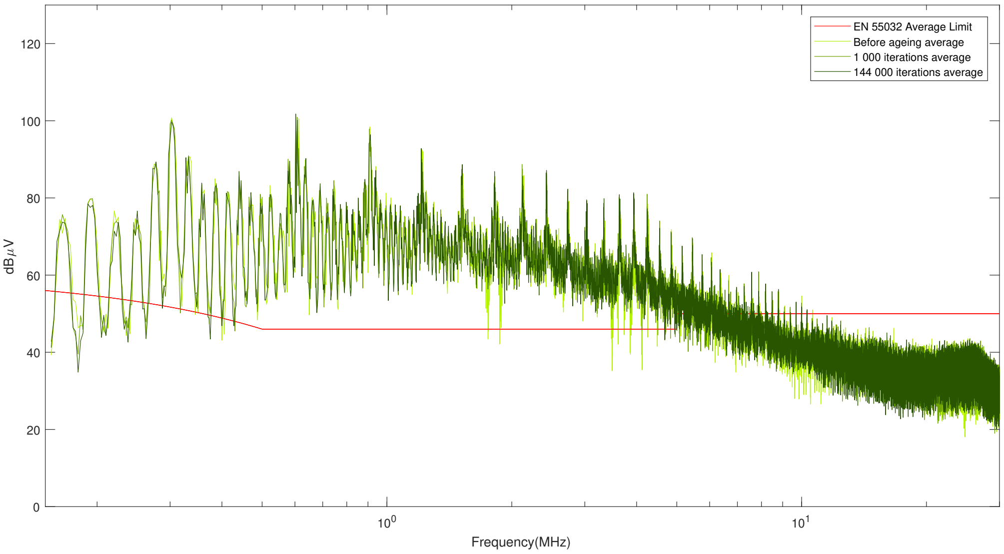

Figure A.35: Average Measurements of DUT #18

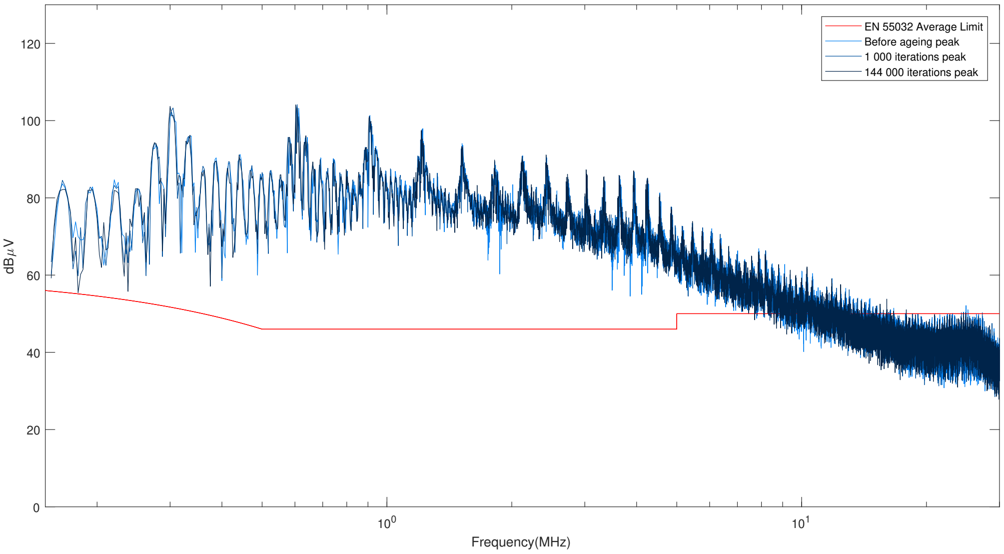

Figure A.36: Peak Measurements of DUT #18

DUT 19

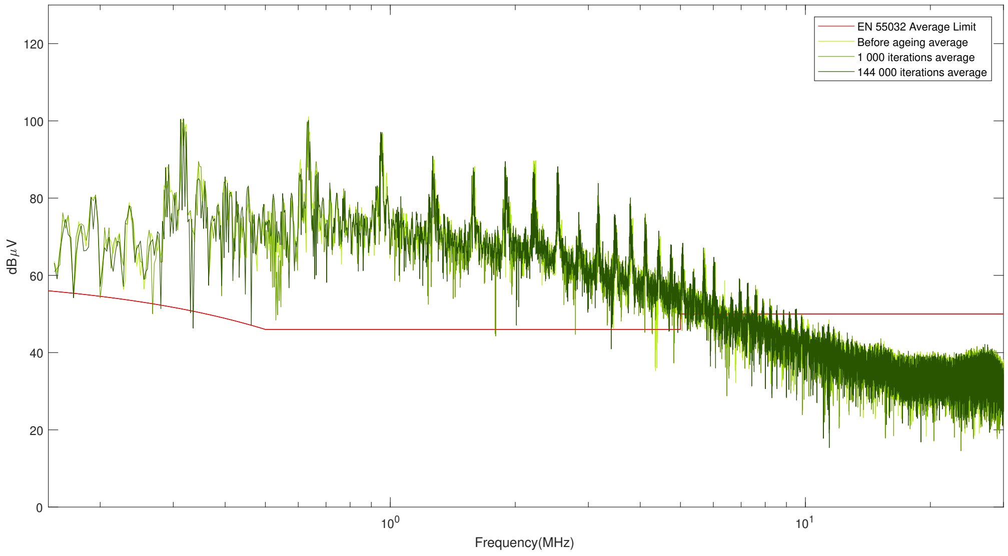

Figure A.37: Average Measurements of DUT #19

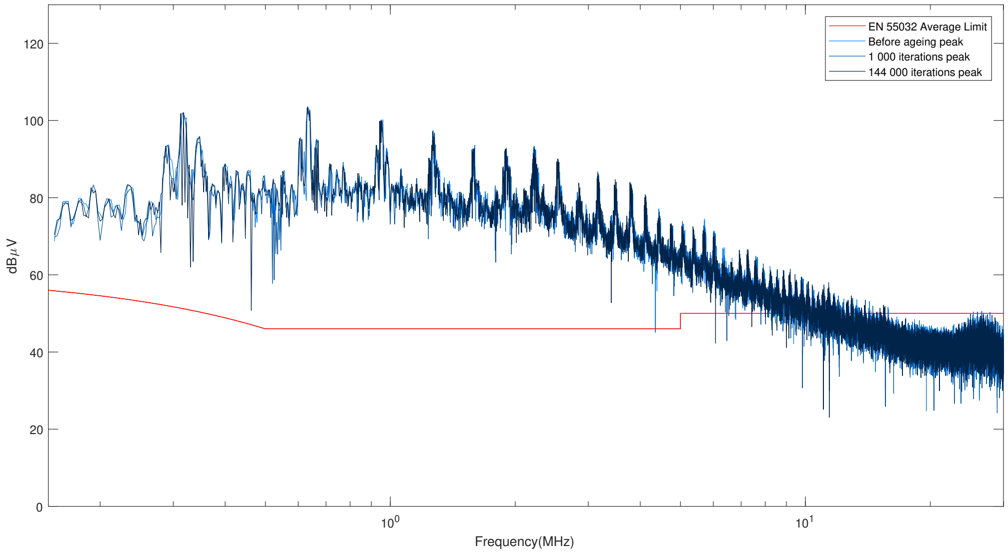

Figure A.38: Peak Measurements of DUT #19

DUT 20

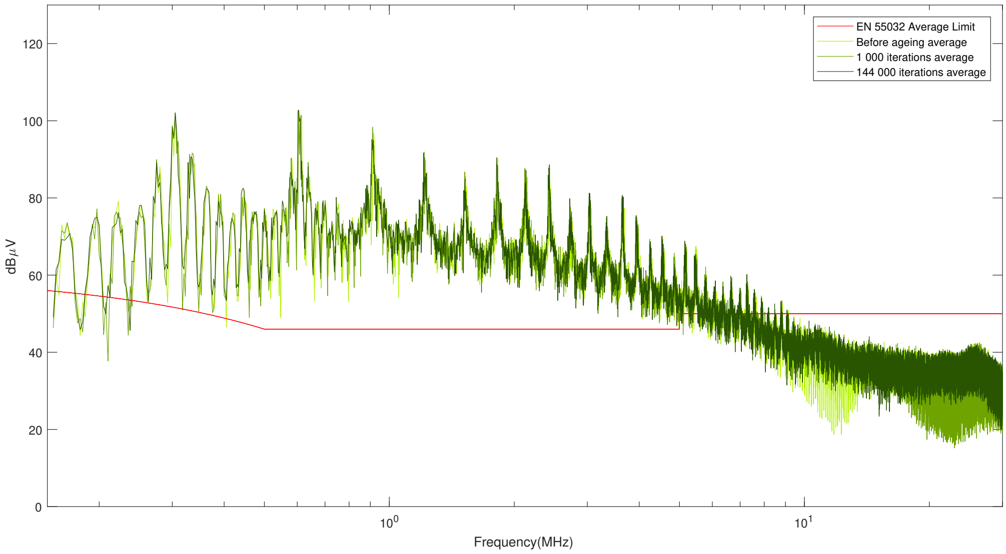

Figure A.39: Average Measurements of DUT #20

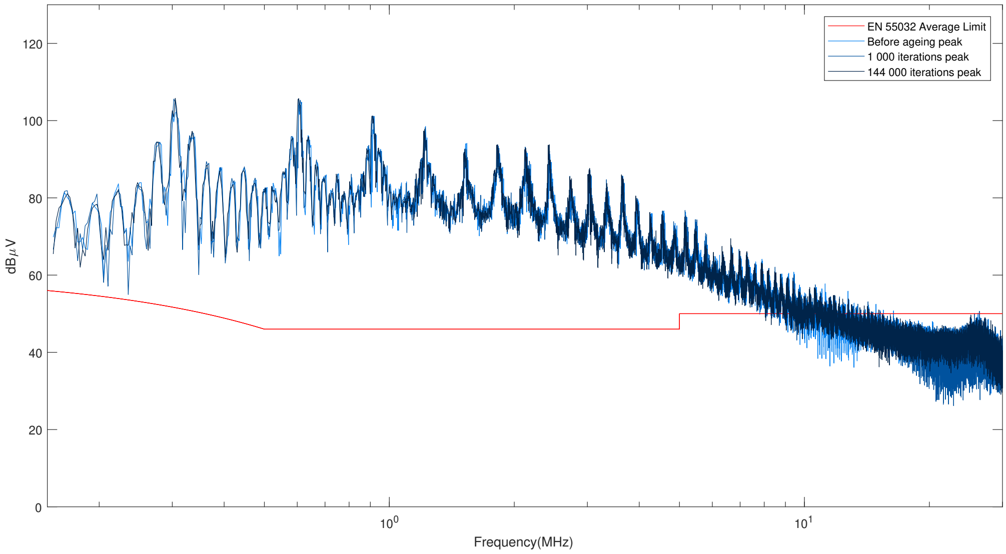

Figure A.40: Peak Measurements of DUT #20

DUT 21

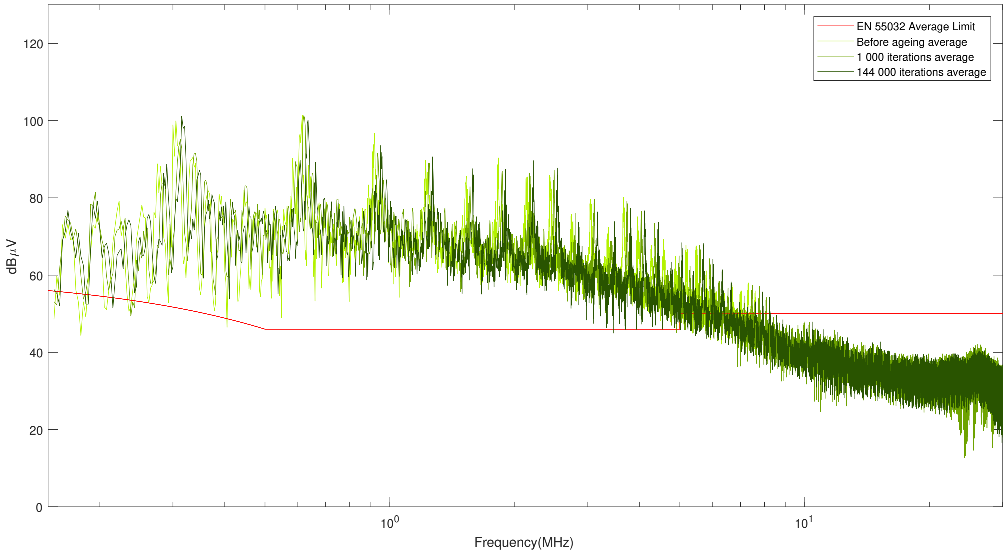

Figure A.41: Average Measurements of DUT #21

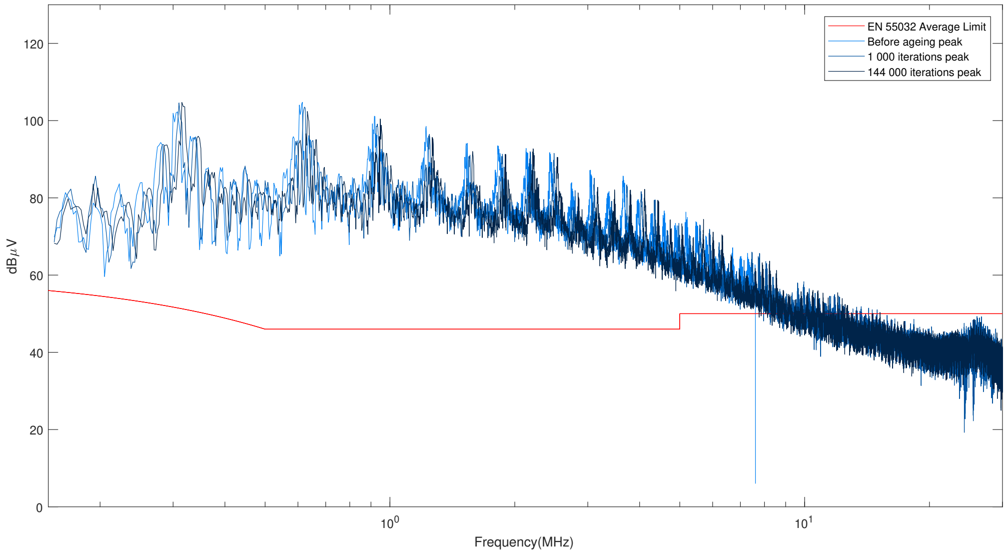

Figure A.42: Peak Measurements of DUT #21

DUT 22

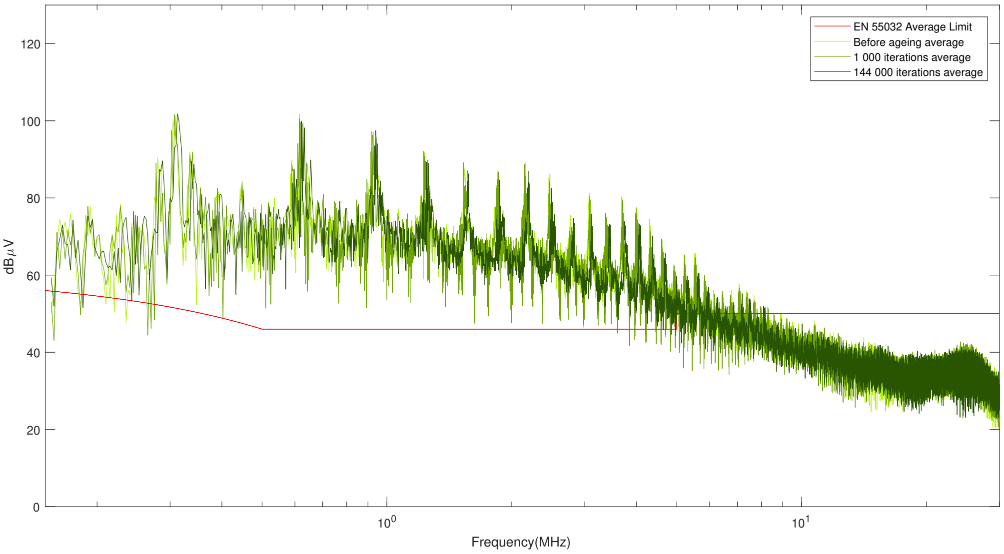

Figure A.43: Average Measurements of DUT #22

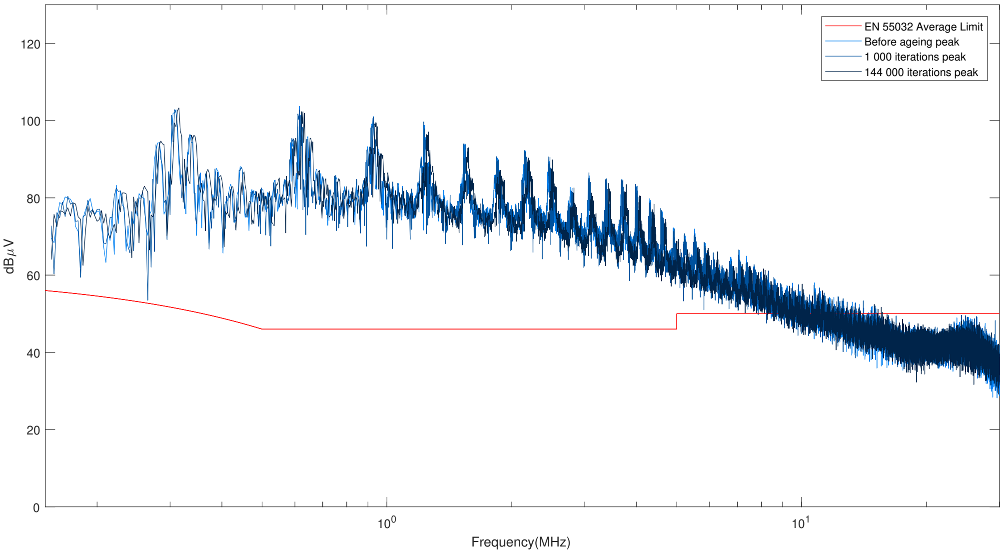

Figure A.44: Peak Measurements of DUT #22

DUT 23

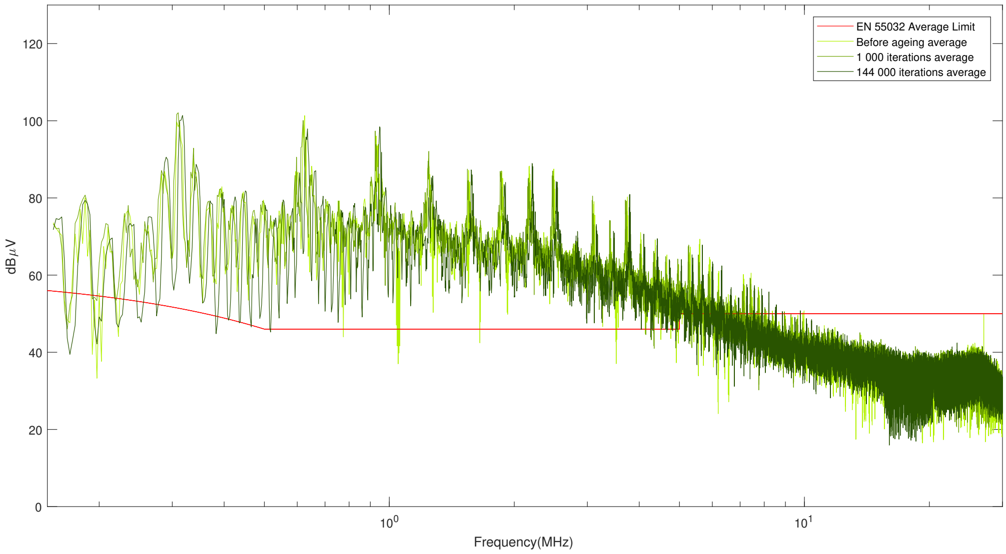

Figure A.45: Average Measurements of DUT #23

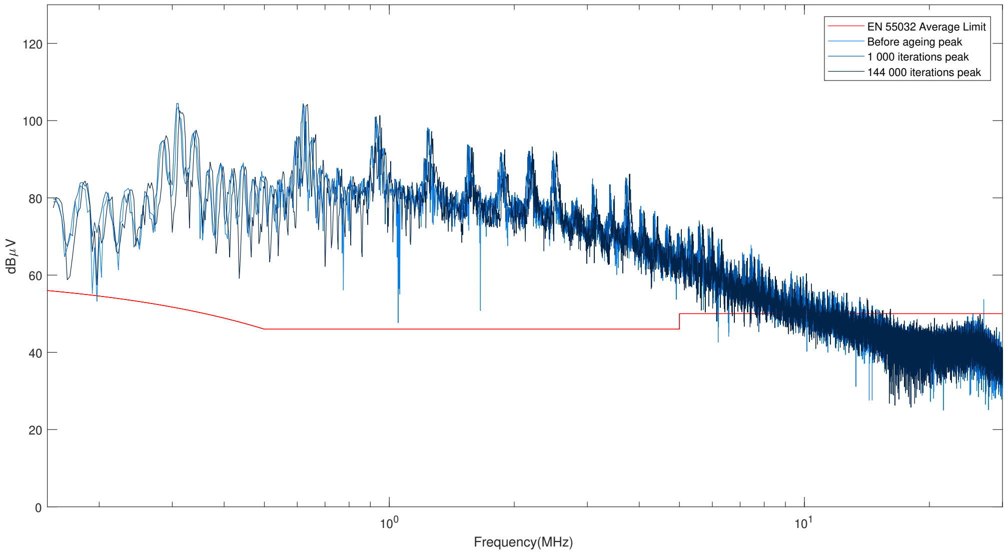

Figure A.46: Peak Measurements of DUT #23

DUT 24

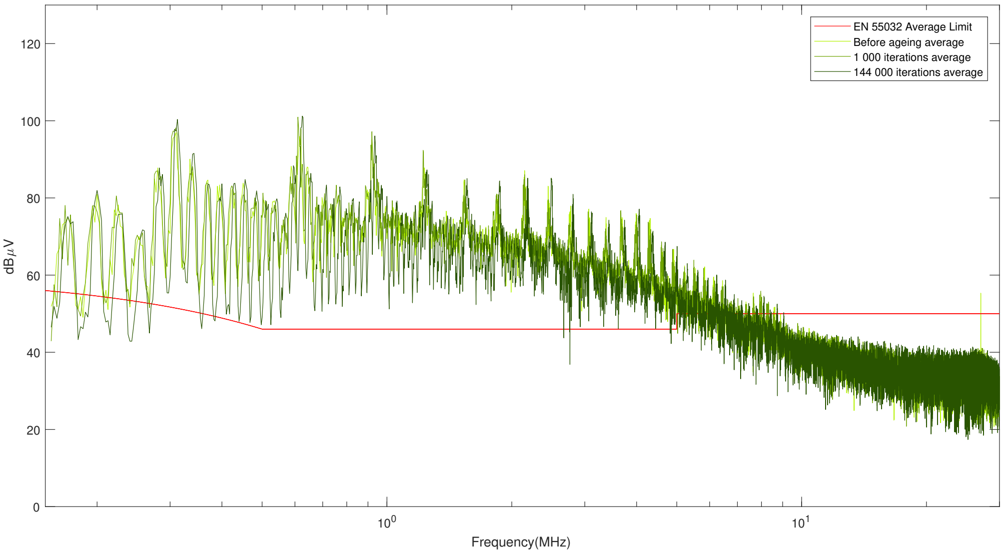

Figure A.47: Average Measurements of DUT #24

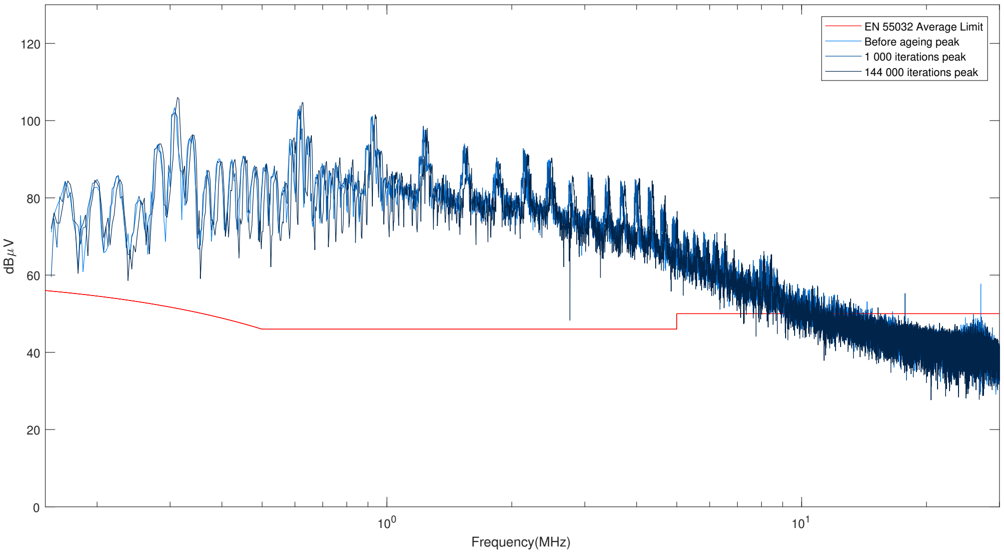

Figure A.48: Peak Measurements of DUT #24

DUT 25

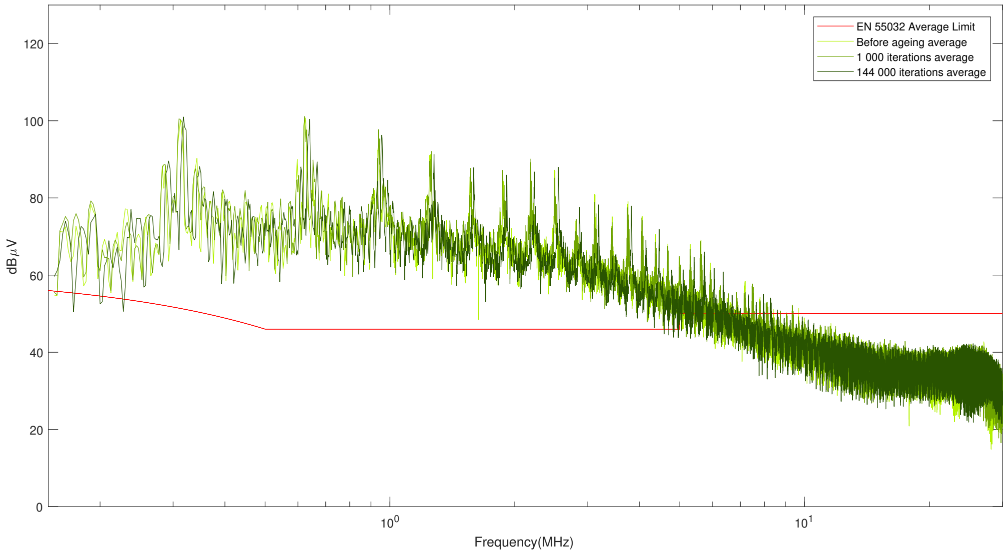

Figure A.49: Average Measurements of DUT #25

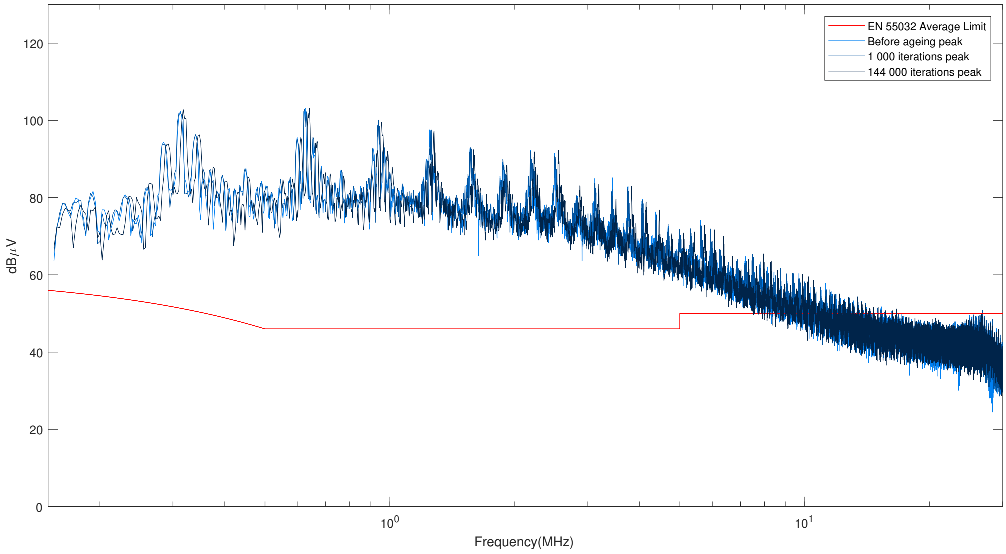

Figure A.50: Peak Measurements of DUT #25

DUT 26

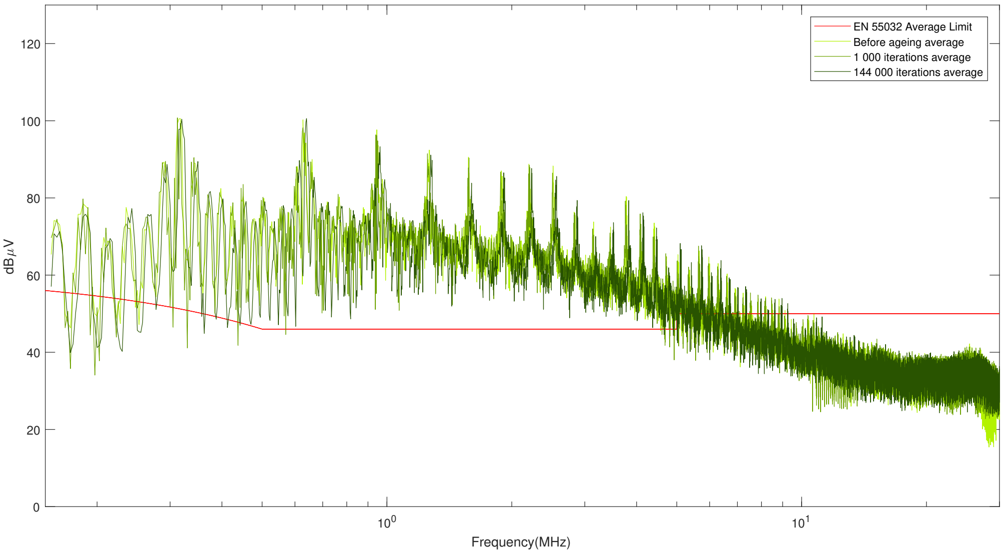

Figure A.51: Average Measurements of DUT #26

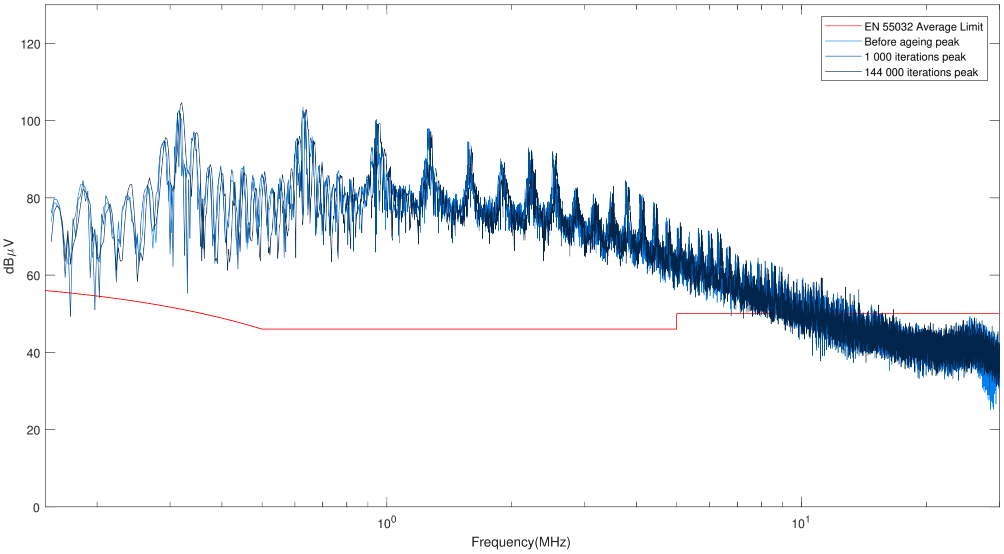

Figure A.52: Peak Measurements of DUT #26

DUT 27

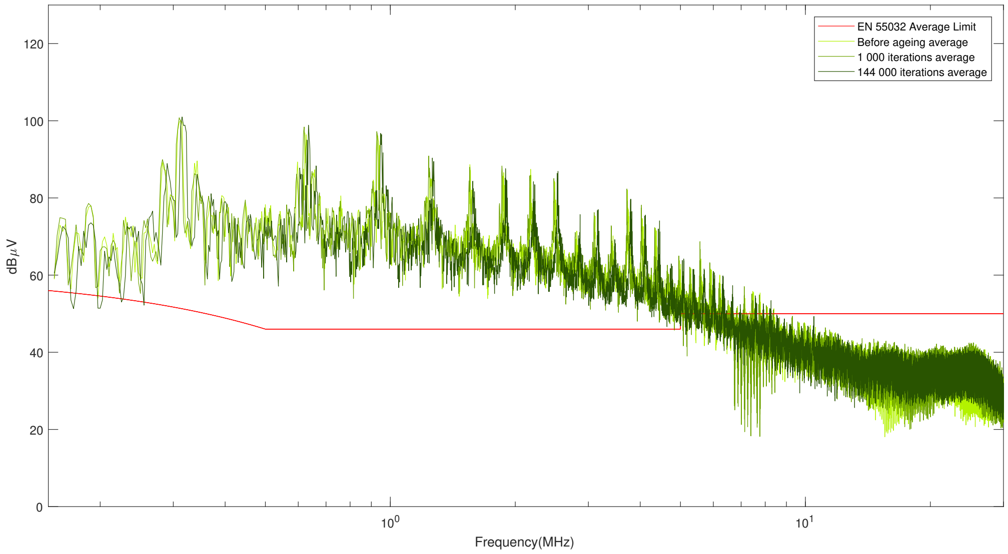

Figure A.53: Average Measurements of DUT #27

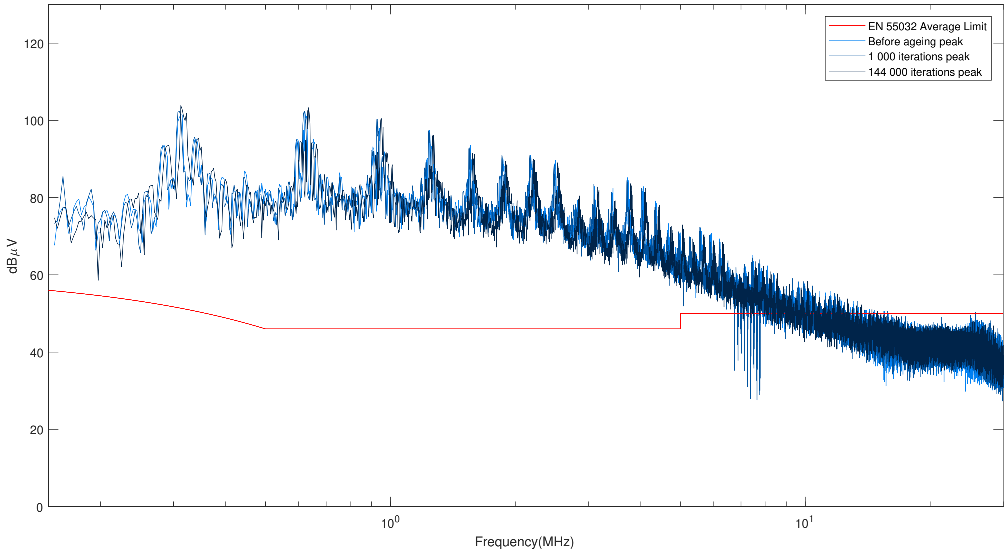

Figure A.54: Peak Measurements of DUT #27

DUT 28

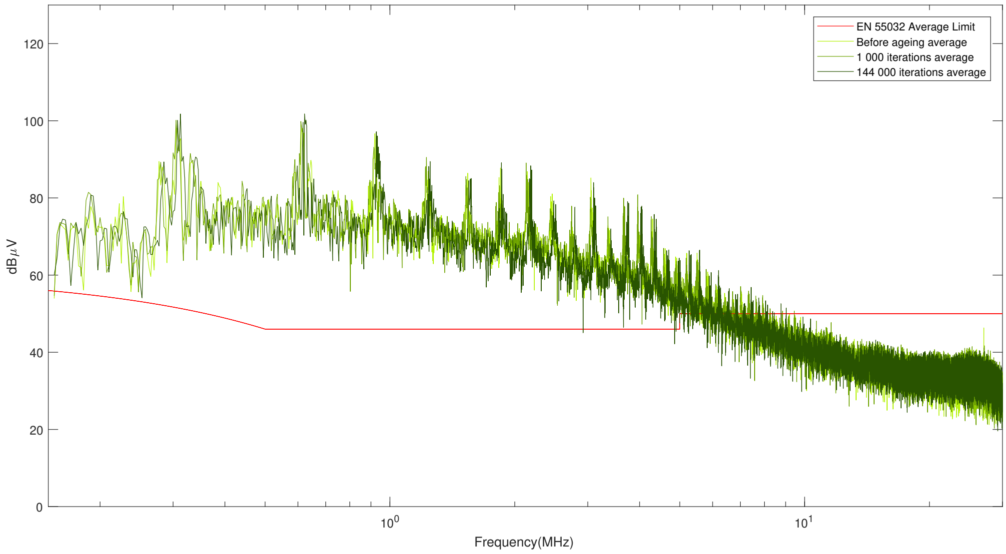

Figure A.55: Average Measurements of DUT #28

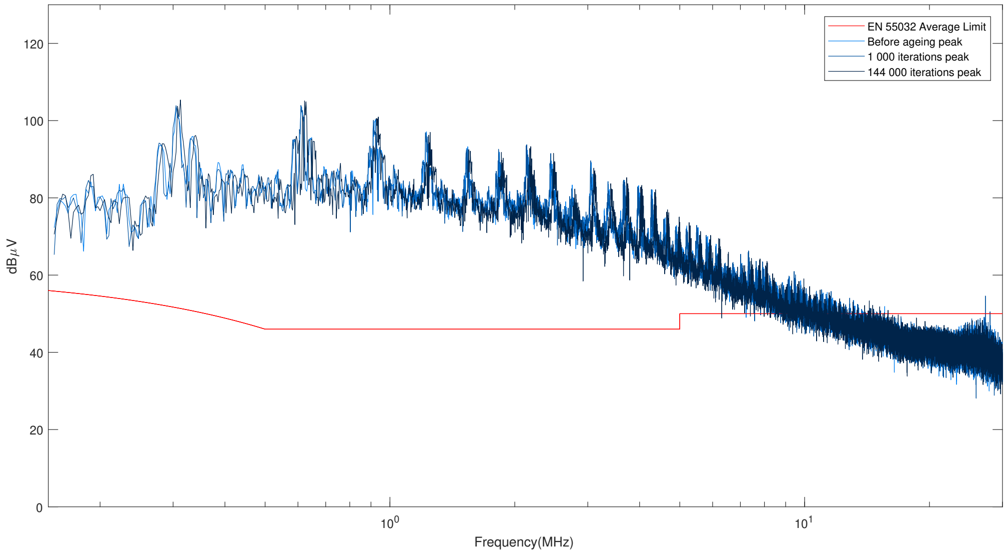

Figure A.56: Peak Measurements of DUT #28

DUT 31

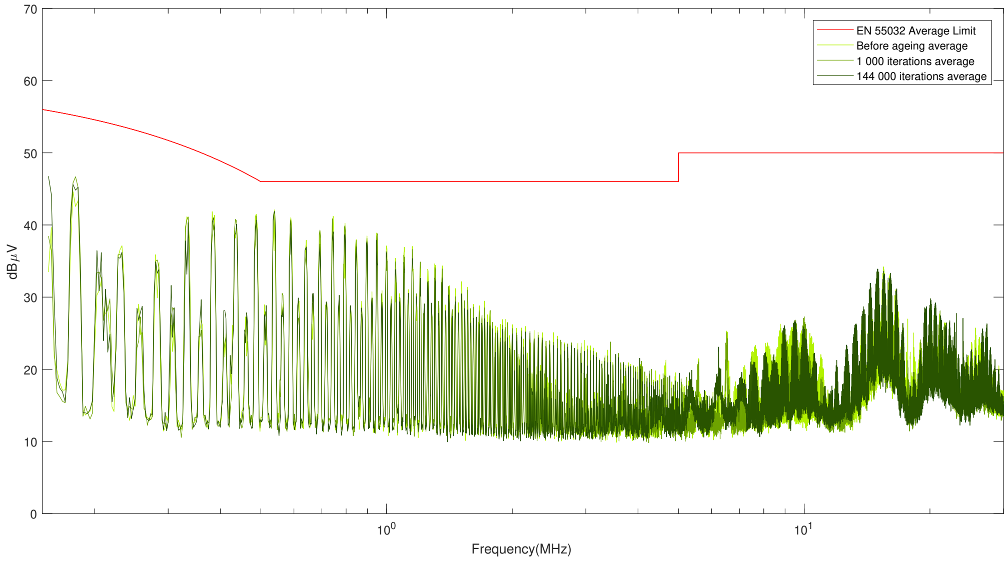

Figure A.57: Average Measurements of DUT #31

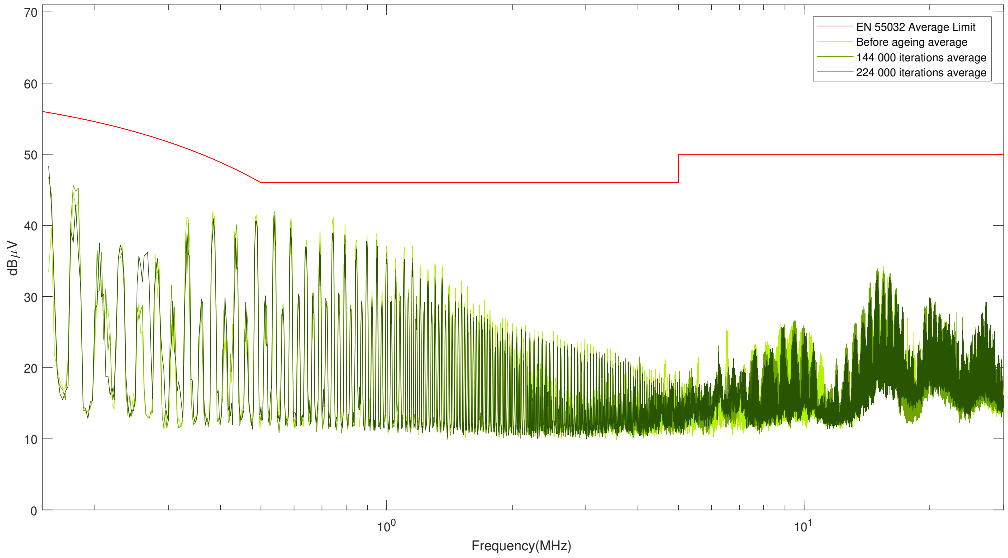

Figure A.58: Average Measurements of DUT #31 after the normal ultimate ageing

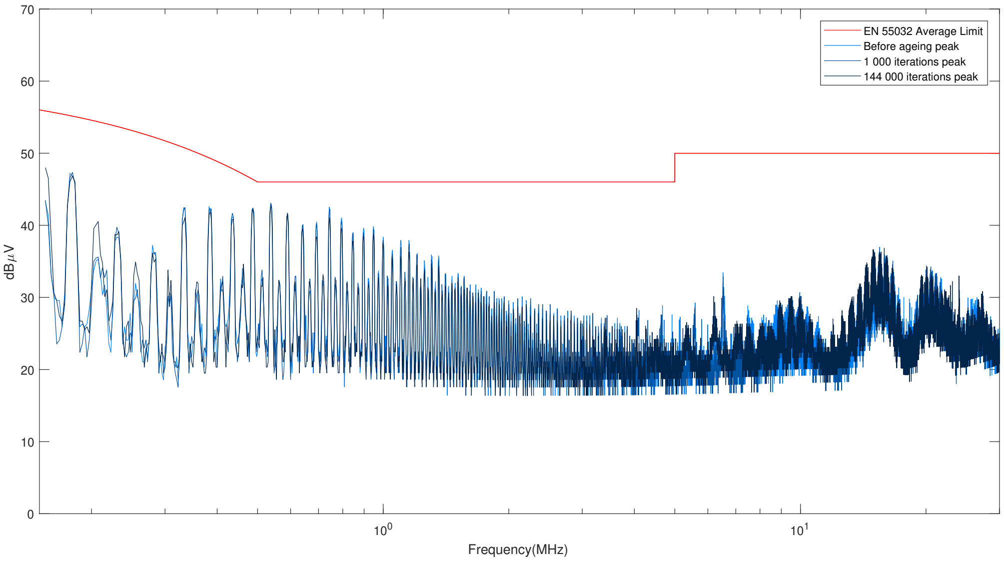

Figure A.59: Peak Measurements of DUT #31

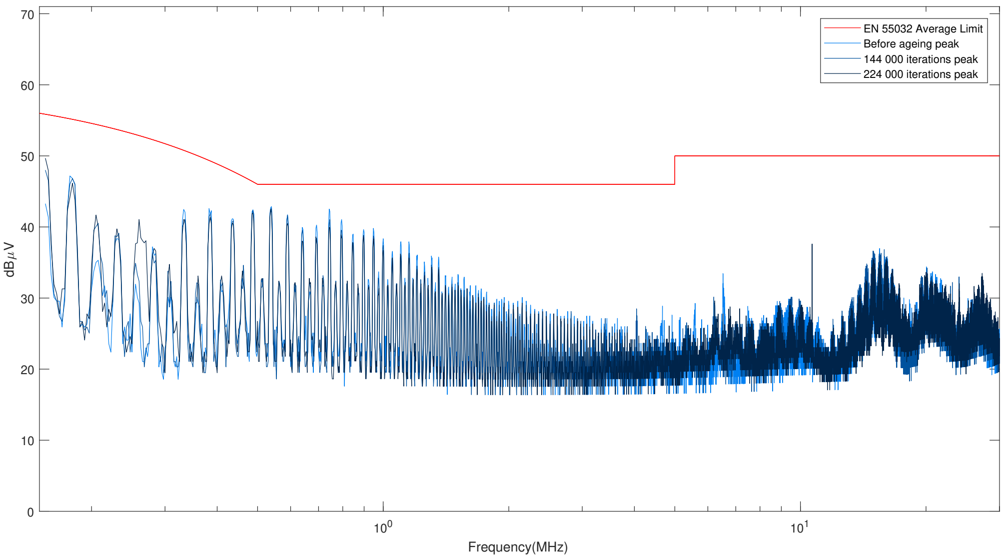

Figure A.60: Peak Measurements of DUT #31 after the normal ultimate ageing

DUT 32

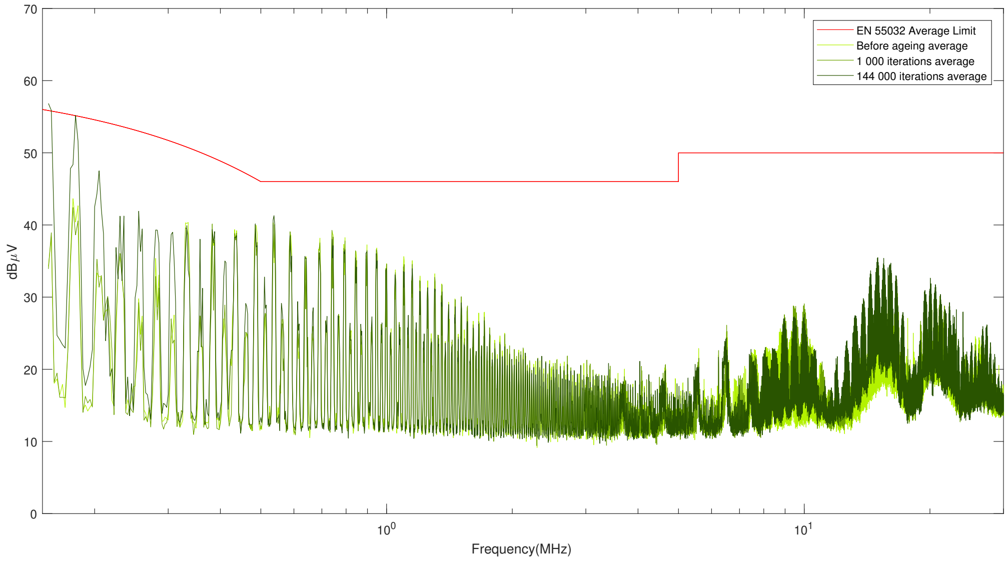

Figure A.61: Average Measurements of DUT #32

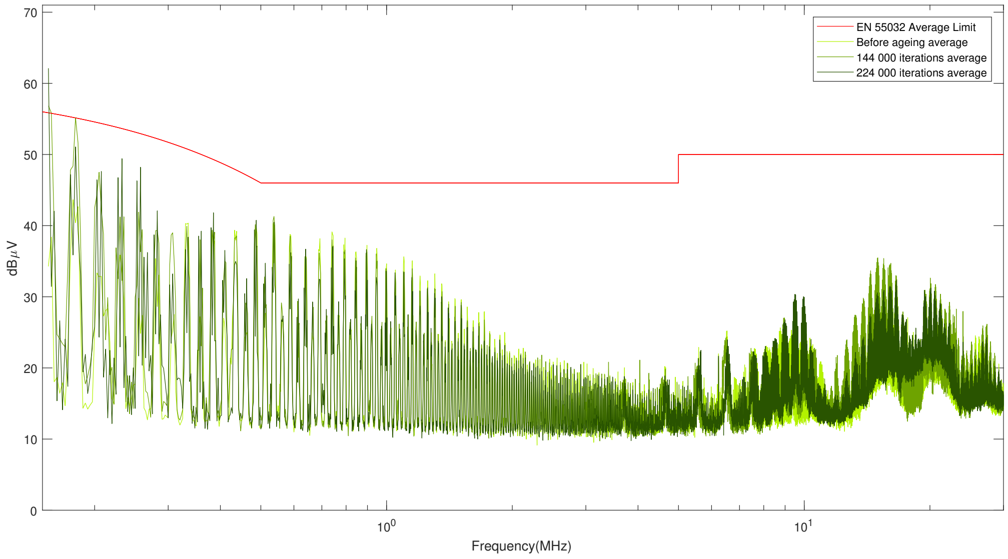

Figure A.62: Average Measurements of DUT #32 after the random ultimate ageing

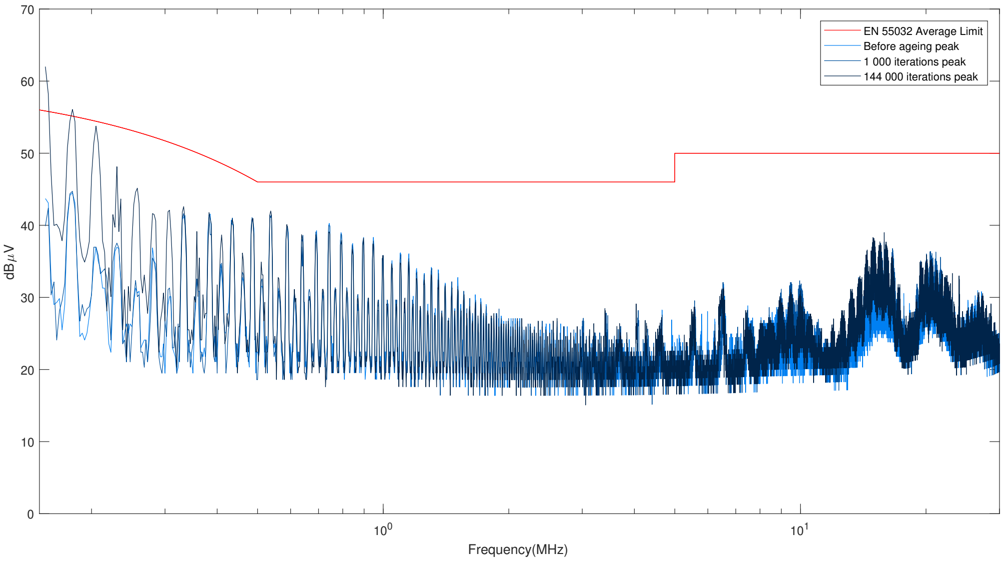

Figure A.63: Peak Measurements of DUT #32

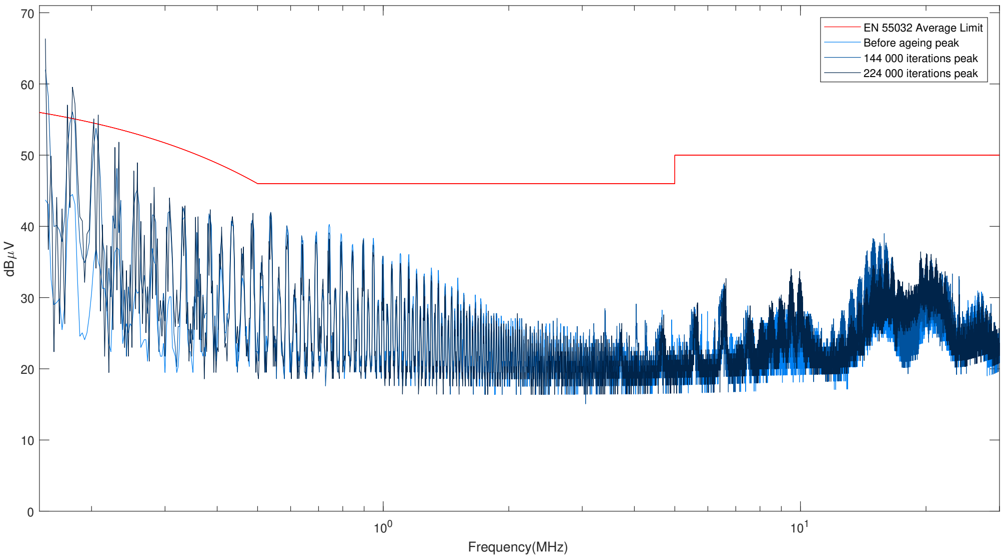

Figure A.64: Peak Measurements of DUT #32 after the random ultimate ageing

DUT 33

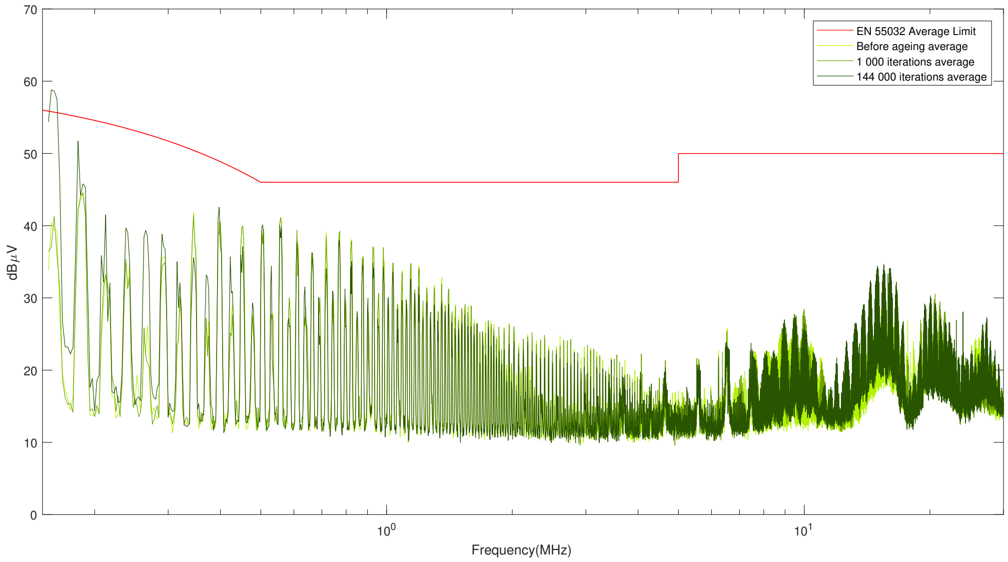

Figure A.65: Average Measurements of DUT #33

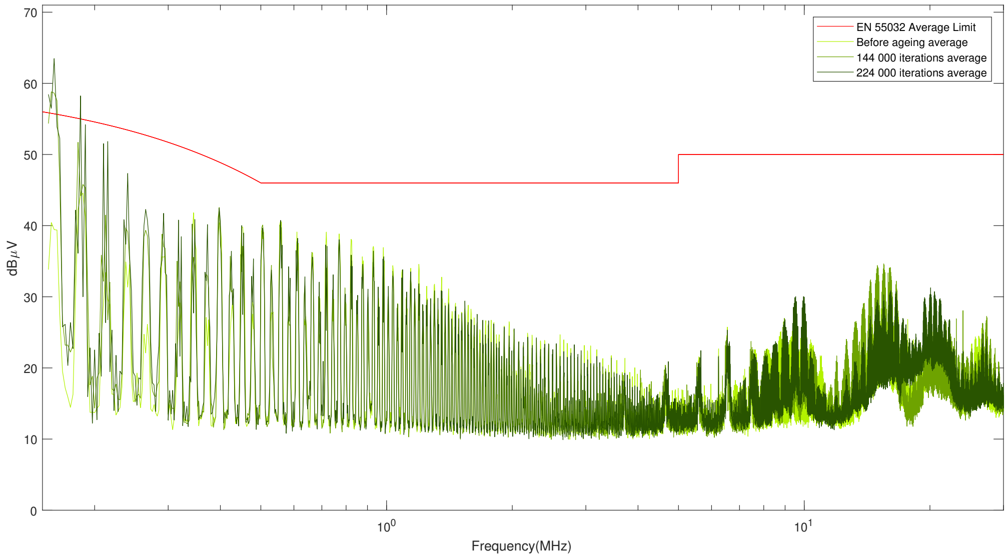

Figure A.66: Average Measurements of DUT #33 after the random ultimate ageing

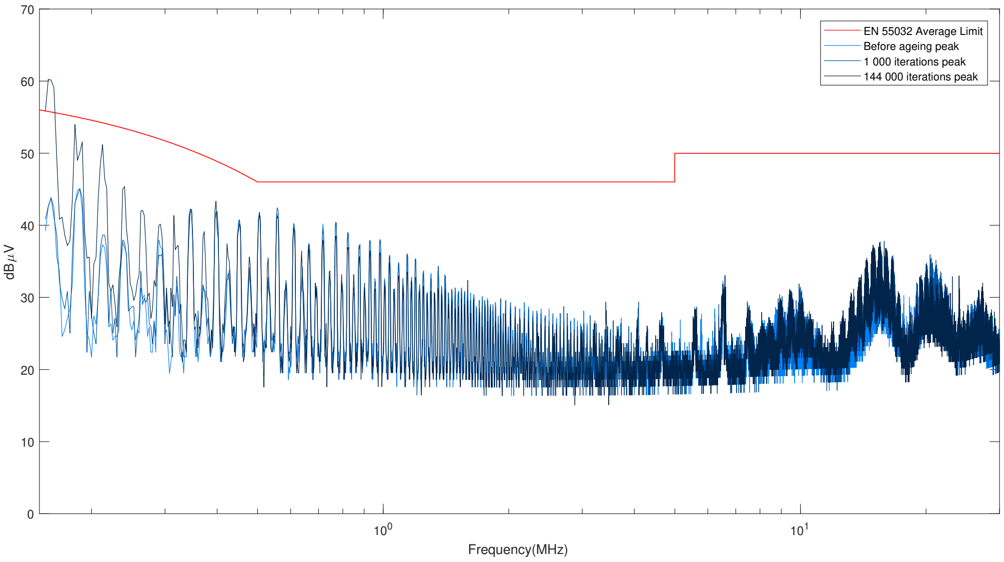

Figure A.67: Peak Measurements of DUT #33

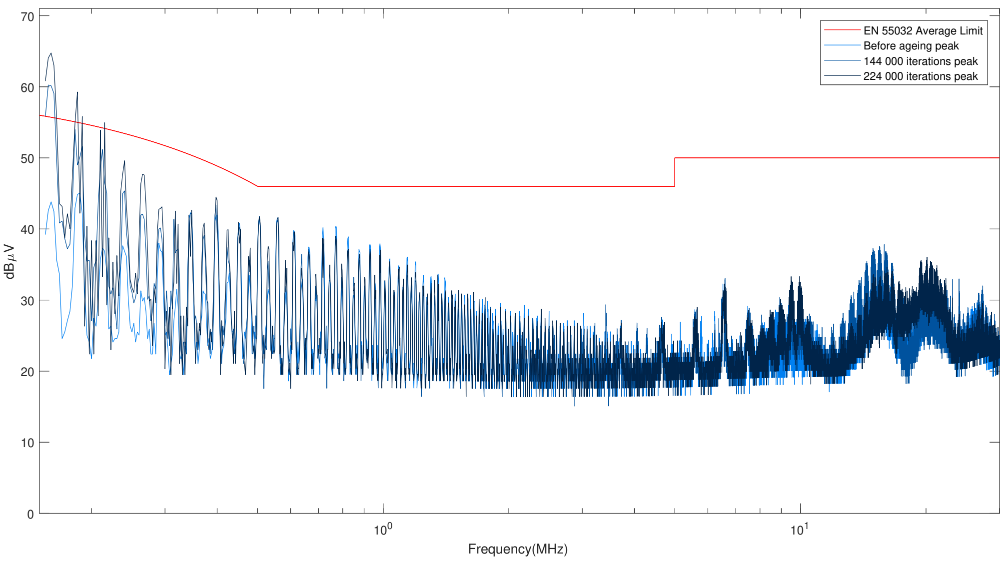

Figure A.68: Peak Measurements of DUT #33 after the random ultimate ageing

DUT 34

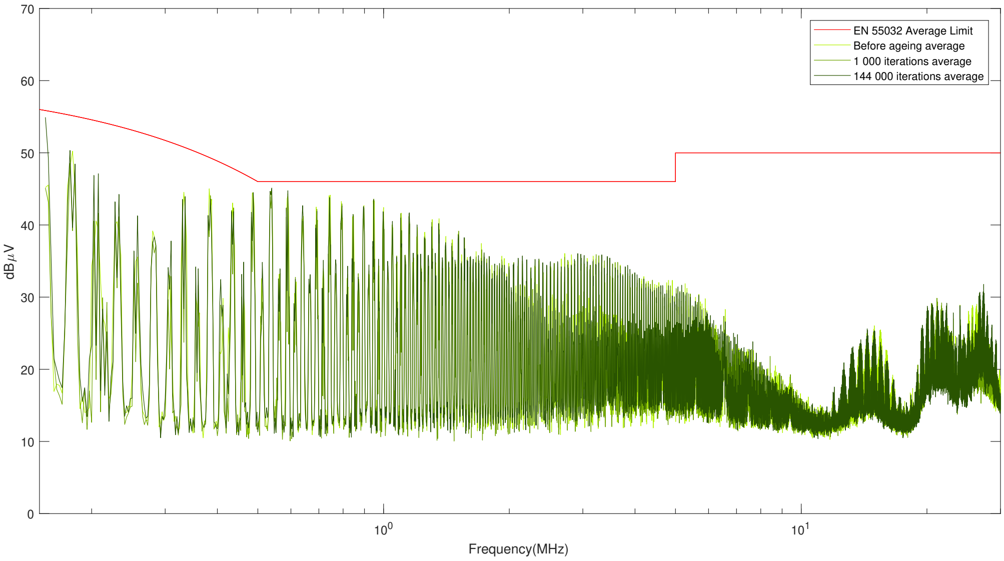

Figure A.69: Average Measurements of DUT #34

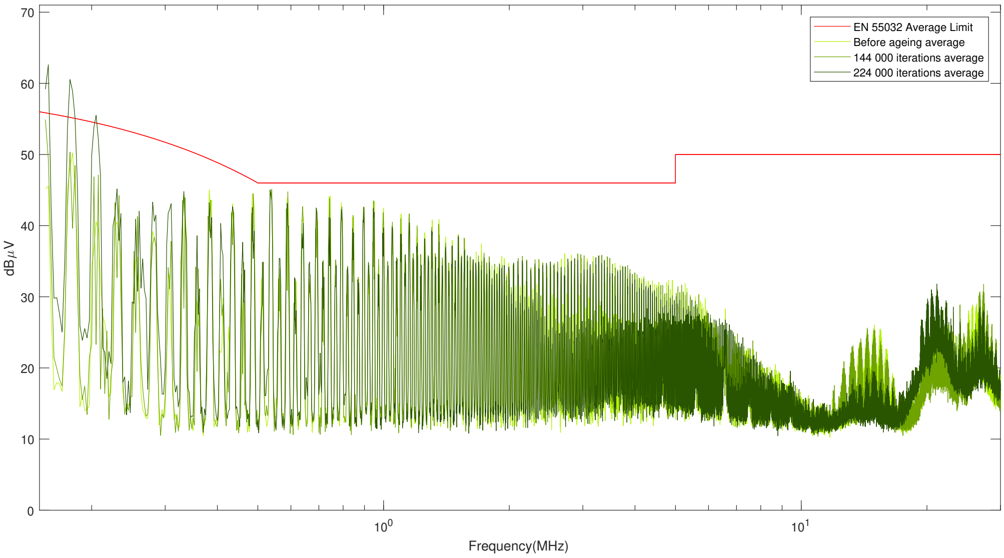

Figure A.70: Average Measurements of DUT #34 after the random ultimate ageing

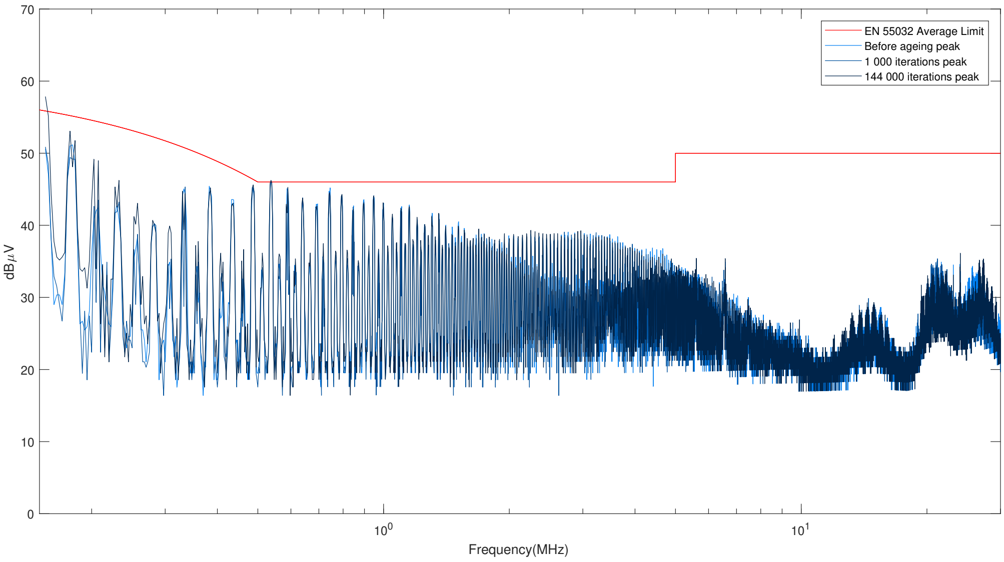

Figure A.71: Peak Measurements of DUT #34

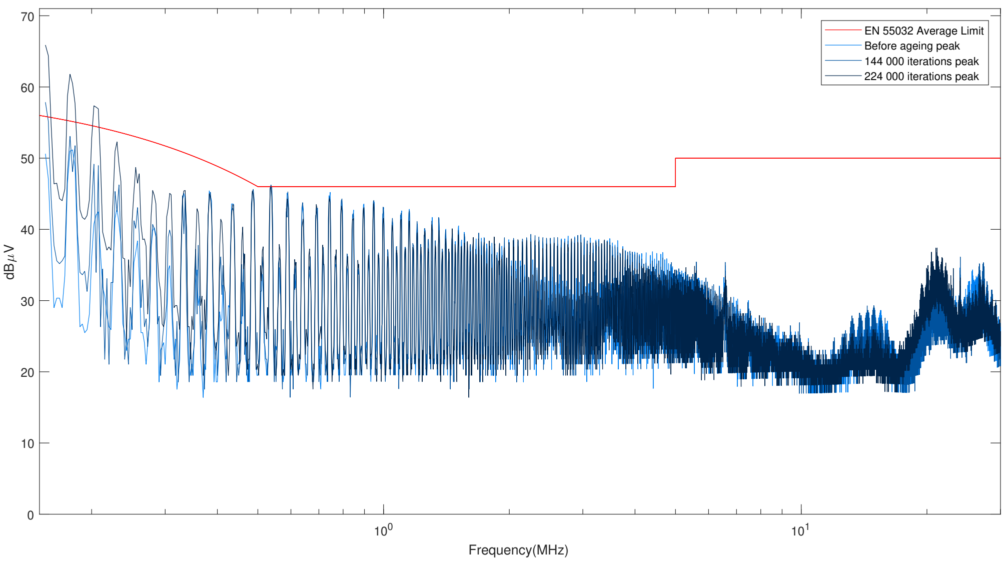

Figure A.72: Peak Measurements of DUT #34 after the random ultimate ageing

DUT 35

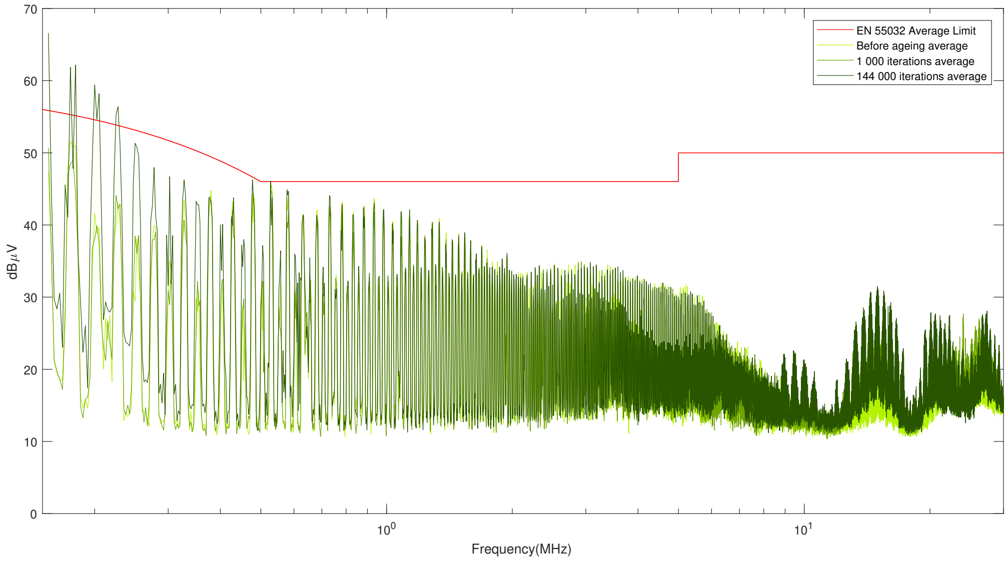

Figure A.73: Average Measurements of DUT #35

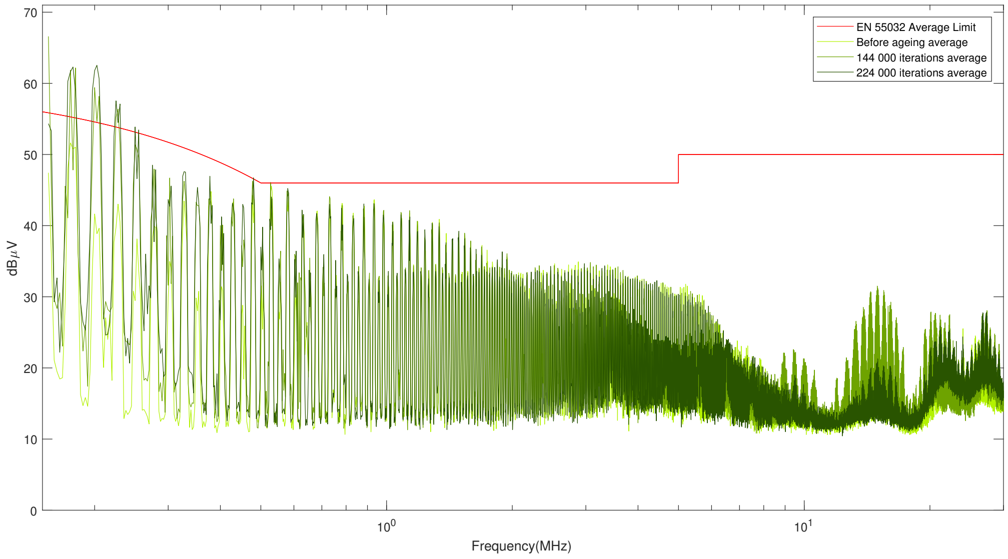

Figure A.74: Average Measurements of DUT #35 after the random ultimate ageing

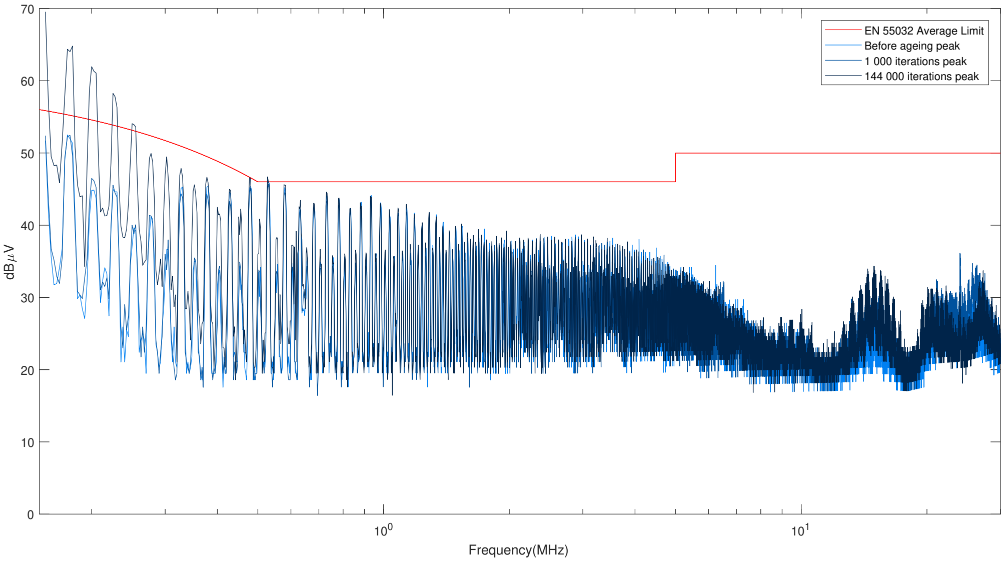

Figure A.75: Peak Measurements of DUT #35

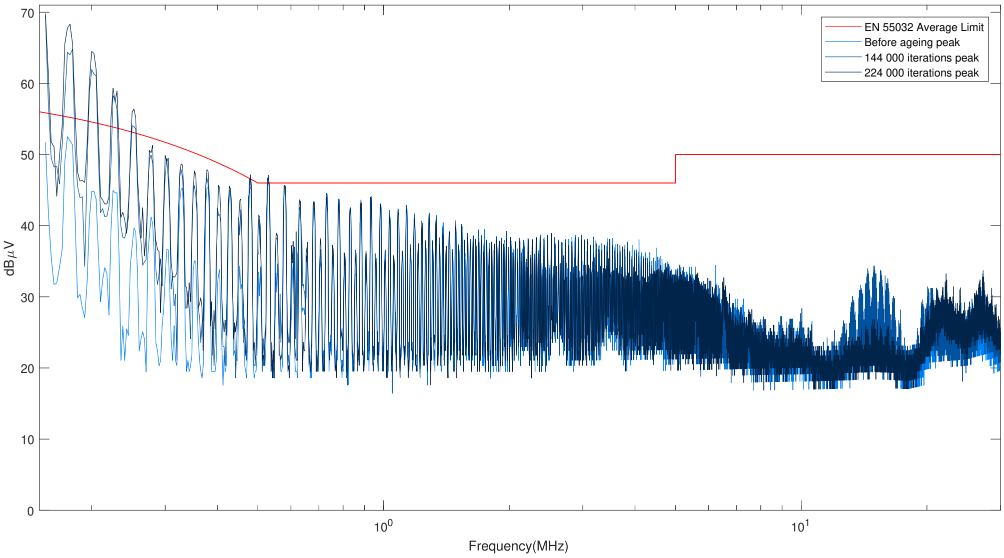

Figure A.76: Peak Measurements of DUT #35 after the random ultimate ageing

DUT 36

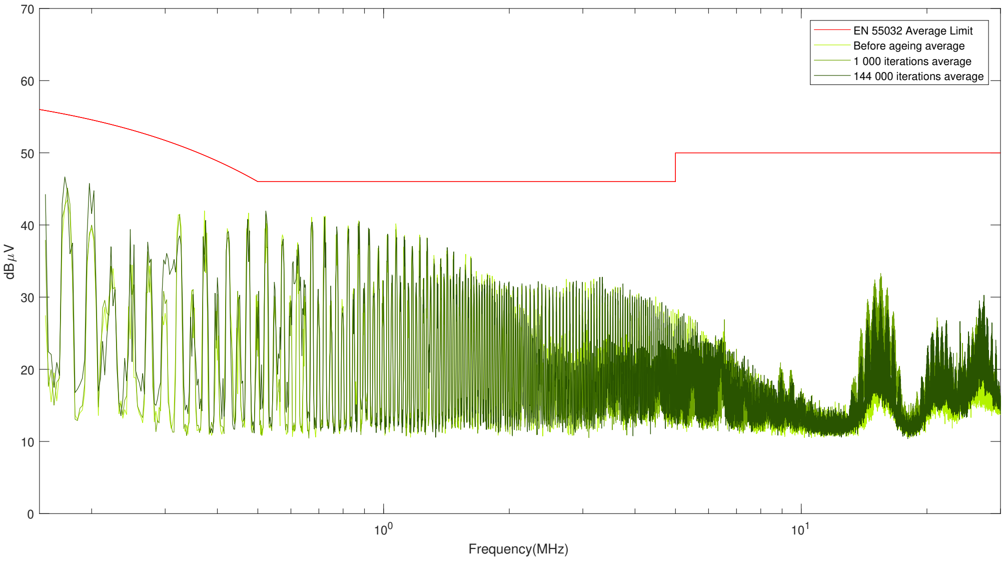

Figure A.77: Average Measurements of DUT #36

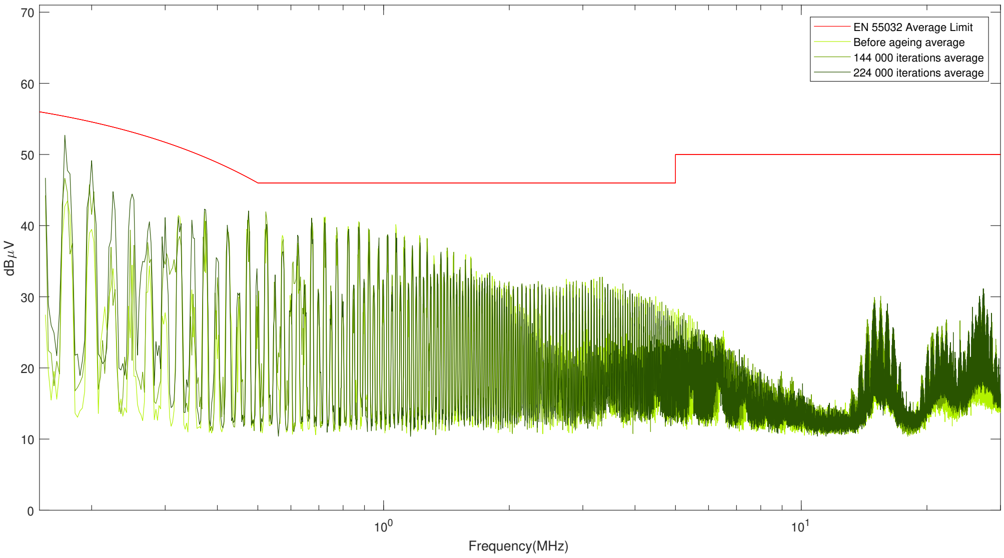

Figure A.78: Average Measurements of DUT #36 after the normal ultimate ageing

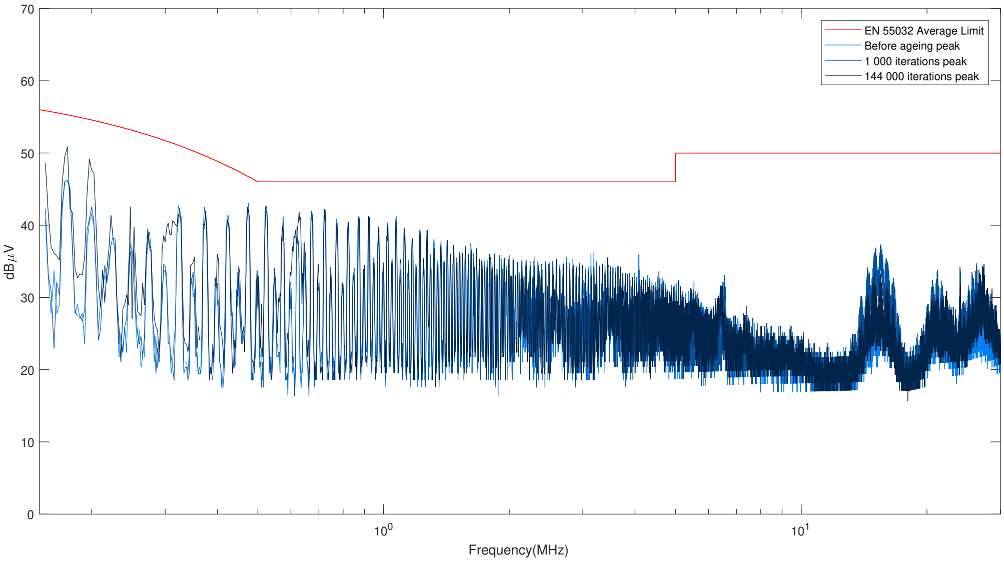

Figure A.79: Peak Measurements of DUT #36

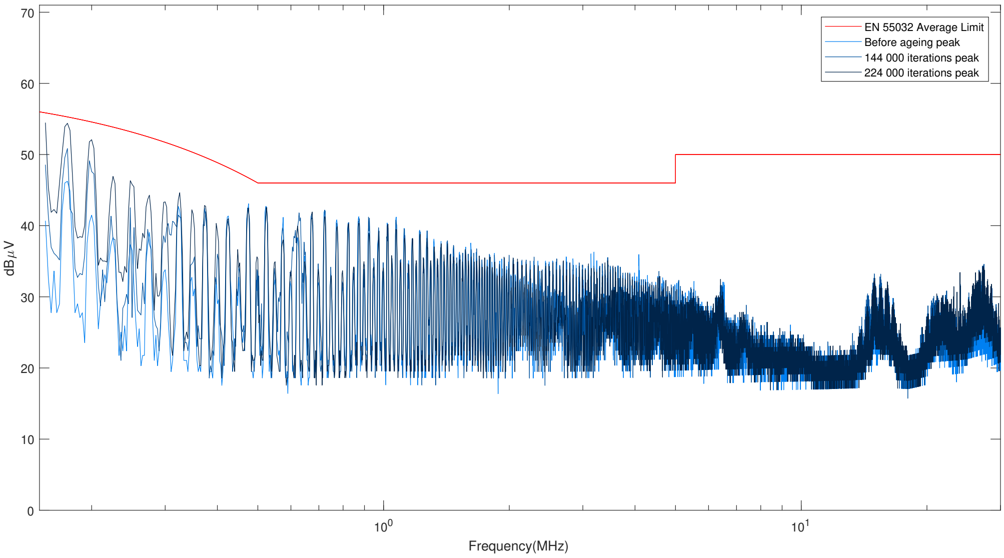

Figure A.80: Peak Measurements of DUT #36 after the normal ultimate ageing

DUT 37

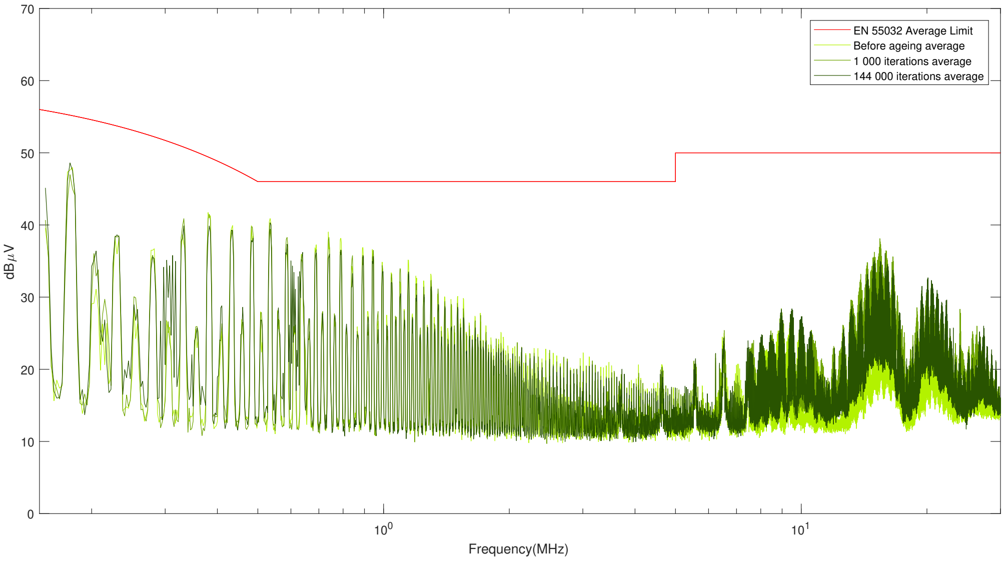

Figure A.81: Average Measurements of DUT #37

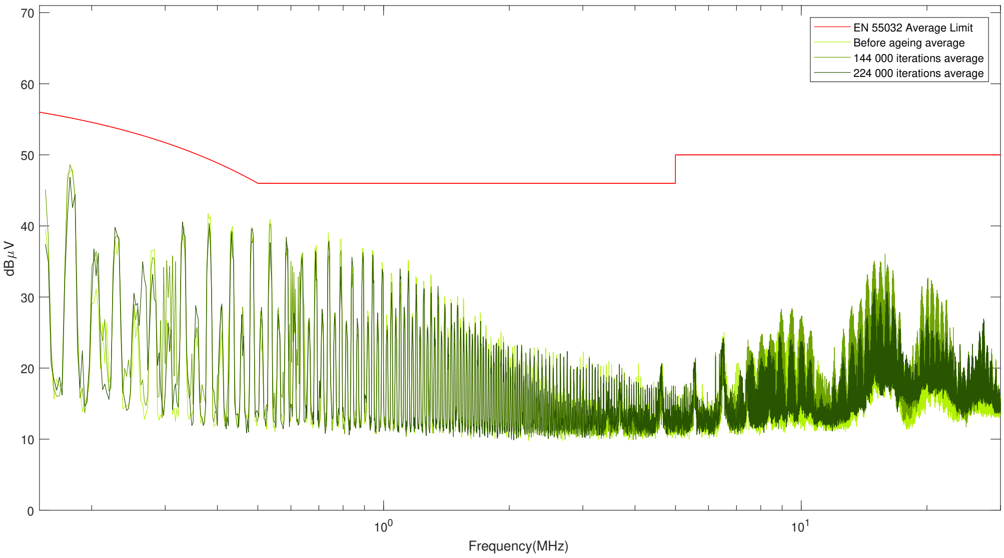

Figure A.82: Average Measurements of DUT #37 after the normal ultimate ageing

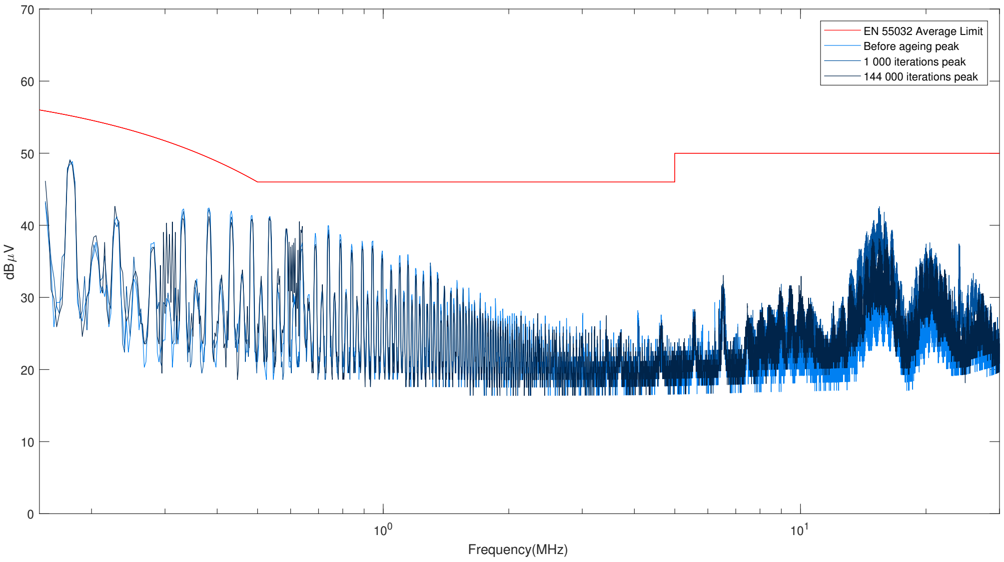

Figure A.83: Peak Measurements of DUT #37

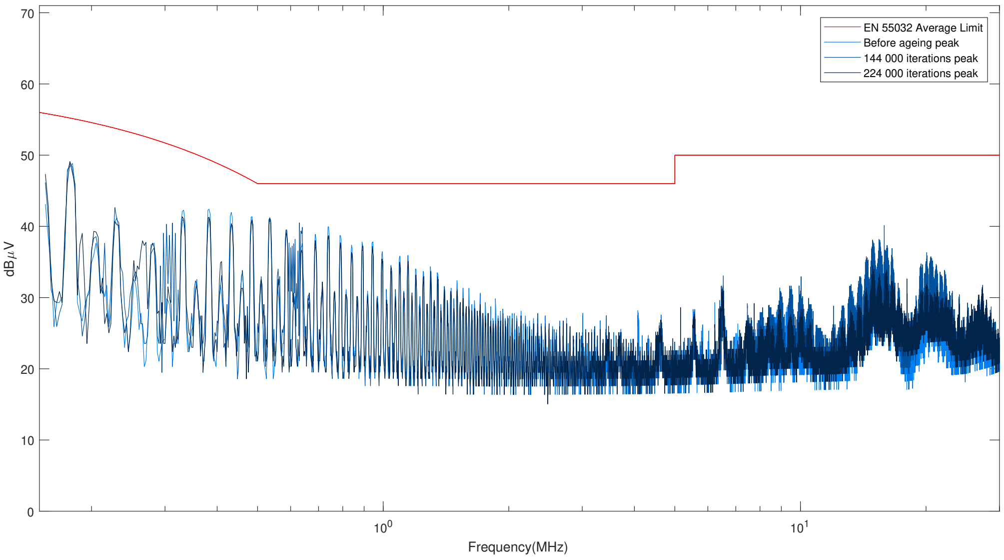

Figure A.84: Peak Measurements of DUT #37 after the normal ultimate ageing

DUT 38

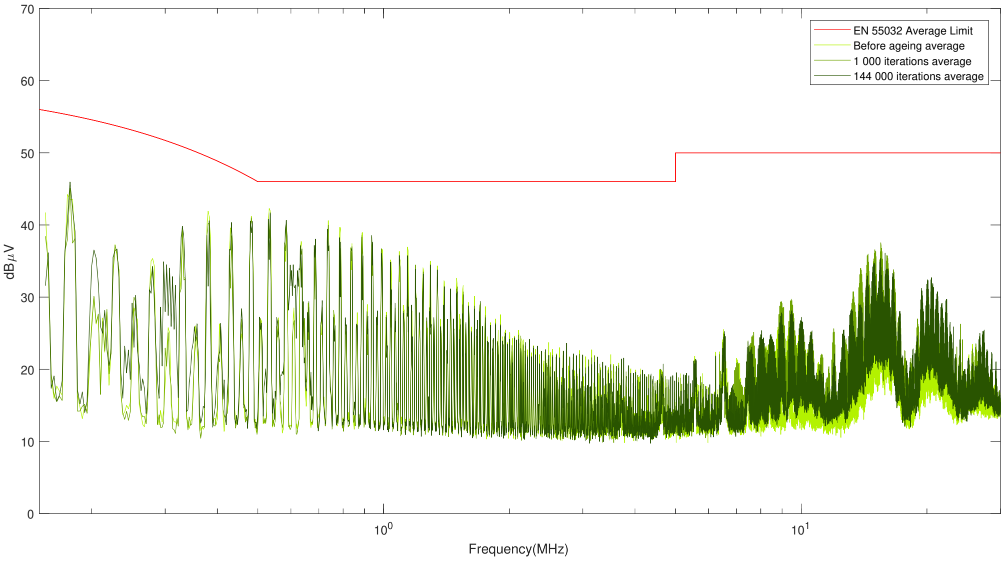

Figure A.85: Average Measurements of DUT #38

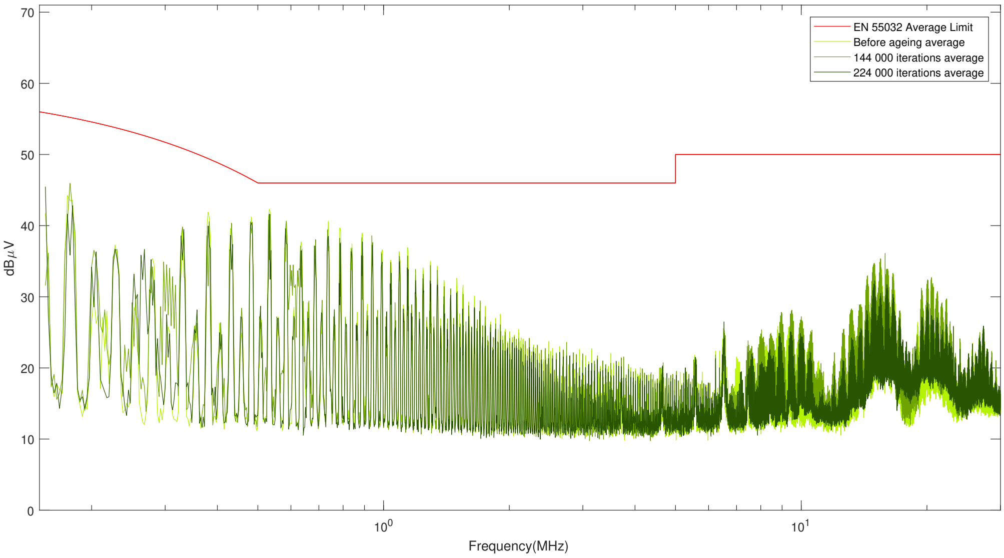

Figure A.86: Average Measurements of DUT #38 after the normal ultimate ageing

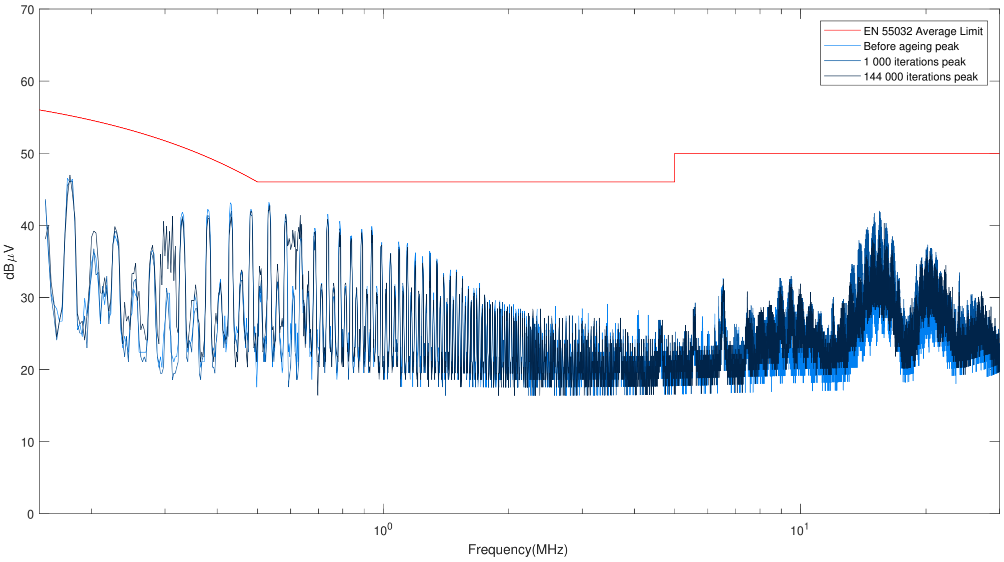

Figure A.87: Peak Measurements of DUT #38

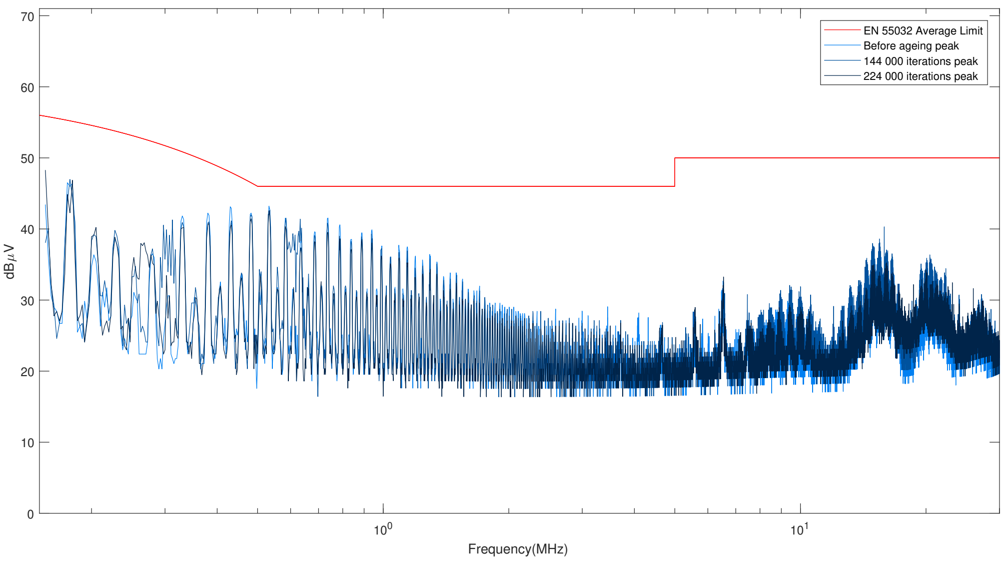

Figure A.88: Peak Measurements of DUT #38 after the normal ultimate ageing

B SSR Operation Code

```
// SSR relay pin setup
int relayPin = 13;// Set pin output for SSR
long int nIt=80000; // Number of desired iterations
long int i=1;

// setup code
void setup() {
  Serial.begin(9600); // Serial COMM
  pinMode(relayPin, OUTPUT); //Set relayPin as OUTPUT
  randomSeed(analogRead(0));
}

// loop code
void loop() {

  for ( i=1; i <= nIt ; i++){ // Do
    Serial.print("\n");
    Serial.print(i);

    // Turn the SSR ON
    digitalWrite(relayPin, HIGH);// set relay pin to HIGH (on)
    //delay(1000); // Set X*1000 for the amount of seconds to ON TIME
    delay(random(500,8000));

    // Turn the SSR OFF
    digitalWrite(relayPin, LOW);// set relay pin to LOW (off)
    //delay(2000); // Set X*1000 for the amount of seconds to OFF TIME
```

```
      delay(random(500,8000));
      }

   Serial.print("\n");
   Serial.print("Number of iterations made: ");
   Serial.print(i-1); // At the last for cycle it increments variable "i" thus
       subtracting 1;

   digitalWrite(relayPin, LOW); // Redundancy to ensure SSR to turn OFF
   exit(0);
}
```